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(54) **AUTONOMOUS TIRE AND WHEEL BALANCER, METHOD THEREFOR AND ROBOTIC AUTOMOTIVE SERVICE SYSTEM**

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(21) Appl. No.: **18/213,239**

(22) Filed: **Jun. 22, 2023**

Related U.S. Application Data

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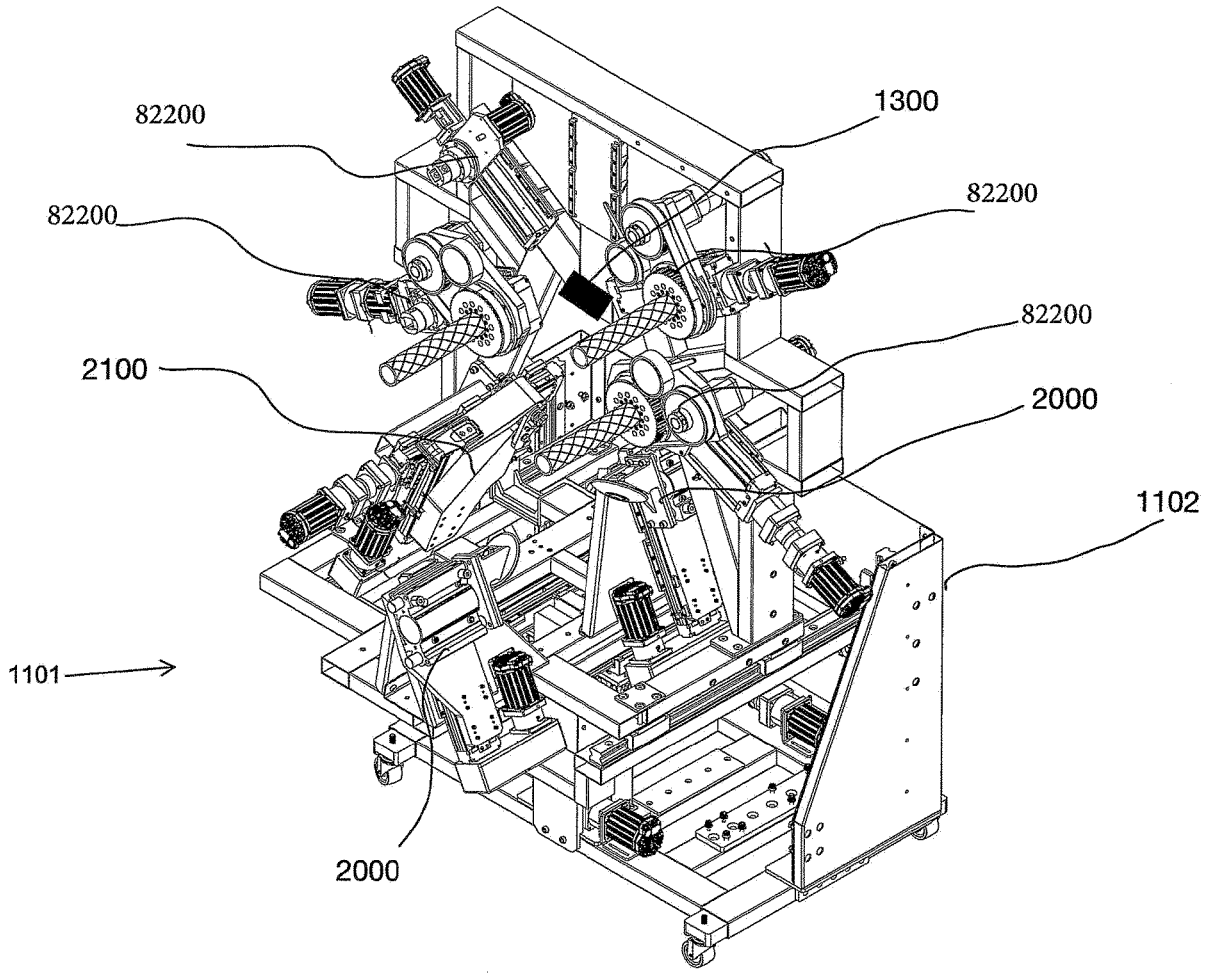
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G01M 1/04 (2006.01)

(52) **U.S. Cl.**
CPC ***G01M 1/28*** (2013.01); ***G01M 1/045*** (2013.01)

(57) **ABSTRACT**

A vehicle component balancing robot apparatus, system and method for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle. The apparatus includes a frame arranged so as to connect with the vehicle. A robot of the apparatus moves relative to the frame, and is configured so that the move, relative to the frame, resolves a predetermined location of a tire-wheel assembly relative to a reference frame of the robot. The robot has at least one end effector arranged to interface the tire-wheel assembly and the robot moves the at least one end effector to other predetermined locations on a wheel rim of the tire-wheel assembly, determined based on resolution of the predetermined location of the tire-wheel assembly relative to the reference frame.



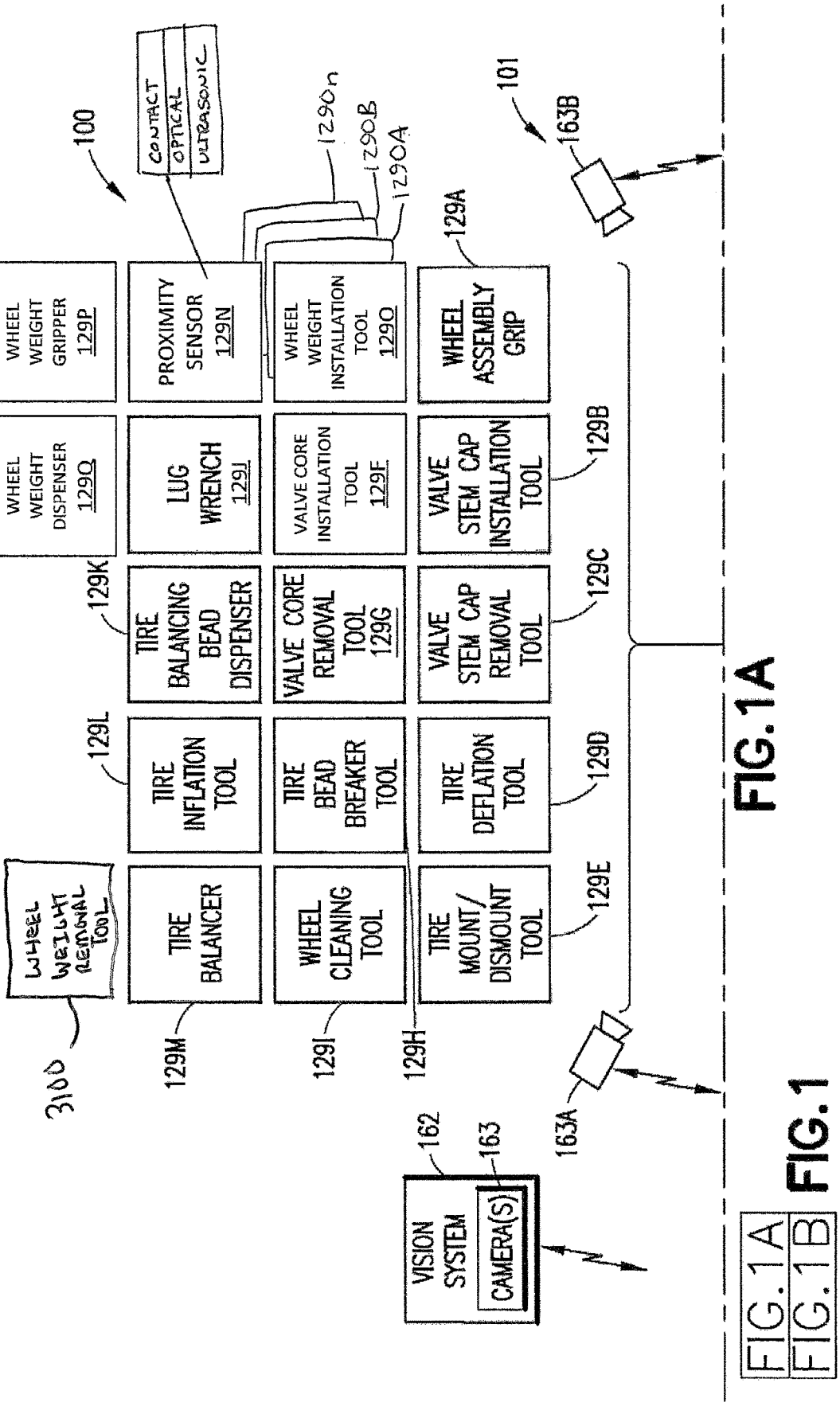


FIG. 1A

FIG. 1B FIG. 1

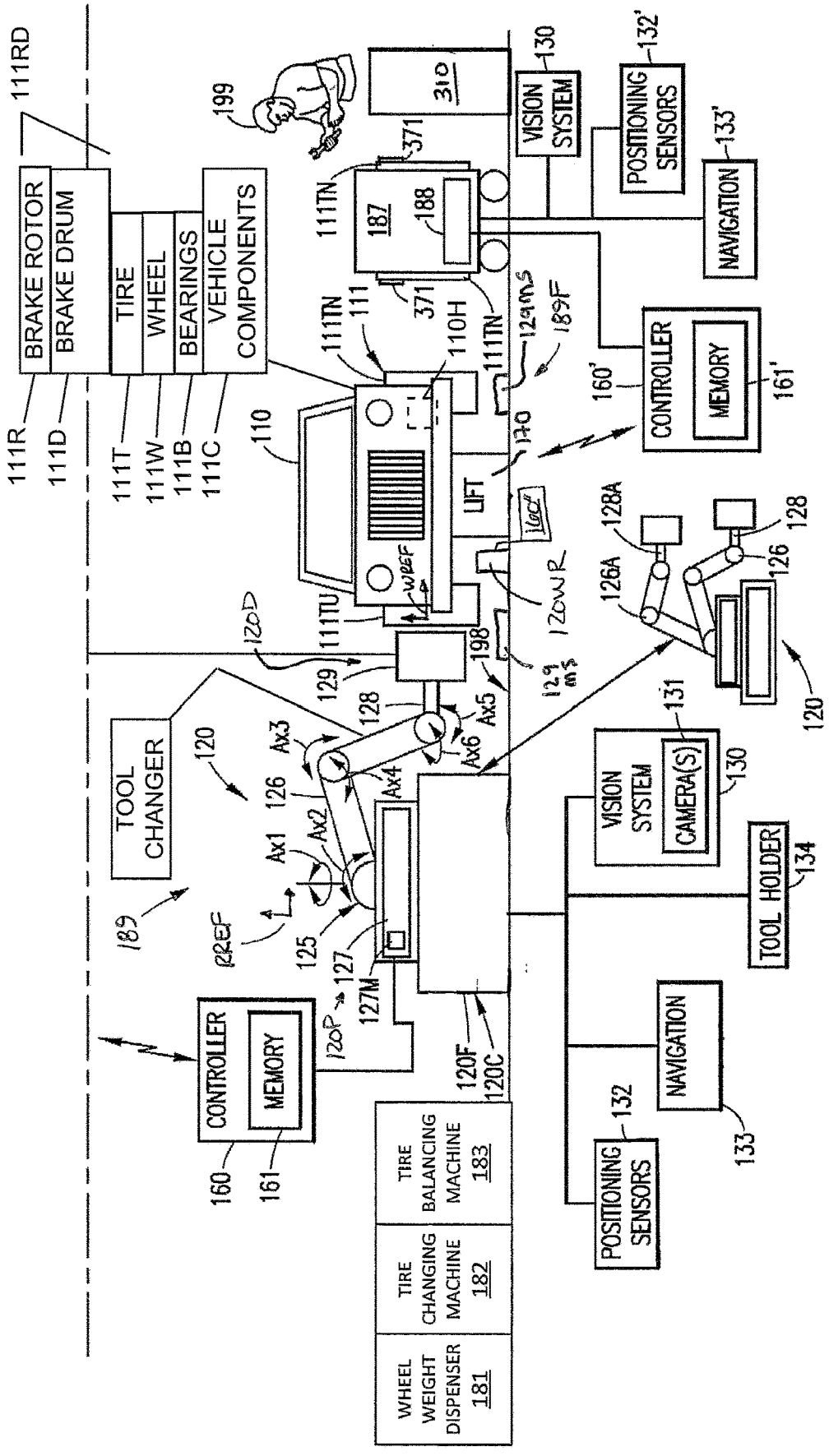

111RD
BRAKE ROTOR
BRAKE DRUM
TIRE
WHEEL
BEARINGS
VEHICLE COMPONENTS
111R
111D
111T
111W
111B
111C
199
310
371
111TN
187
188
VISION SYSTEM
130
POSITIONING SENSORS
132'
NAVIGATION
133'
110
111
110H
LIFT
140
CONTROLLER
MEMORY
160'
161'
189F
129MS
WREF
111TU
120D
198
129
128
120WR
128A
126A
126
120
TOOL CHANGER
189
BREF
120
Ax1
Ax2
Ax3
Ax4
Ax5
Ax6
125
127
127M
120P
120F
120C
131
VISION SYSTEM
CAMERA(S)
130
TOOL HOLDER
134
CONTROLLER
MEMORY
160
161
132
POSITIONING SENSORS
NAVIGATION
133
TIRE BALANCING MACHINE 183
TIRE CHANGING MACHINE 182
WHEEL WEIGHT DISPENSER 181

FIG. 1B

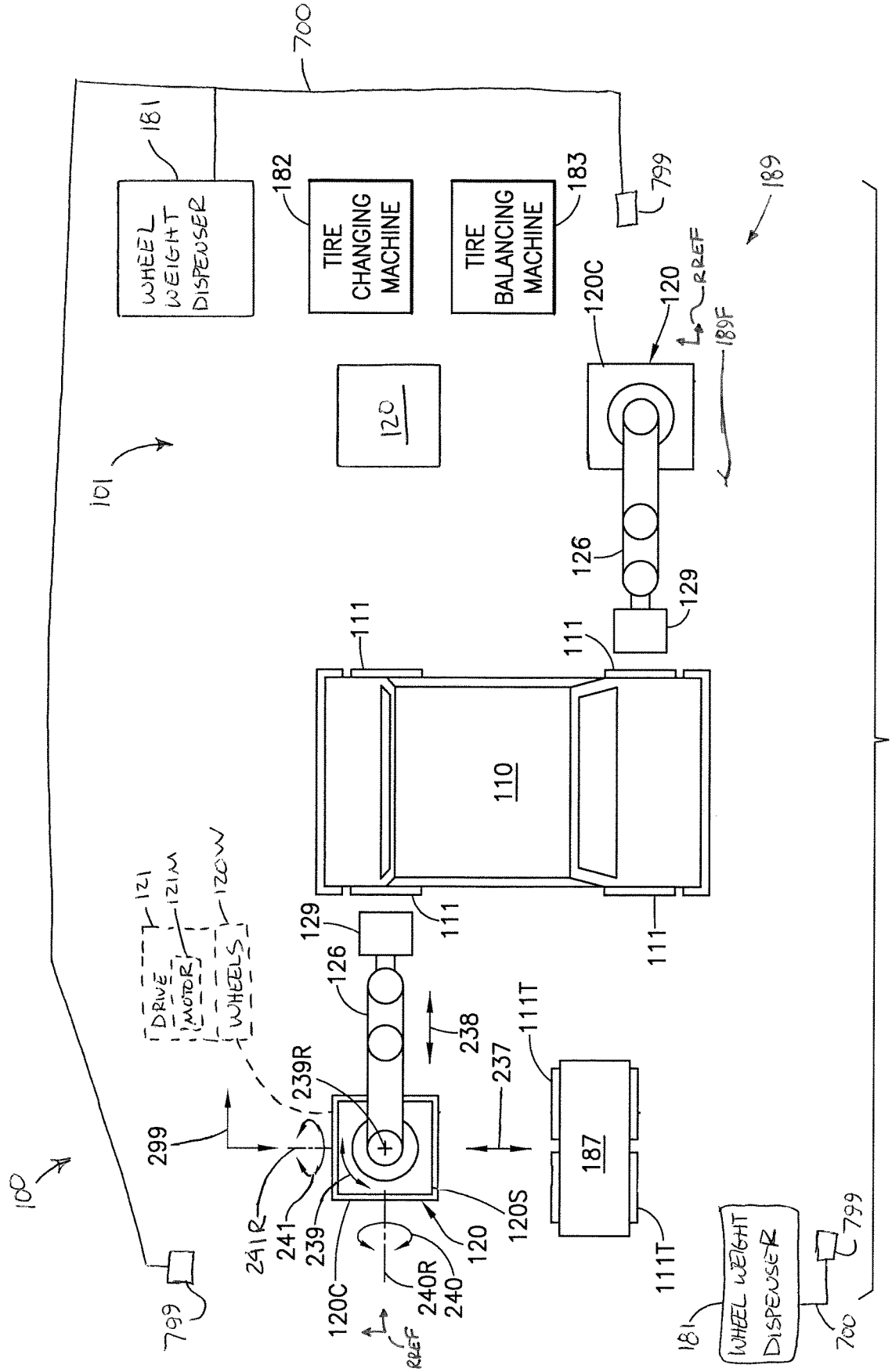

700
181
WHEEL WEIGHT DISPENSER
182
TIRE CHANGING MACHINE
183
TIRE BALANCING MACHINE
799
189
120C
120
RREF
189F
120
101
126
129
111
110
DRIVE
MOTOR
WHEELS
121
121M
120W
299
239R
241R
241
239
120C
240R
240
RREF
120
120S
238
237
111T
187
111T
181
WHEEL WEIGHT DISPENSER
799
700
100

FIG.2A

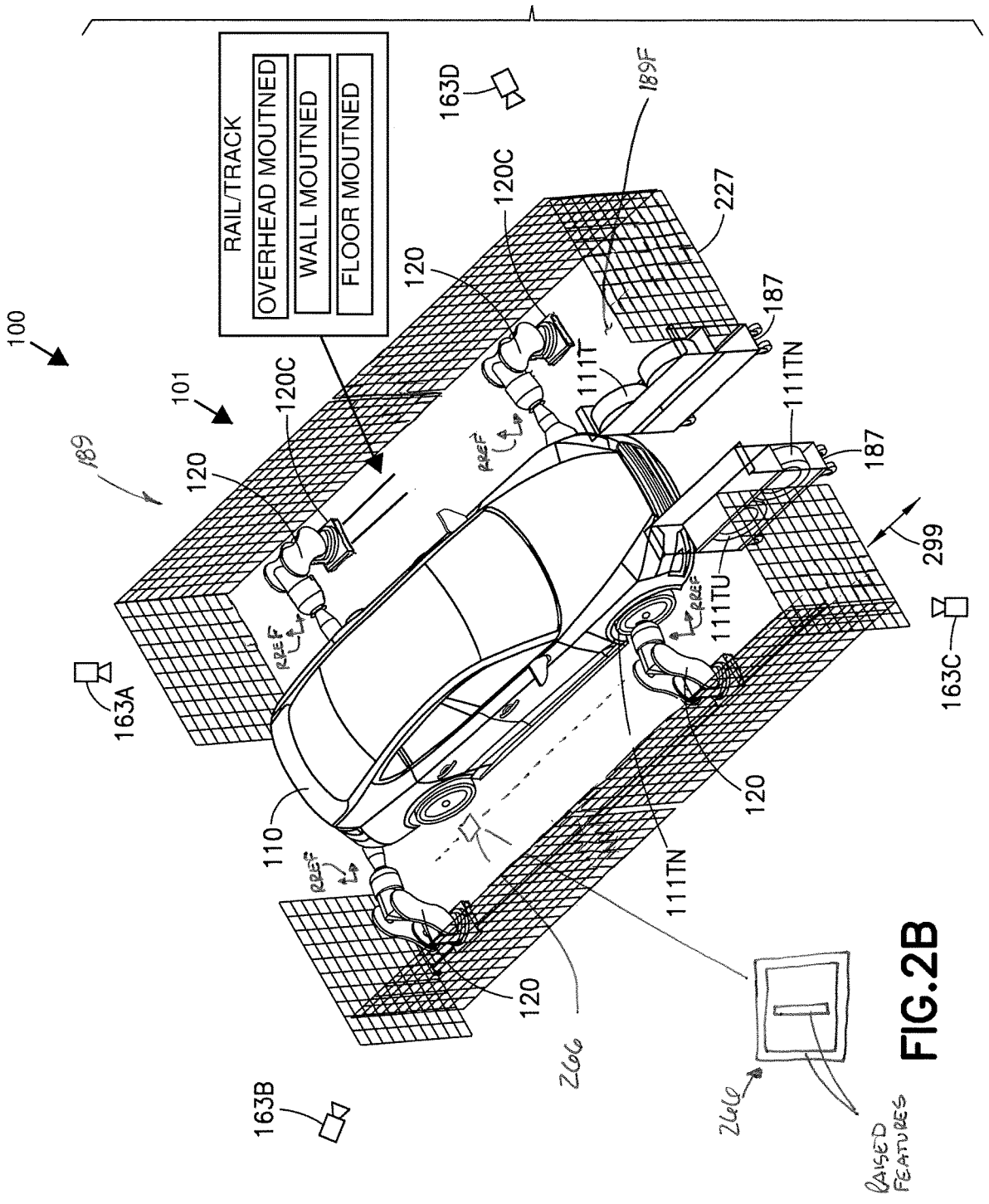

RAIL/TRACK
OVERHEAD MOUTNED
WALL MOUTNED
FLOOR MOUTNED
100
101
189
120
120C
163A
163B
163C
163D
110
111T
111TN
111TU
187
189F
227
299
206
206
RAISED FEATURES
REF

FIG.2B

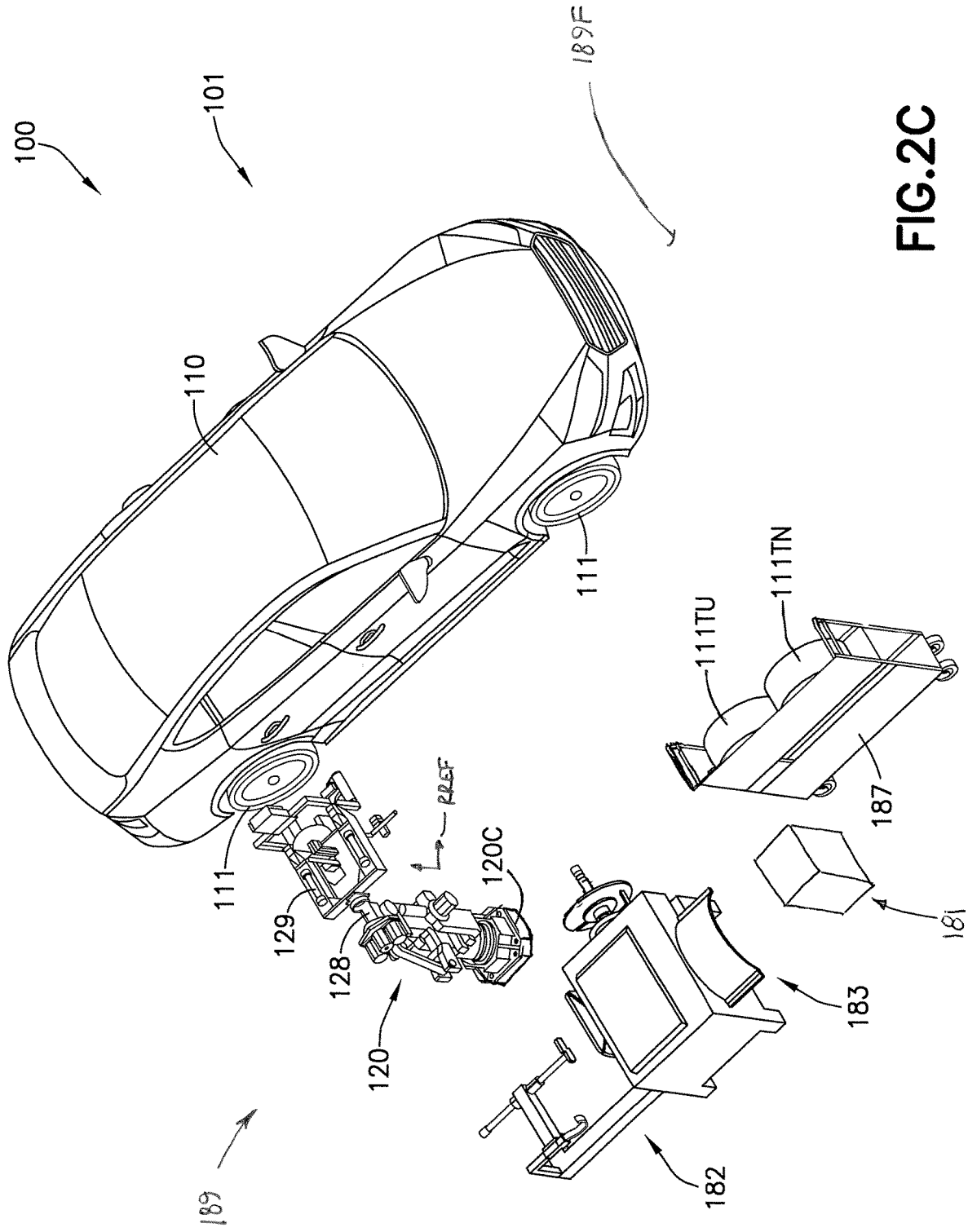

100
101
189F
110
111
111TU
111TN
187
181
183
182
189
120
128
129
120C
RLSF
111

FIG.2C

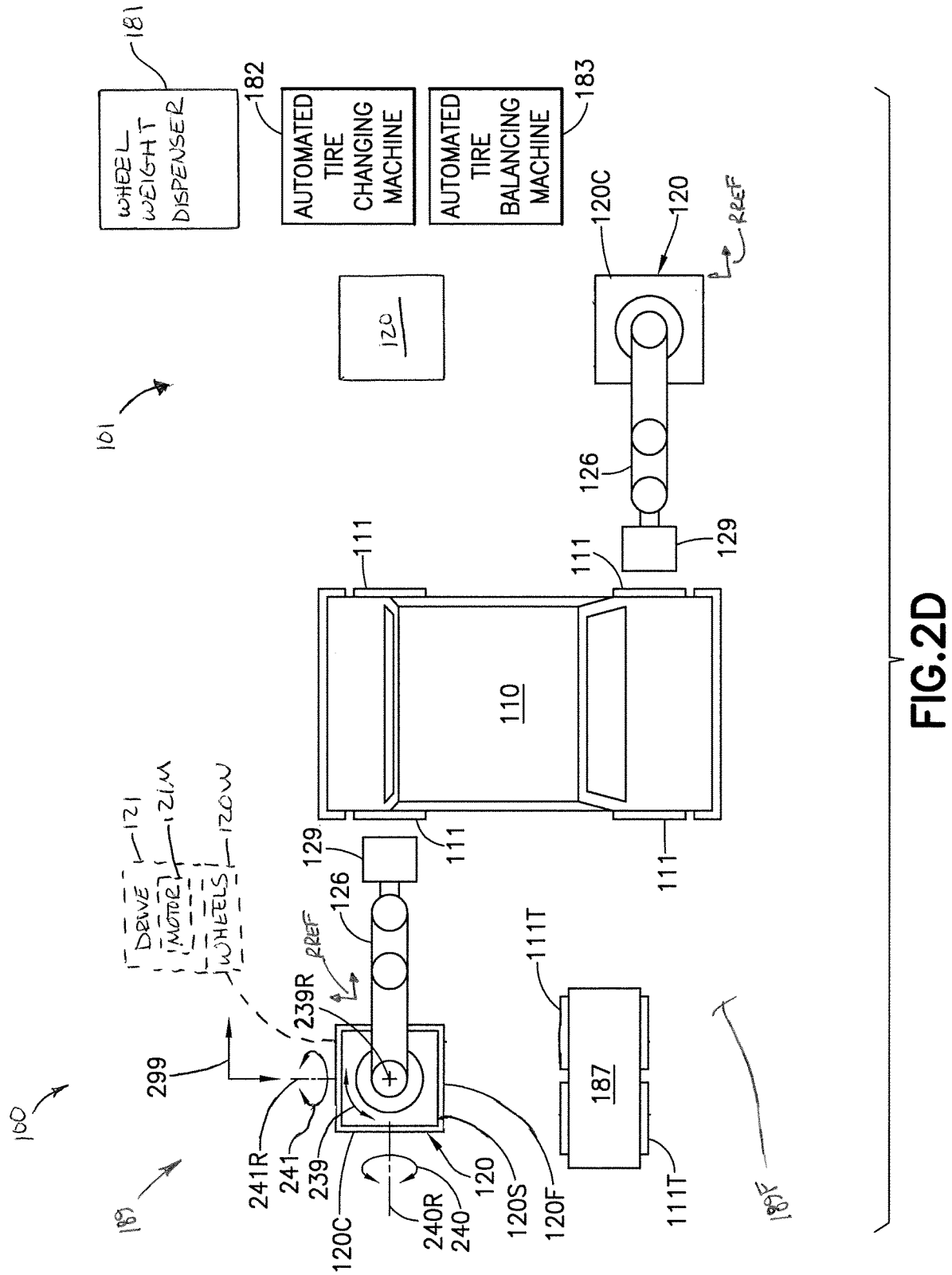

181
WHEEL WEIGHT DISPENSER
182
AUTOMATED TIRE CHANGING MACHINE
183
AUTOMATED TIRE BALANCING MACHINE
120C
120
REF
120
101
126
129
111
110
111
111
129
126
REF
239R
111T
187
DRIVE 121
MOTOR 121M
WHEELS 120W
299
241R
241
239
120C
240R
240
120
120S
120F
111T
189F
189
100

FIG.2D

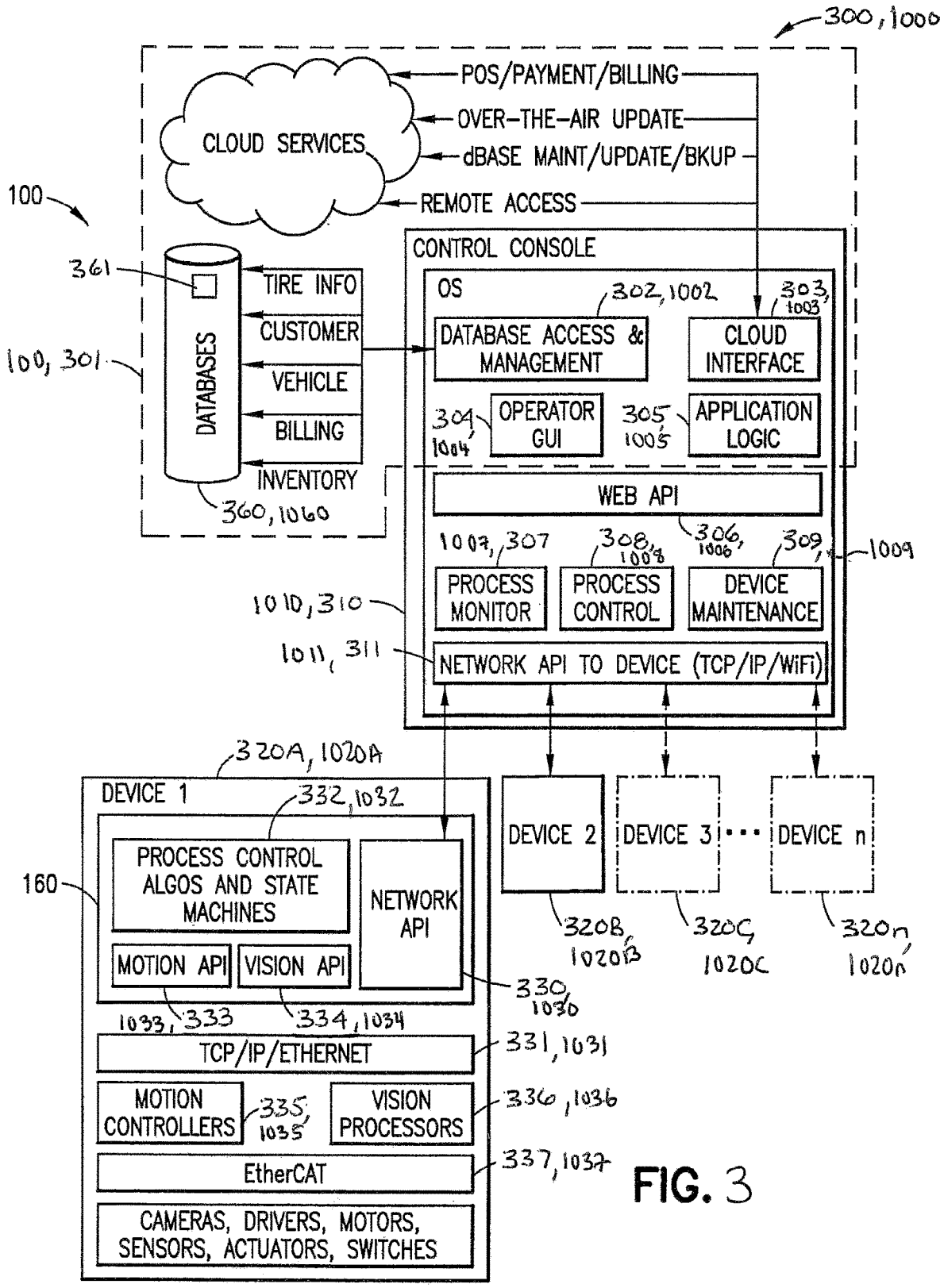

300, 1000
POS/PAYMENT/BILLING
OVER-THE-AIR UPDATE
dBASE MAINT/UPDATE/BKUP
REMOTE ACCESS
CLOUD SERVICES
100
CONTROL CONSOLE
OS
302, 1002
303, 1003
DATABASE ACCESS & MANAGEMENT
CLOUD INTERFACE
304, 1004
OPERATOR GUI
305, 1005
APPLICATION LOGIC
WEB API
306, 1006
1007, 307
308, 1008
309, 1009
PROCESS MONITOR
PROCESS CONTROL
DEVICE MAINTENANCE
1010, 310
1011, 311
NETWORK API TO DEVICE (TCP/IP/WiFi)
361
DATABASES
TIRE INFO
CUSTOMER
VEHICLE
BILLING
INVENTORY
100, 301
360, 1060
320A, 1020A
DEVICE 1
332, 1032
PROCESS CONTROL ALGOS AND STATE MACHINES
NETWORK API
160
MOTION API
VISION API
330, 1030
1033, 333
334, 1034
TCP/IP/ETHERNET
331, 1031
MOTION CONTROLLERS
335, 1035
VISION PROCESSORS
336, 1036
EtherCAT
337, 1037
CAMERAS, DRIVERS, MOTORS, SENSORS, ACTUATORS, SWITCHES
DEVICE 2
DEVICE 3
DEVICE n
320B, 1020B
320C, 1020C
320n, 1020n

FIG. 3

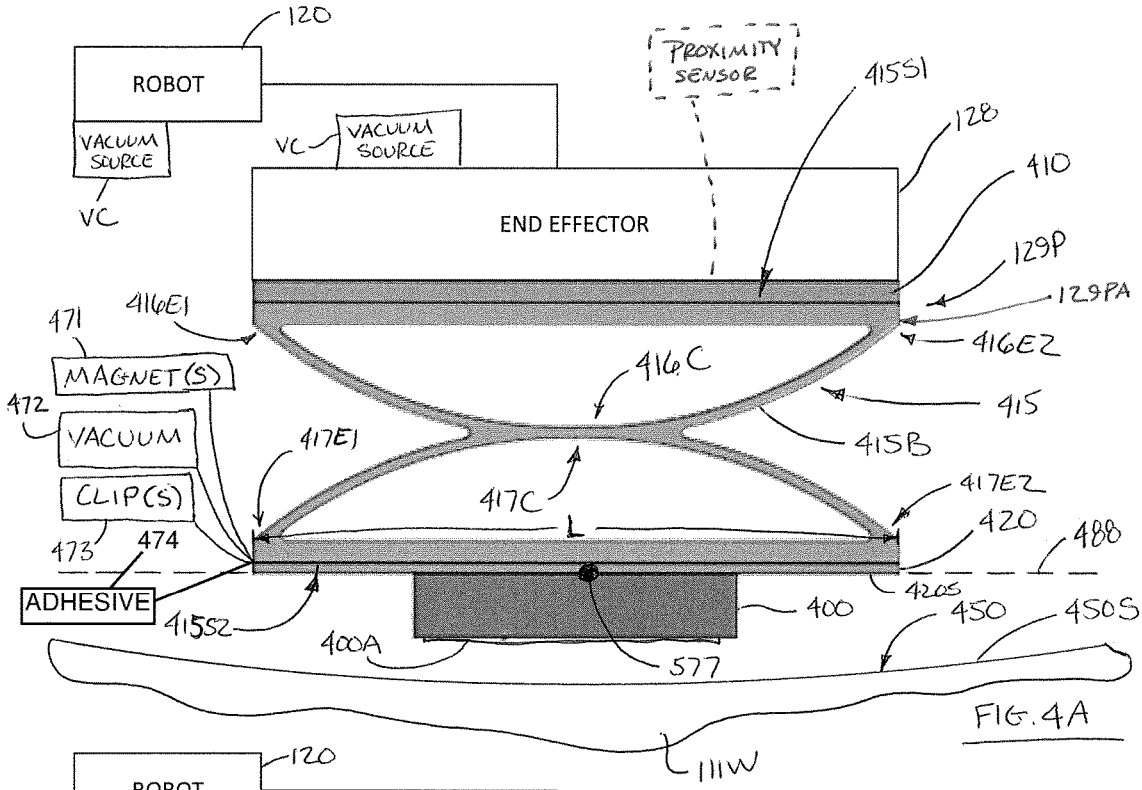

120
ROBOT
VACUUM SOURCE
VC
PROXIMITY SENSOR
415S1
128
410
END EFFECTOR
129P
129PA
416E2
416E1
471
MAGNET(S)
472
VACUUM
CLIP(S)
473
474
ADHESIVE
416C
415
415B
417E1
417C
417E2
L
420
488
420S
400
450
450S
415S2
400A
577
111W

FIG. 4A

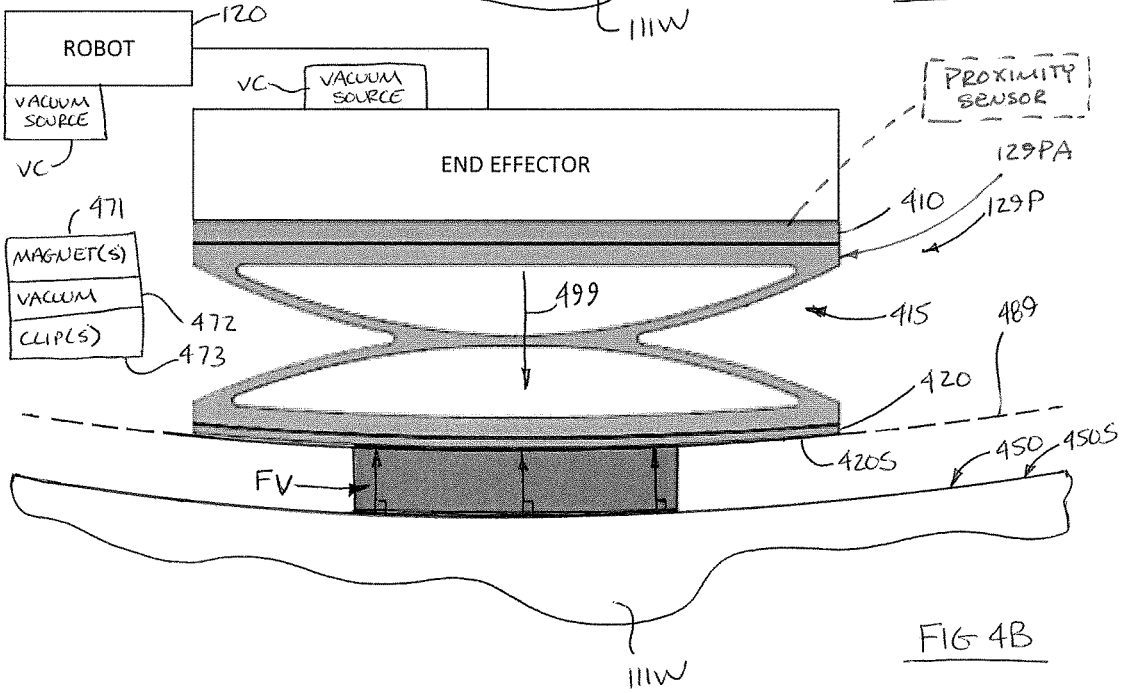

120
ROBOT
VACUUM SOURCE
VC
PROXIMITY SENSOR
129PA
END EFFECTOR
410
129P
471
MAGNET(S)
VACUUM
CLIP(S)
472
473
499
415
489
420
420S
450
450S
FV
111W

FIG 4B

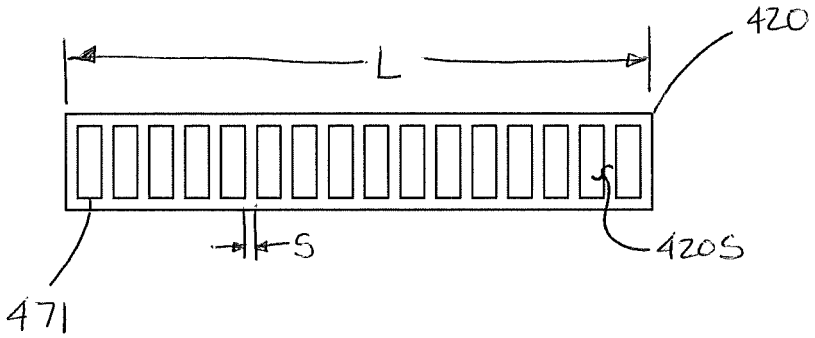


FIG 4C

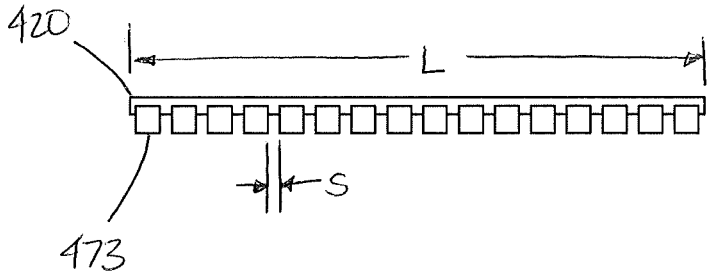


FIG. 4D

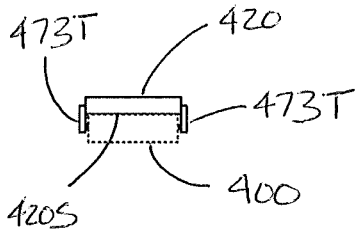


FIG. 4E

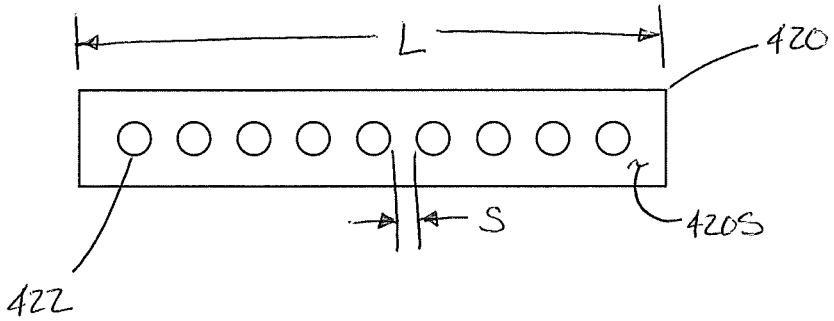


FIG 4F

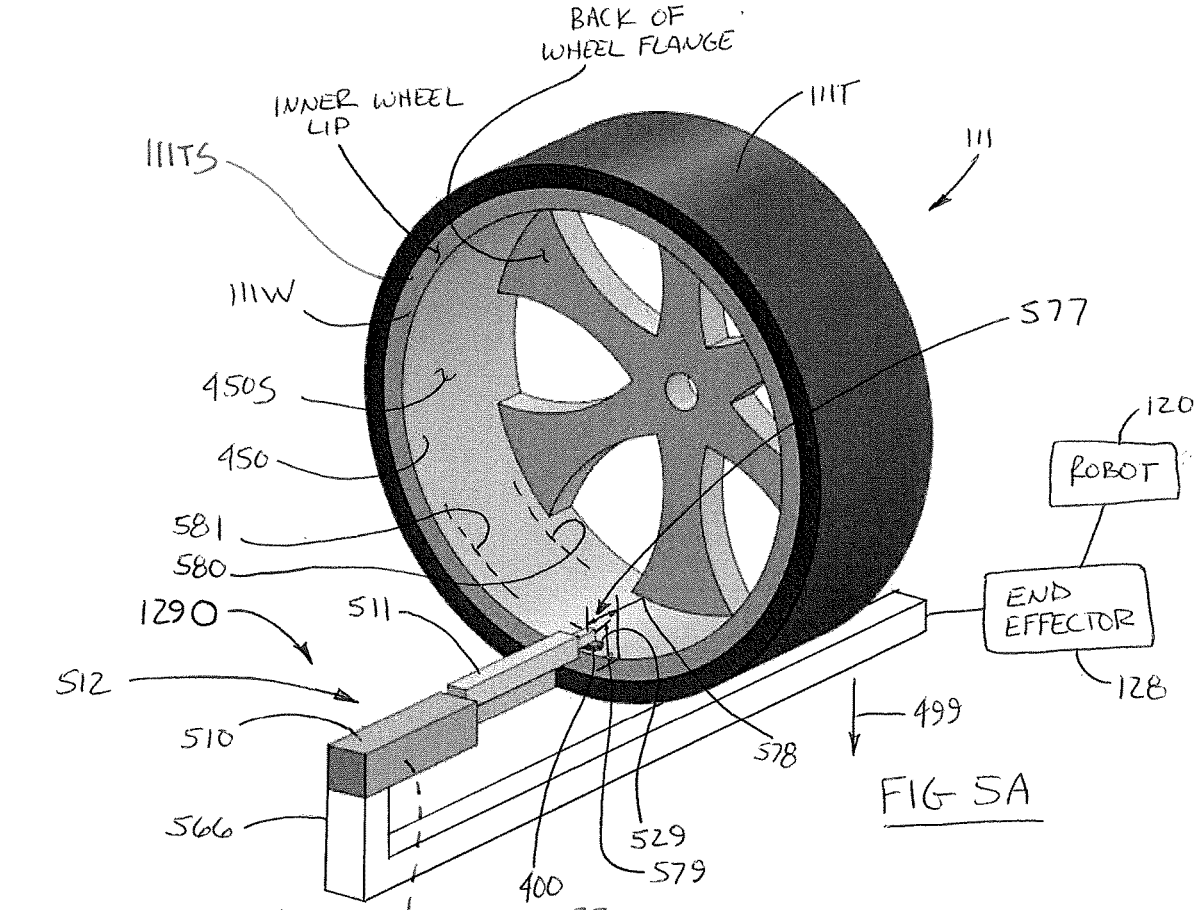

BACK OF WHEEL FLANGE
INNER WHEEL LIP
111TS
111T
111
111W
577
450S
450
581
580
1290
511
512
510
566
578
499
529
579
400
120
ROBOT
END EFFECTOR
128
120D
PROXIMITY SENSOR
ENCODER
DISTANCE SENSOR

FIG. 5A

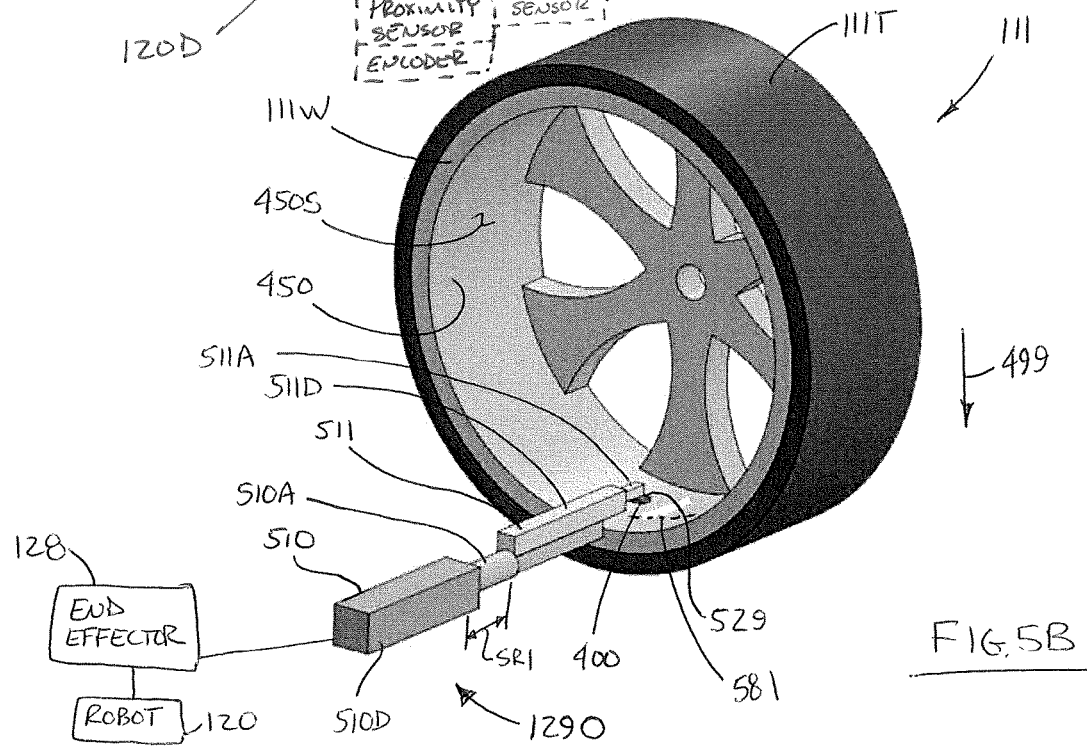

111T
111
111W
450S
450
511A
511D
511
510A
510
128
END EFFECTOR
ROBOT
120
510D
SR1
400
529
581
1290
499

FIG. 5B

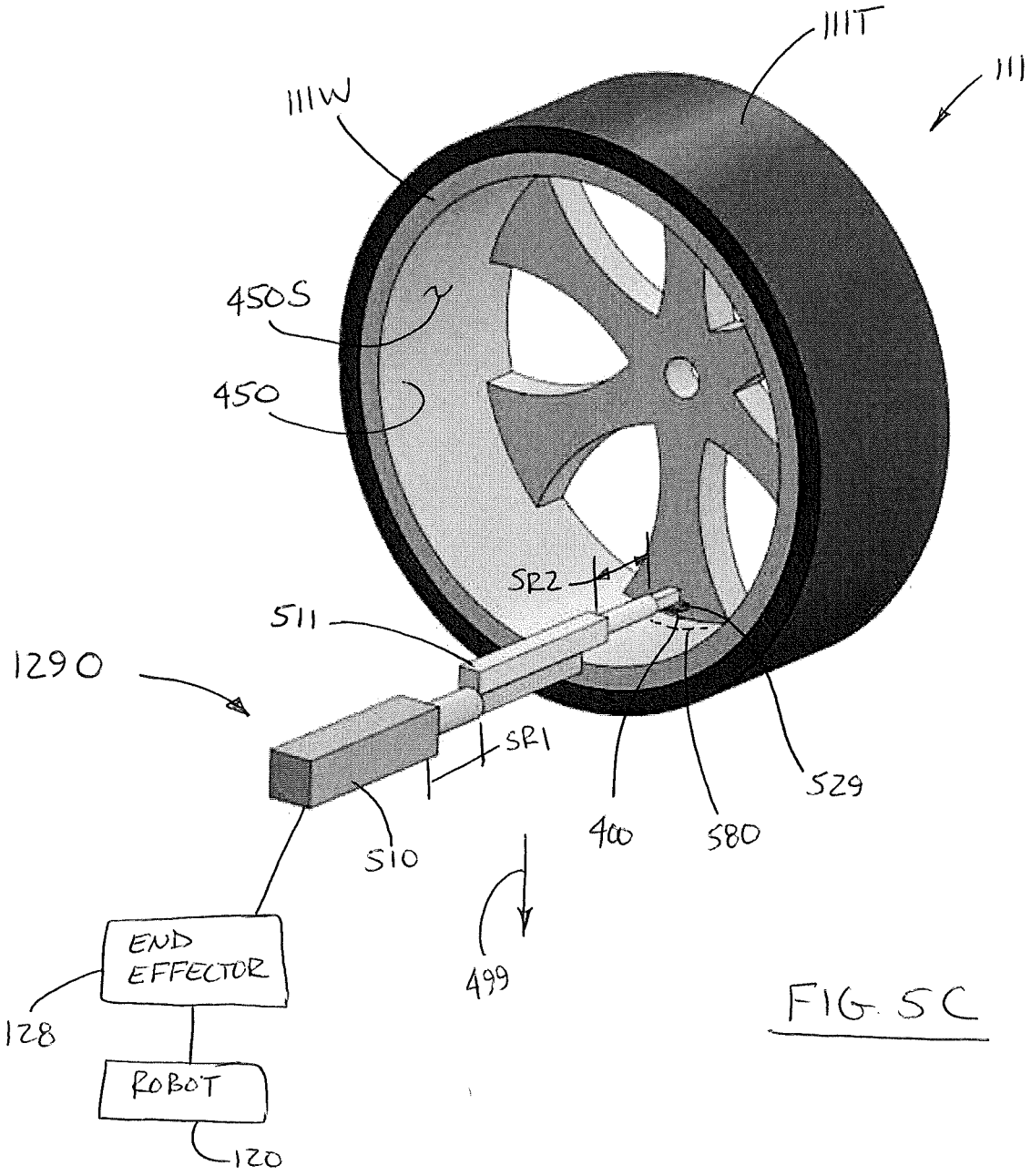

111T
111
111W
450S
450
SR2
511
1290
SR1
529
400
580
510
499
END EFFECTOR
128
ROBOT
120

FIG. 5C

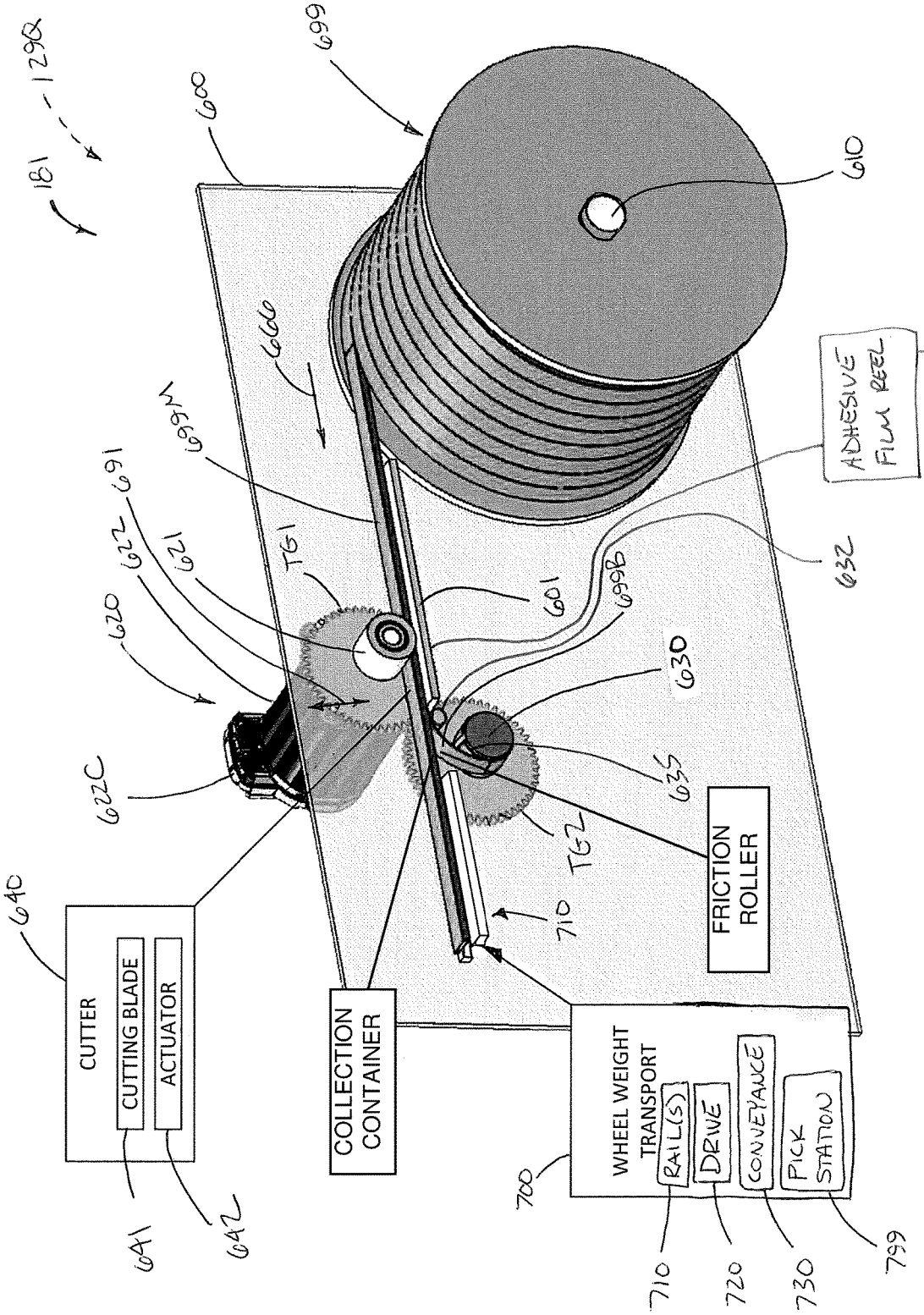

181
1298
699
600
610
631
ADHESIVE FILM REEL
632
698M
691
627
621
620
TG1
601
698B
630
635
622C
TG2
710
FRICTION ROLLER
640
CUTTER
CUTTING BLADE
ACTUATOR
641
642
COLLECTION CONTAINER
700
WHEEL WEIGHT TRANSPORT
RAIL(S)
DRIVE
CONVEYANCE
PICK STATION
710
720
730
799

FIG 6A

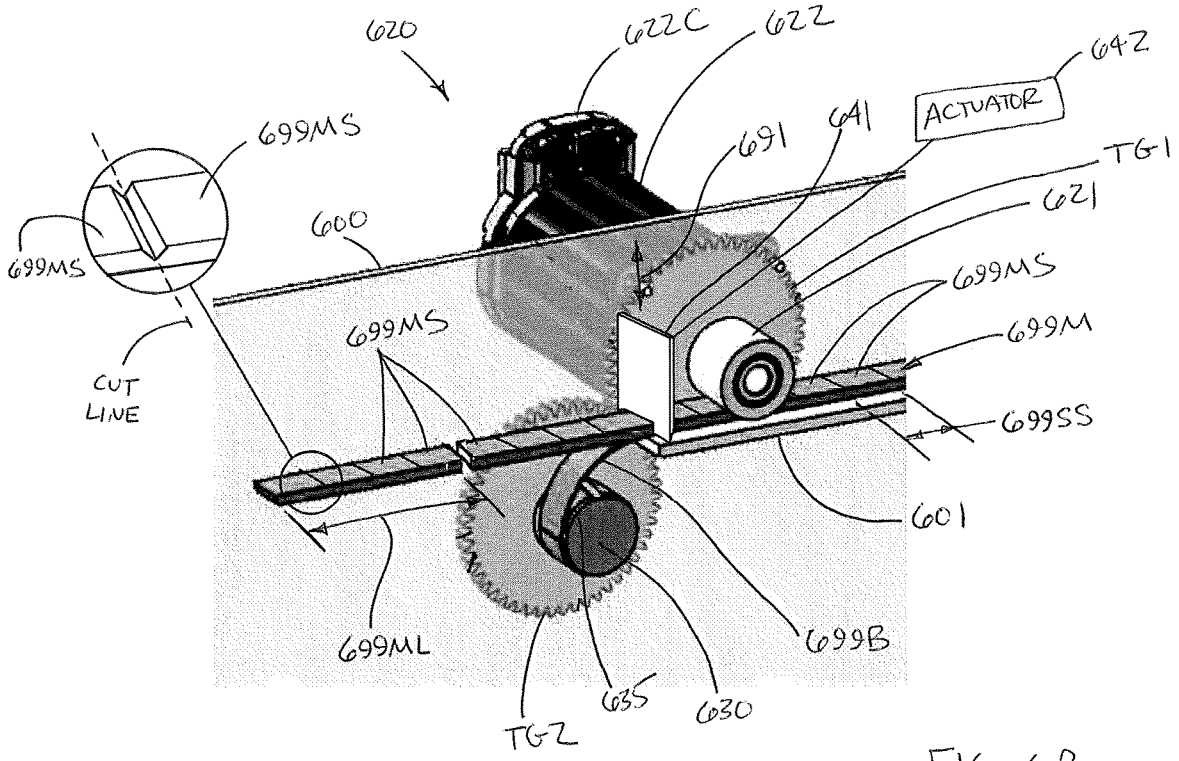

620
622C
622
642
ACTUATOR
699MS
691
641
TG1
621
600
699MS
699MS
699M
699SS
CUT LINE
601
699ML
699B
635
630
TG2

FIG 6B

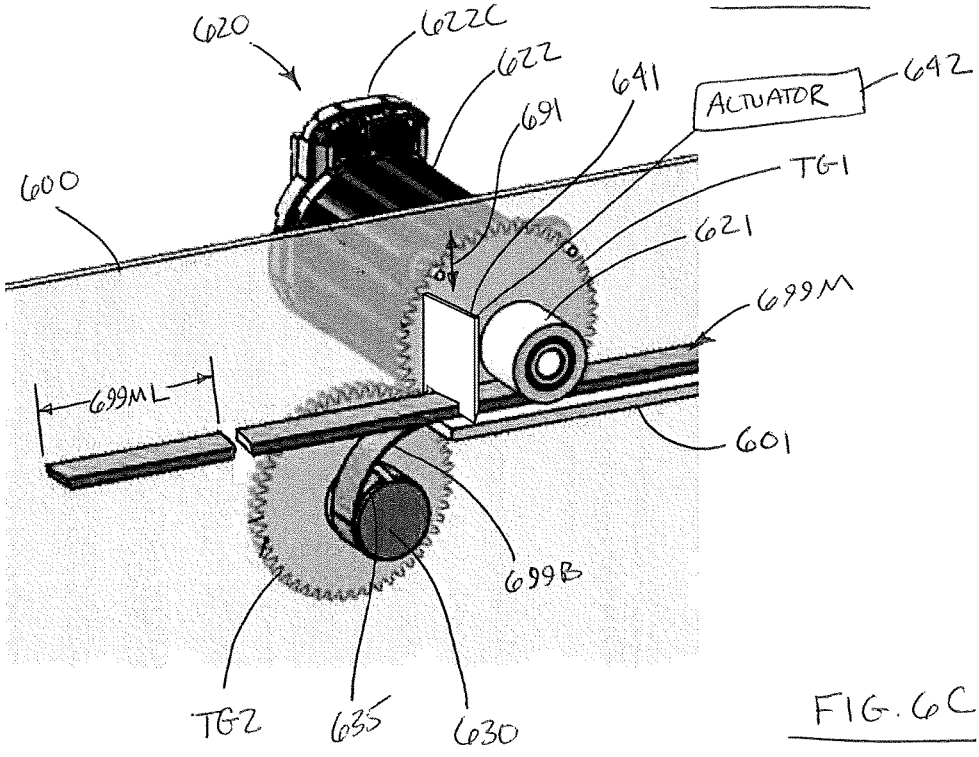
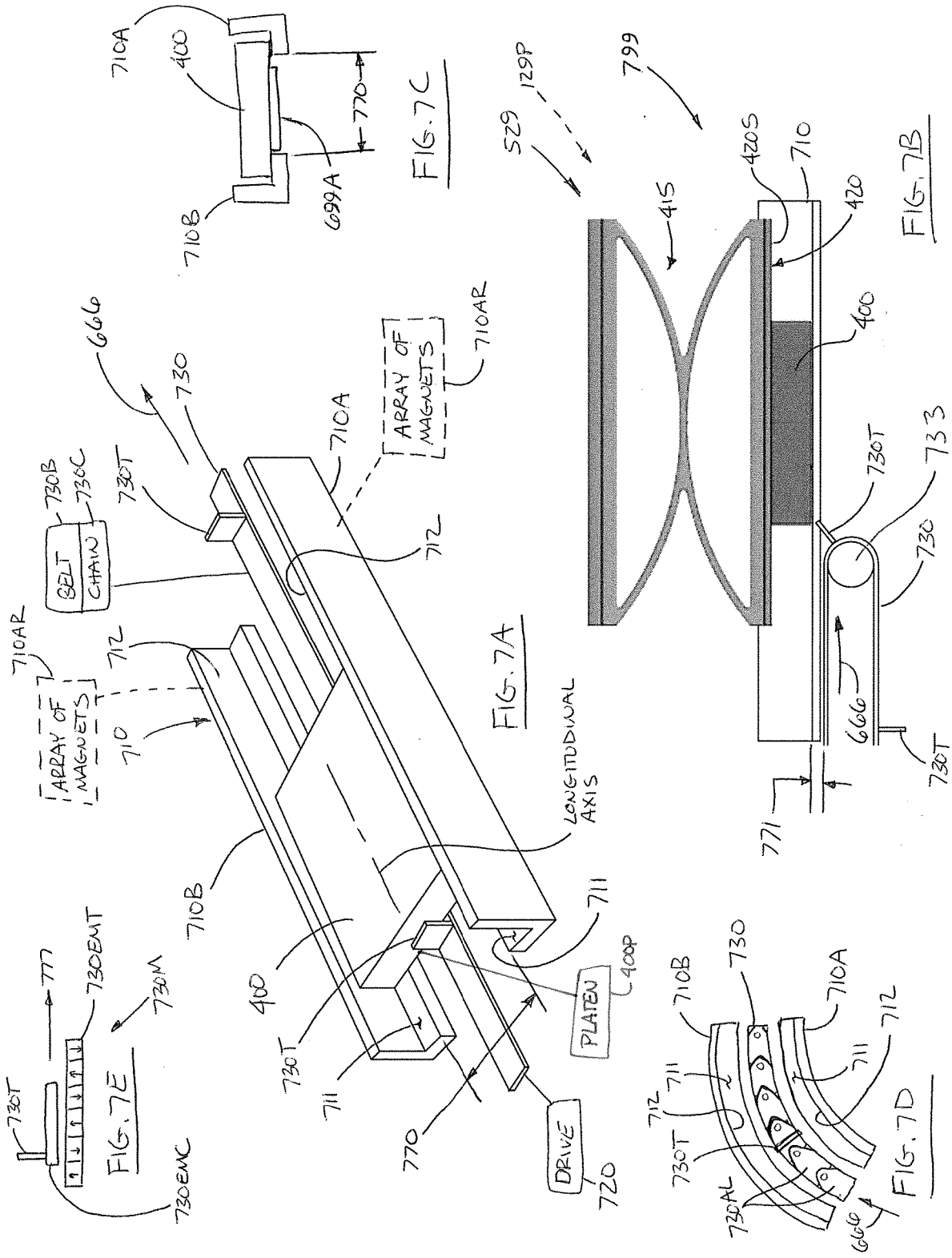

620
622C
622
641
642
ACTUATOR
691
TG1
600
621
699M
699ML
601
699B
TG2
635
630

FIG. 6C


710A
400
770
710B
699A
FIG. 7C
529
1299
799
415
420S
710
420
400
730T
733
730
666
730T
771
FIG. 7B
666
730
730T
ARRAY OF MAGNETS
710AR
712
710A
710AR
ARRAY OF MAGNETS
710
712
710B
LONGITUDINAL AXIS
400
730T
711
770
711
PLATEN
400P
DRIVE
720
FIG. 7A
730T
777
730EMT
730M
730EMC
FIG. 7E
710B
730
710A
712
711
711
712
730T
730AL
666
FIG. 7D

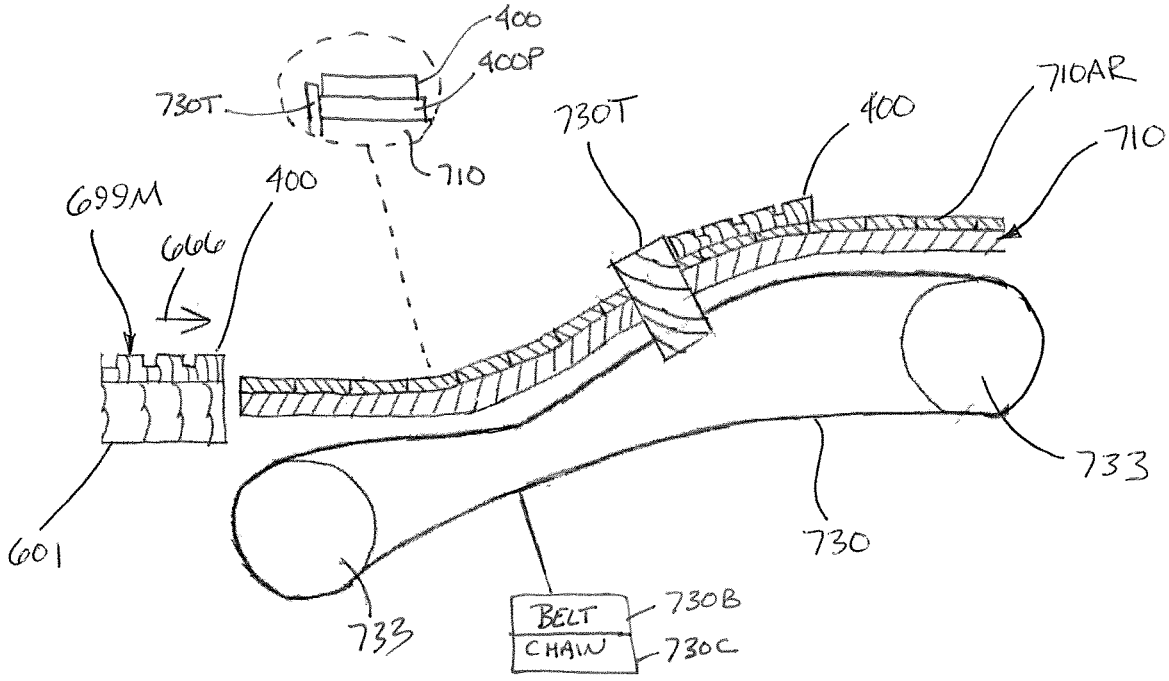

400
400P
730T
710
730T
400
710AR
710
699M
400
6666
601
733
730
733
BELT
CHAIN
730B
730C

FIG. 7F

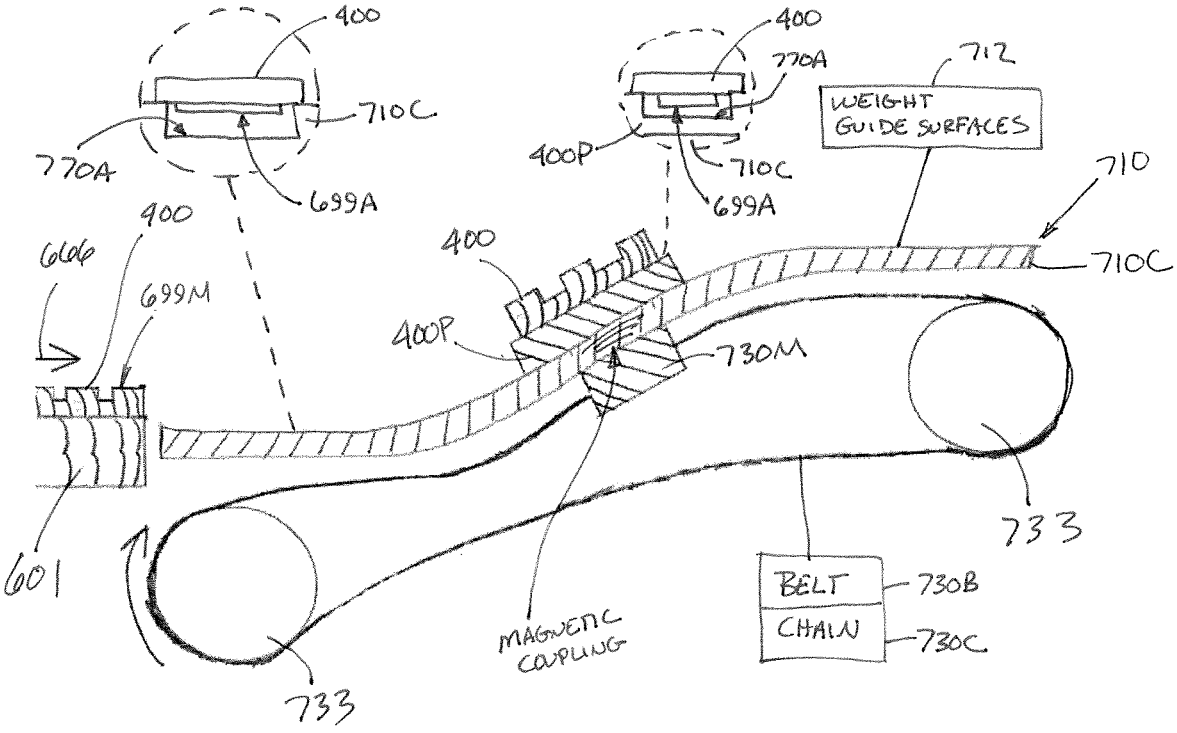

400
710C
770A
699A
400
770A
712
WEIGHT
GUIDE SURFACES
400P
710C
699A
710
400
6666
699M
400
400P
730M
710C
601
733
MAGNETIC
COUPLING
BELT
CHAIN
730B
730C

FIG 8C

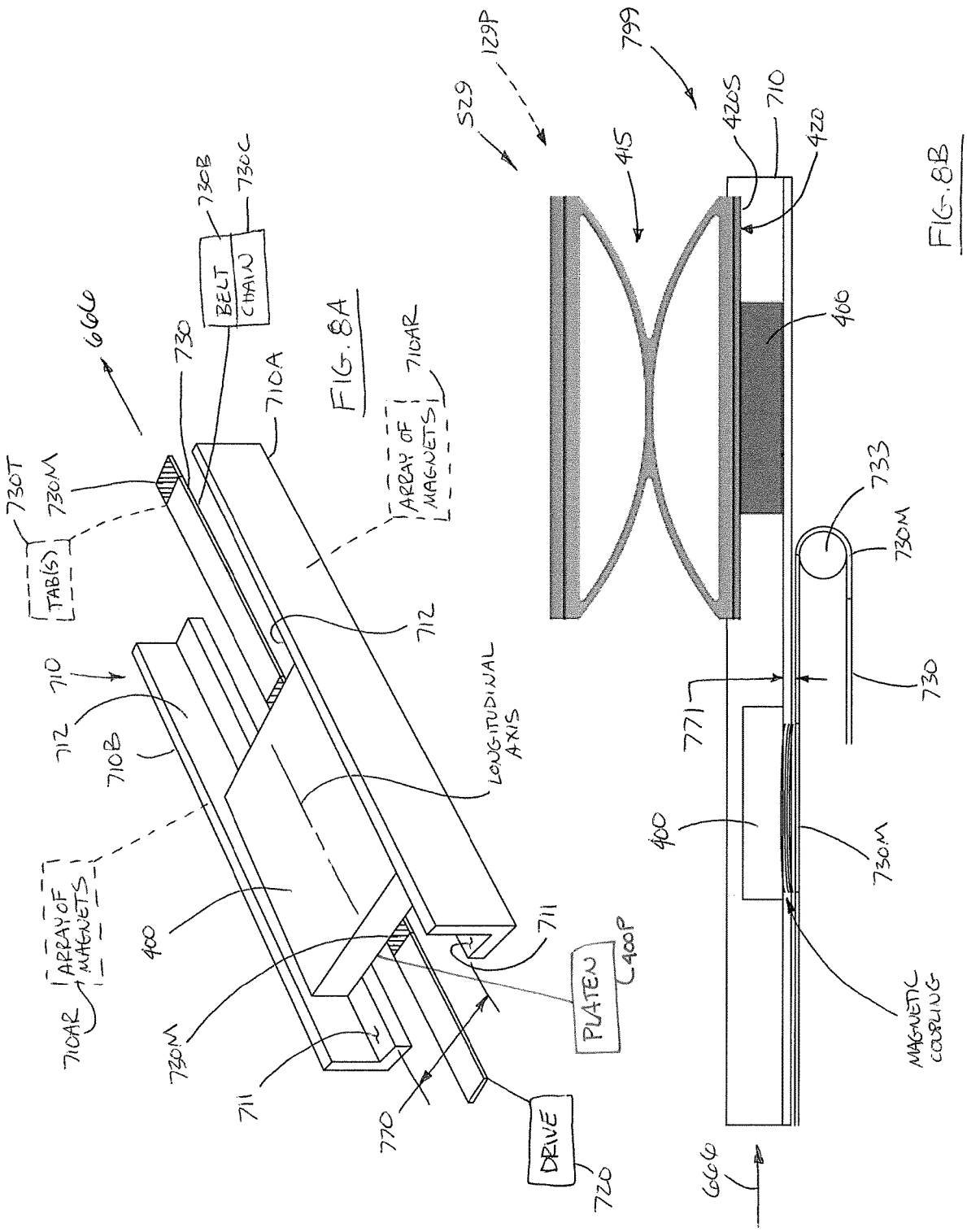

600
730T
TAB(S)
730M
730
730B
730C
BELT CHAIN
710A
710AR
ARRAY OF MAGNETS
712
710
710B
LONGITUDINAL AXIS
400
711
770
DRIVE
720
PLATEN
400P
529
129P
799
415
420S
420
460
733
771
730M
MAGNETIC COUPLING
600

FIG. 8A

FIG. 8B

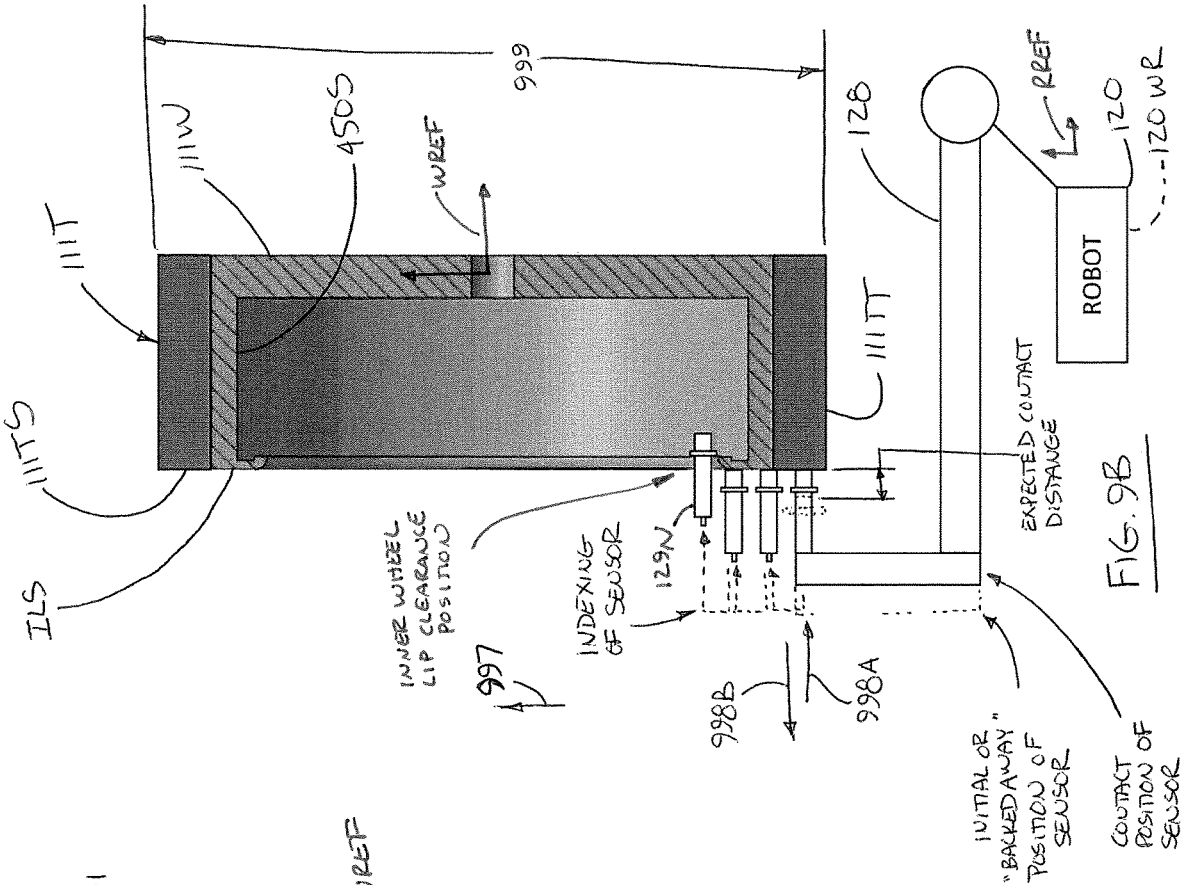

999
111W
4505
WREF
111T
111TS
ILS
INNER WHEEL CLEARANCE POSITION
997
INDEXING OF SENSOR
129N
998B
998A
128
111TT
EXPECTED CONTACT DISTANCE
ROBOT
RREF
120
120WR
INITIAL OR "BACKED AWAY" POSITION OF SENSOR
CONTACT POSITION OF SENSOR

FIG. 9B

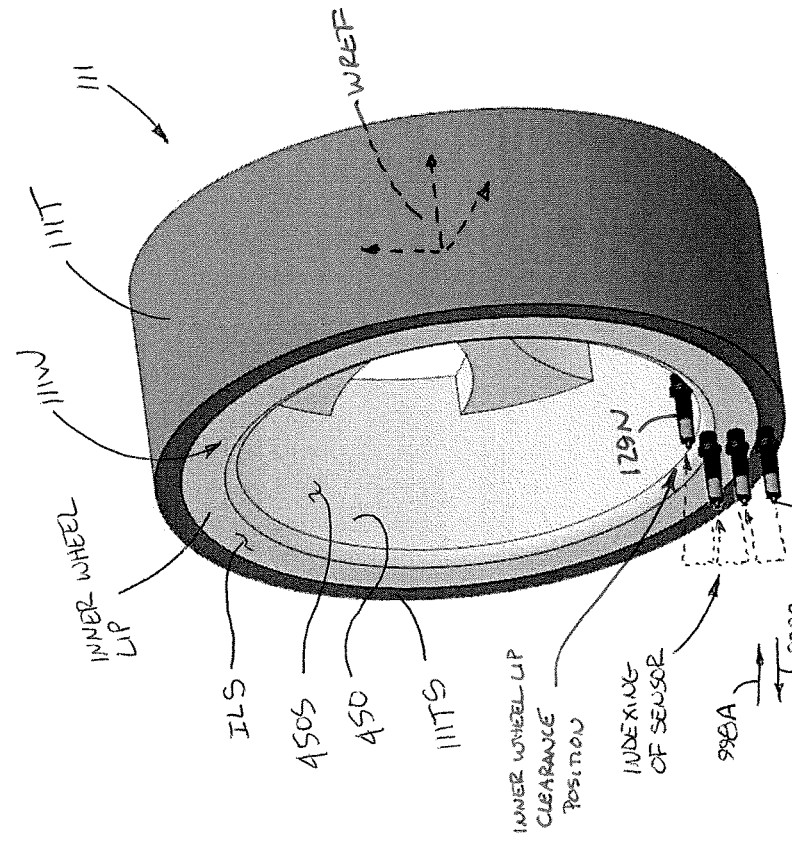

111
WREF
111T
111W
INNER WHEEL LIP
ILS
4505
450
111TS
INNER WHEEL LIP CLEARANCE POSITION
129N
INDEXING OF SENSOR
998A
998B
ROBOT
RREF
120
120WR

FIG 9A

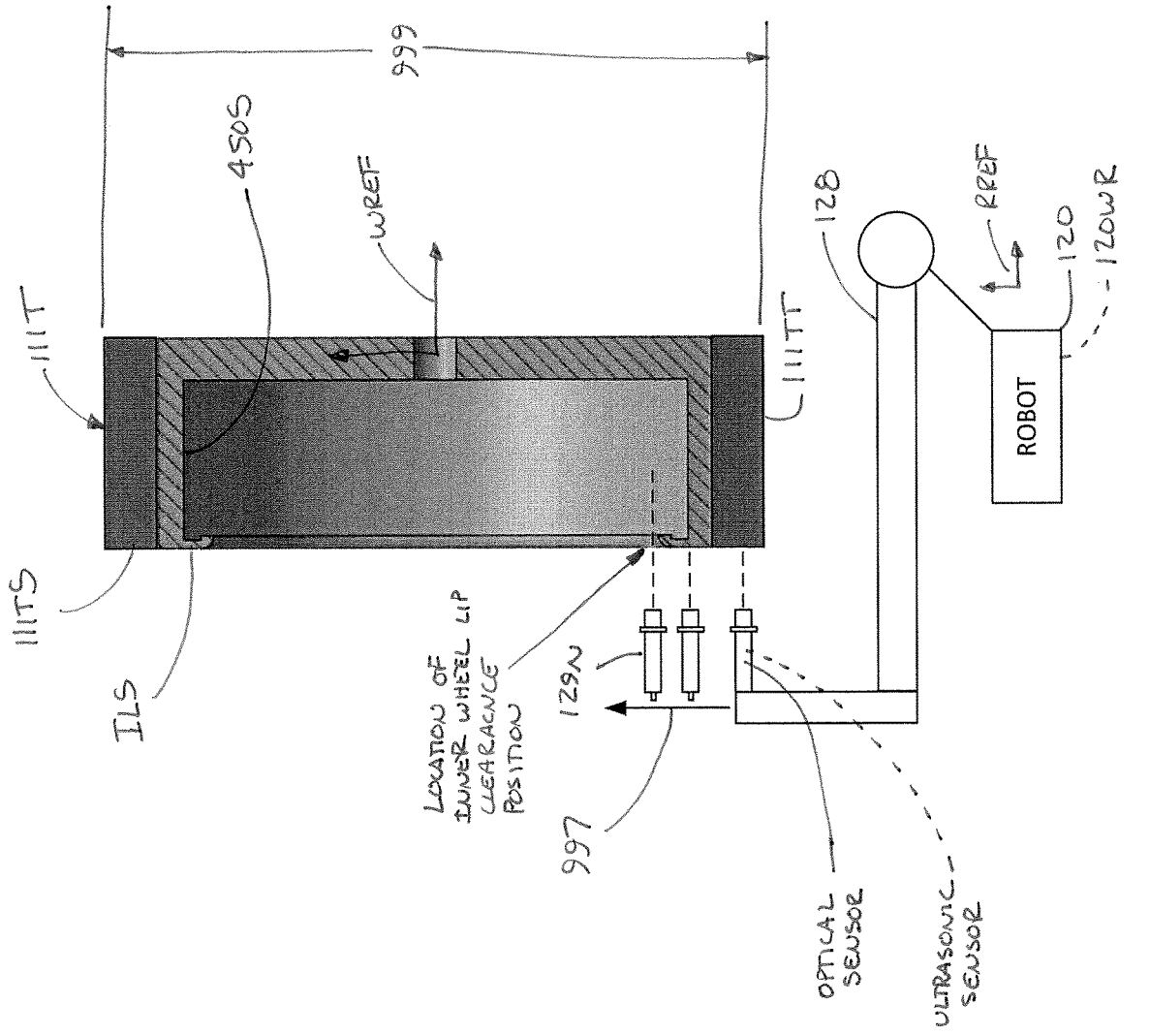

999
450S
WREF
111T
111TT
128
RREF
120
120WR
ROBOT
111TS
ILS
LOCATION OF INNER WHEEL LIP CLEARANCE POSITION
129N
997
OPTICAL SENSOR
ULTRASONIC SENSOR

FIG 9C

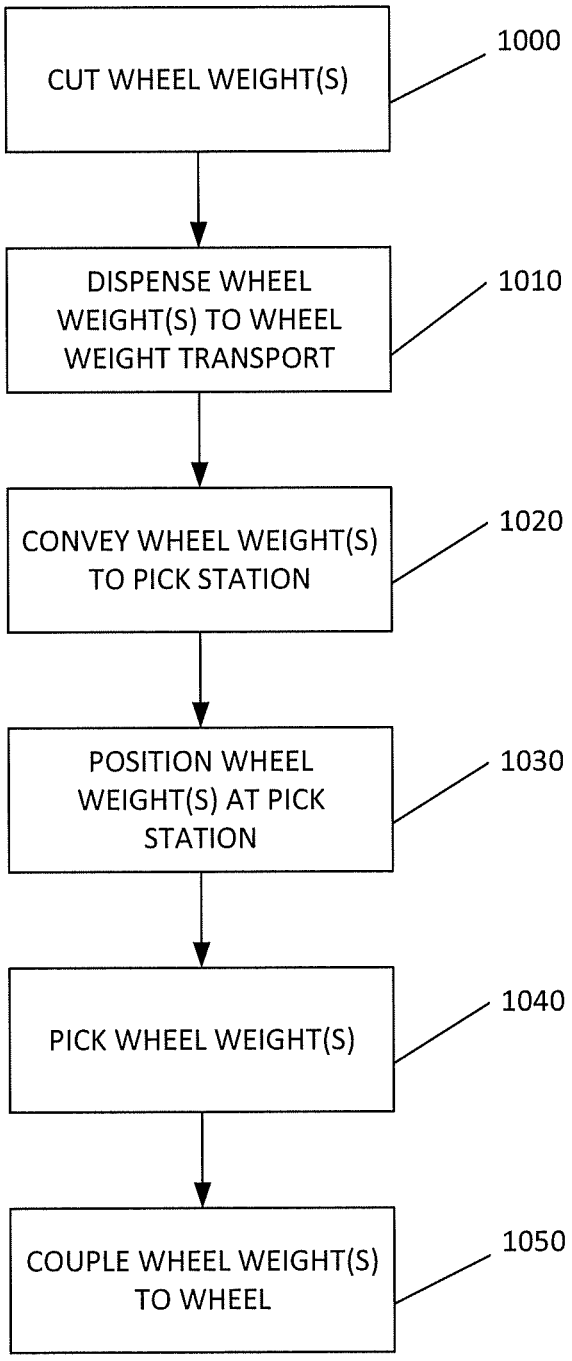

CUT WHEEL WEIGHT(S)
1000
DISPENSE WHEEL WEIGHT(S) TO WHEEL WEIGHT TRANSPORT
1010
CONVEY WHEEL WEIGHT(S) TO PICK STATION
1020
POSITION WHEEL WEIGHT(S) AT PICK STATION
1030
PICK WHEEL WEIGHT(S)
1040
COUPLE WHEEL WEIGHT(S) TO WHEEL
1050

FIG. 10

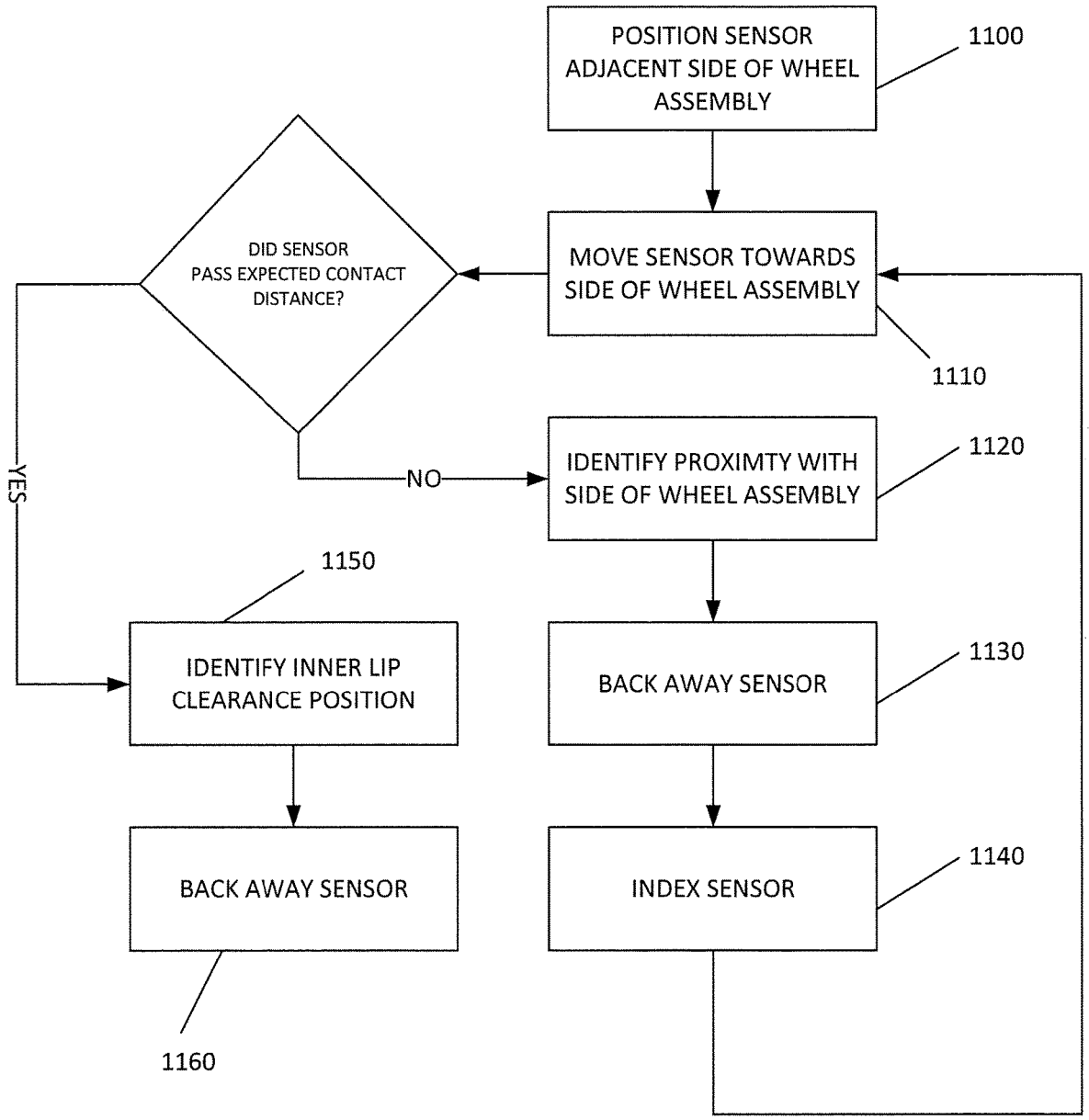

POSITION SENSOR ADJACENT SIDE OF WHEEL ASSEMBLY
1100
MOVE SENSOR TOWARDS SIDE OF WHEEL ASSEMBLY
1110
DID SENSOR PASS EXPECTED CONTACT DISTANCE?
YES
NO
IDENTIFY PROXIMTY WITH SIDE OF WHEEL ASSEMBLY
1120
BACK AWAY SENSOR
1130
INDEX SENSOR
1140
1150
IDENTIFY INNER LIP CLEARANCE POSITION
BACK AWAY SENSOR
1160

FIG. 11

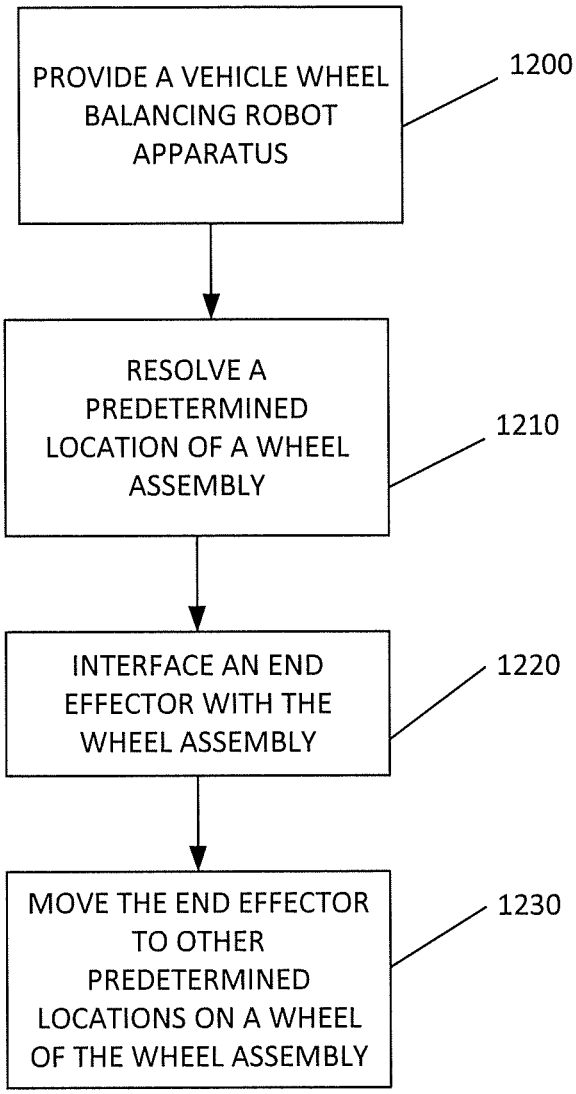

PROVIDE A VEHICLE WHEEL BALANCING ROBOT APPARATUS
1200
RESOLVE A PREDETERMINED LOCATION OF A WHEEL ASSEMBLY
1210
INTERFACE AN END EFFECTOR WITH THE WHEEL ASSEMBLY
1220
MOVE THE END EFFECTOR TO OTHER PREDETERMINED LOCATIONS ON A WHEEL OF THE WHEEL ASSEMBLY
1230

FIG. 12

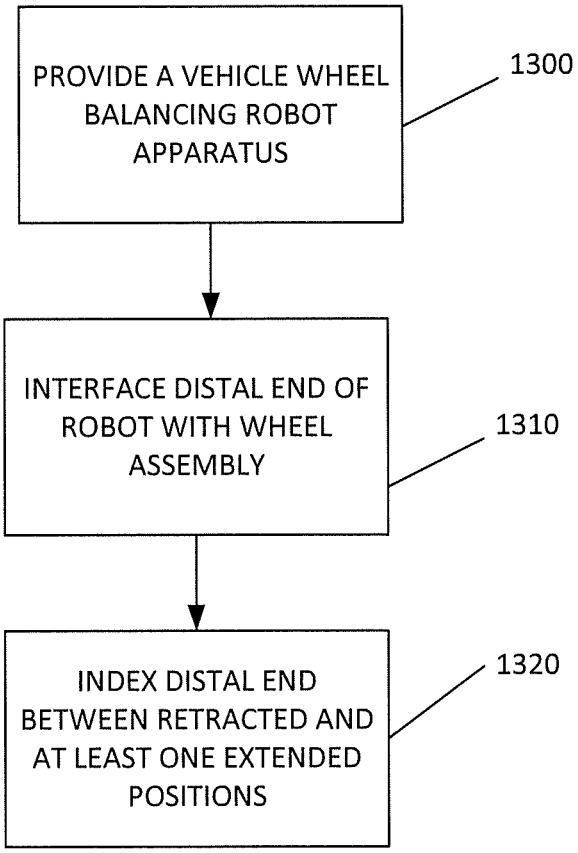

PROVIDE A VEHICLE WHEEL BALANCING ROBOT APPARATUS
1300
INTERFACE DISTAL END OF ROBOT WITH WHEEL ASSEMBLY
1310
INDEX DISTAL END BETWEEN RETRACTED AND AT LEAST ONE EXTENDED POSITIONS
1320

FIG. 13

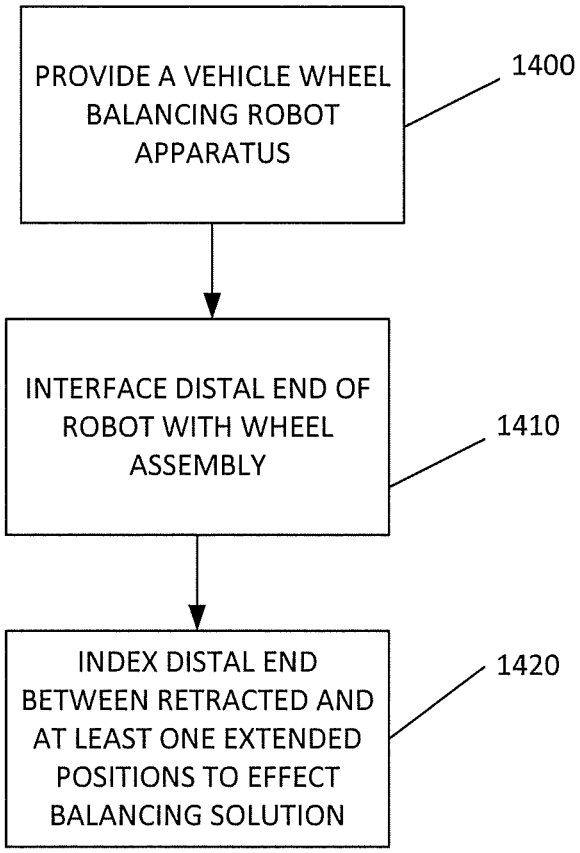

PROVIDE A VEHICLE WHEEL BALANCING ROBOT APPARATUS
1400
INTERFACE DISTAL END OF ROBOT WITH WHEEL ASSEMBLY
1410
INDEX DISTAL END BETWEEN RETRACTED AND AT LEAST ONE EXTENDED POSITIONS TO EFFECT BALANCING SOLUTION
1420

FIG. 14

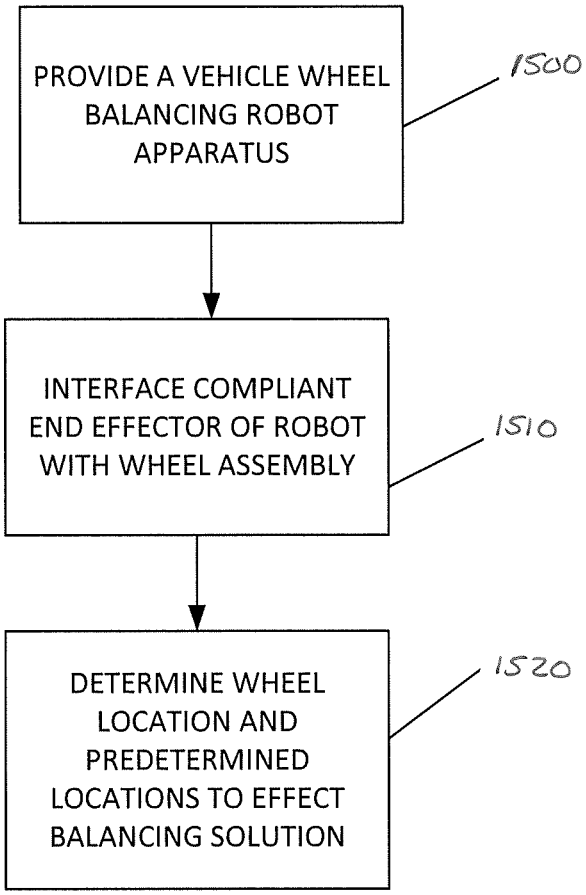

PROVIDE A VEHICLE WHEEL BALANCING ROBOT APPARATUS
1500
INTERFACE COMPLIANT END EFFECTOR OF ROBOT WITH WHEEL ASSEMBLY
1510
DETERMINE WHEEL LOCATION AND PREDETERMINED LOCATIONS TO EFFECT BALANCING SOLUTION
1520

FIG. 15

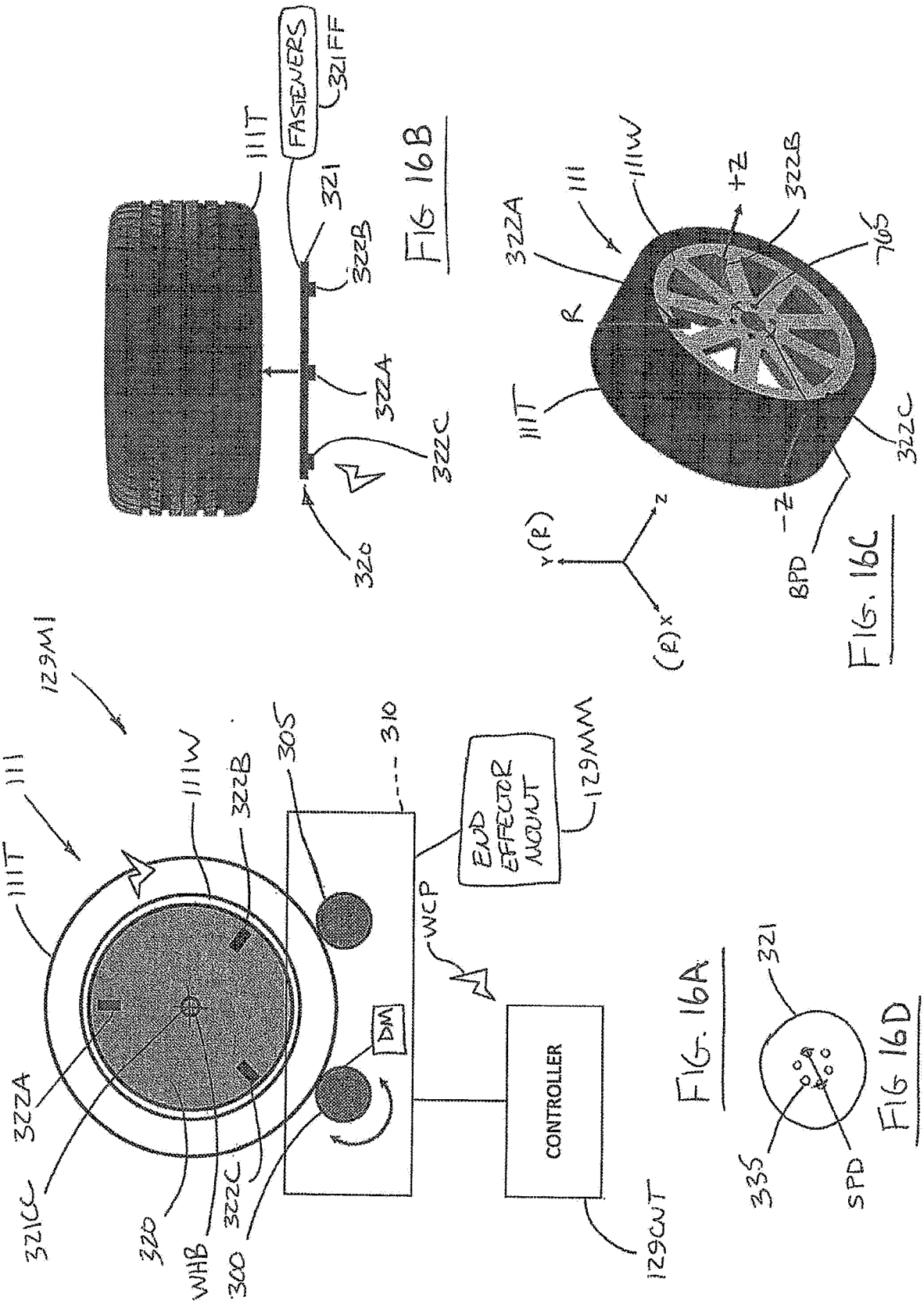


FIG. 16A

FIG 16B

FIG. 16C

FIG 16D

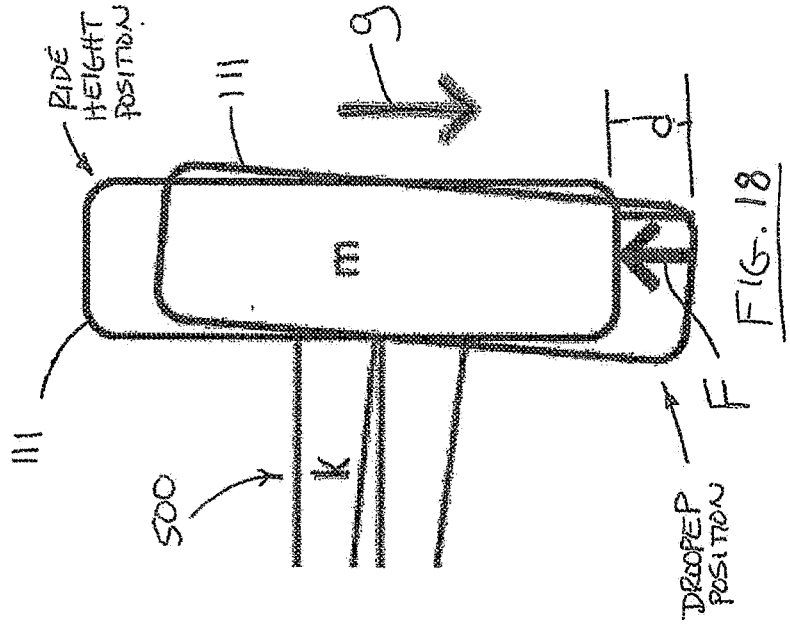


FIG. 18

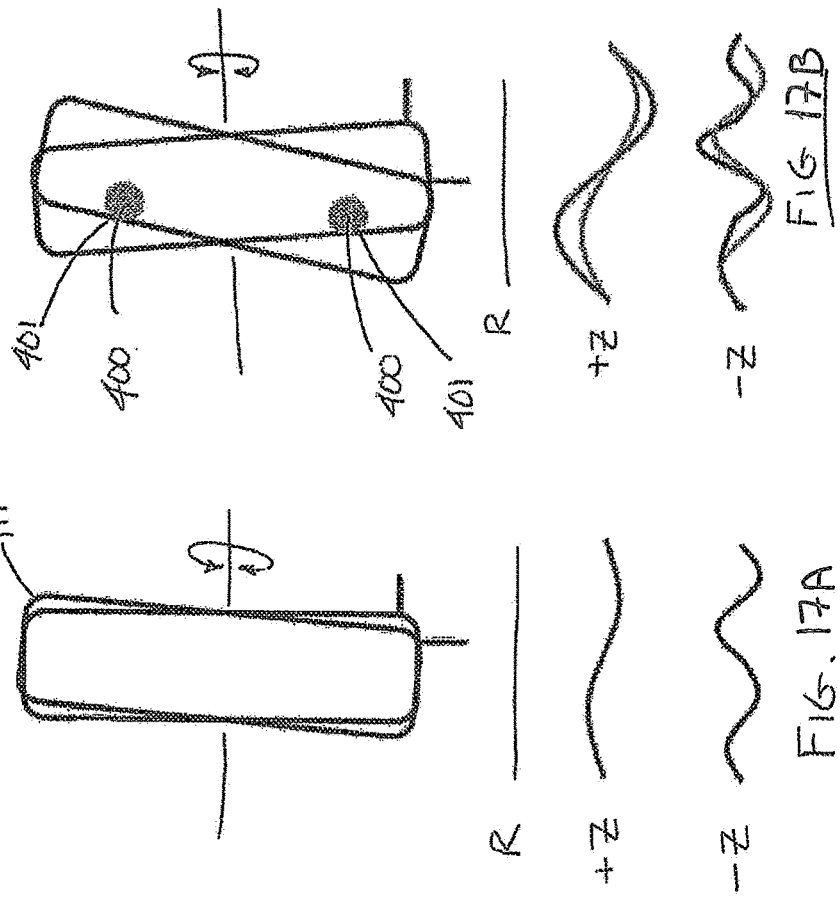


FIG. 17B

FIG. 17A

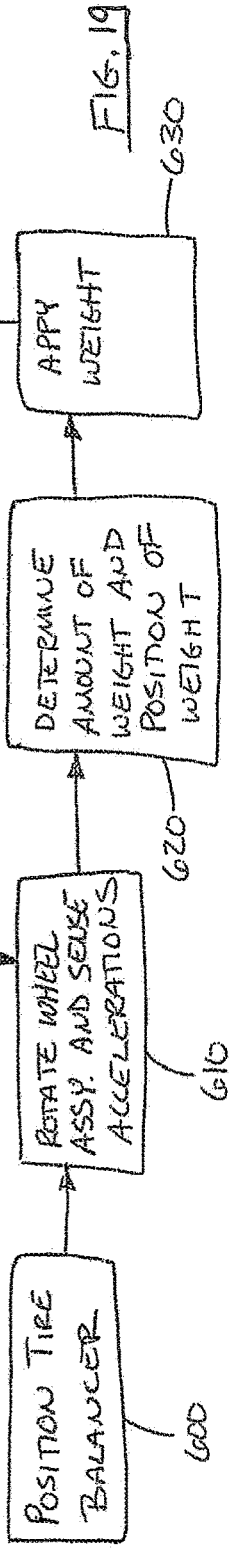


FIG. 19

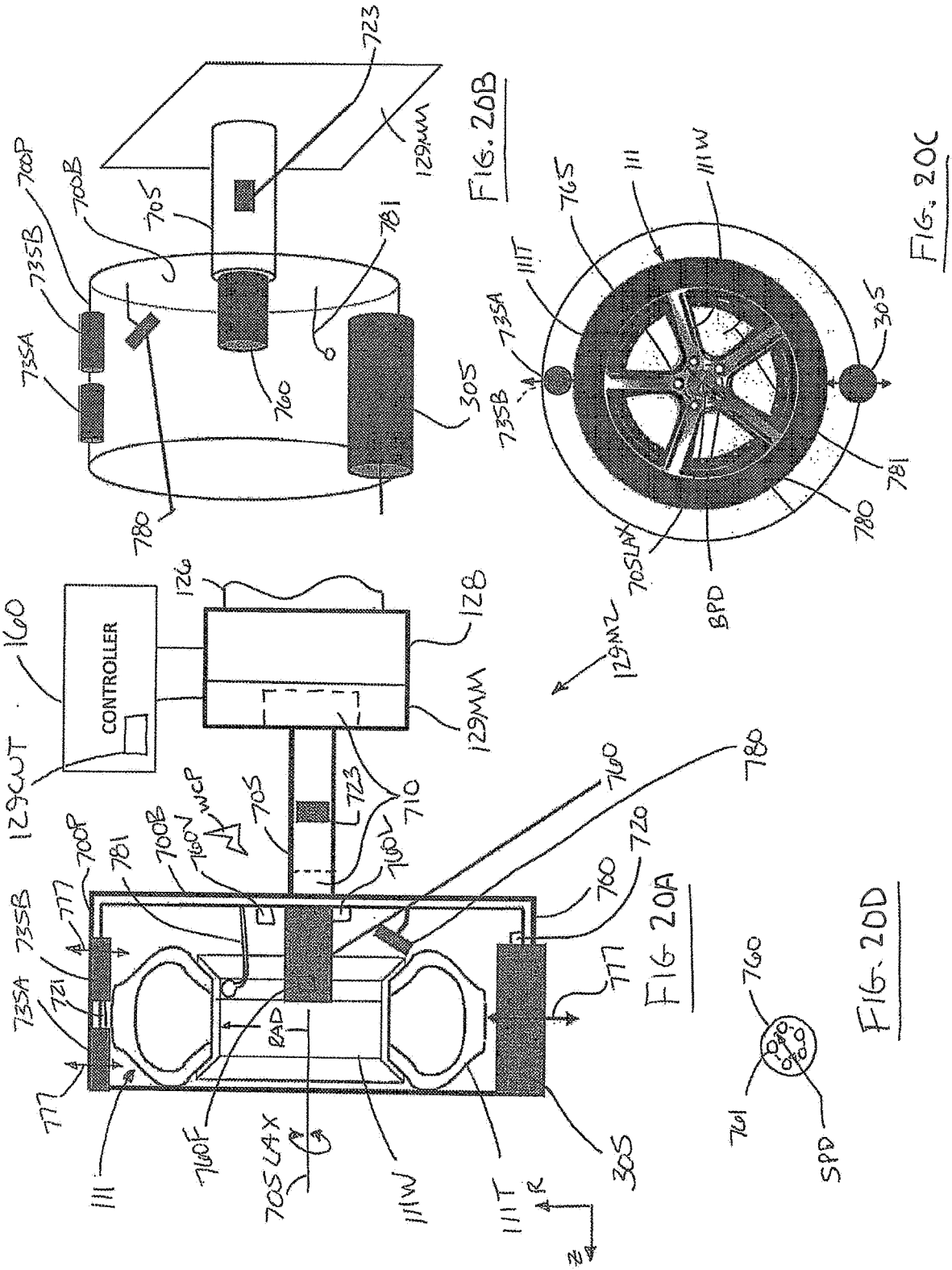


FIG. 20A

FIG. 20B

FIG. 20C

FIG. 20D

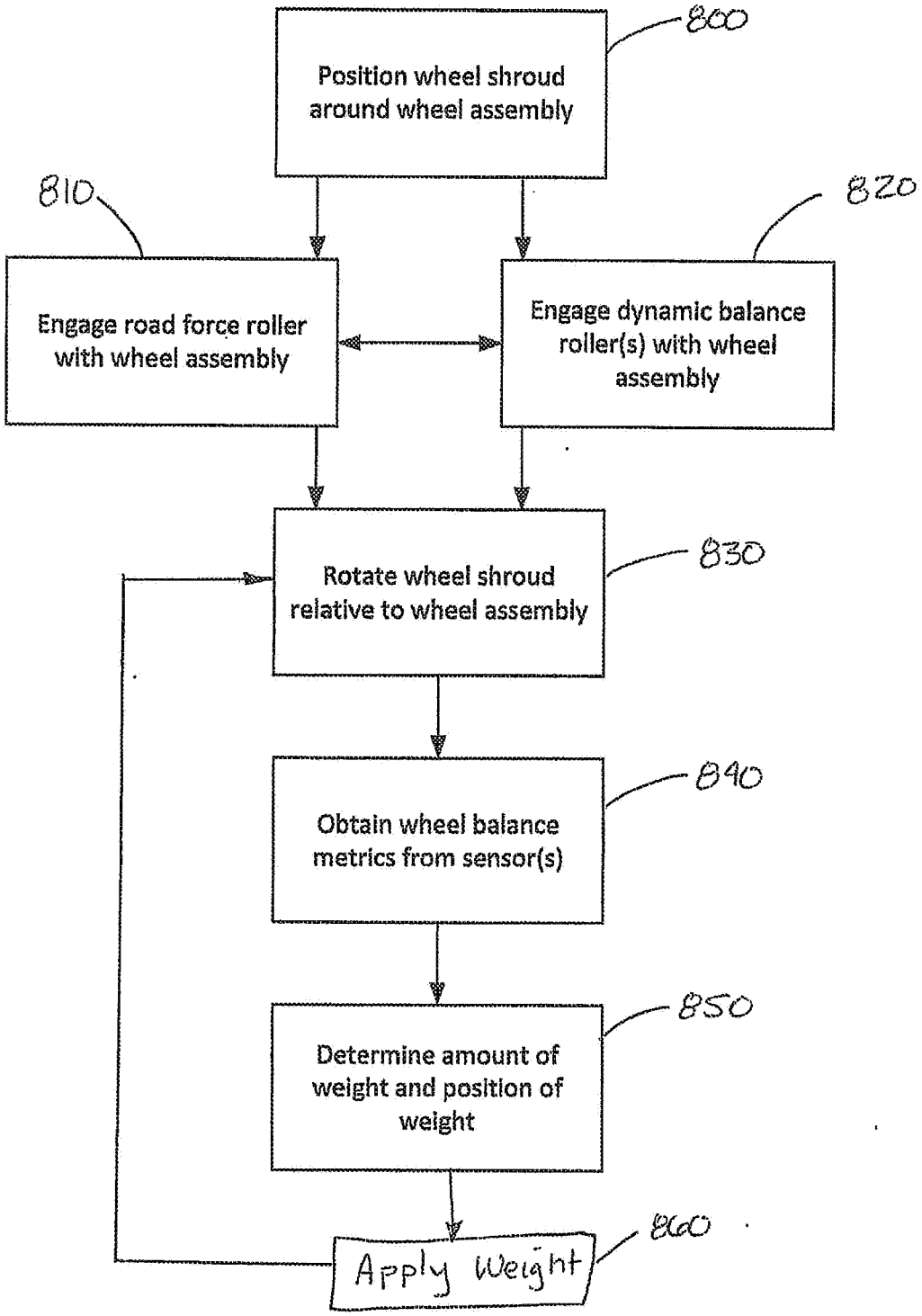

Position wheel shroud around wheel assembly
800
810
820
Engage road force roller with wheel assembly
Engage dynamic balance roller(s) with wheel assembly
Rotate wheel shroud relative to wheel assembly
830
Obtain wheel balance metrics from sensor(s)
840
Determine amount of weight and position of weight
850
Apply Weight
860

FIG 21

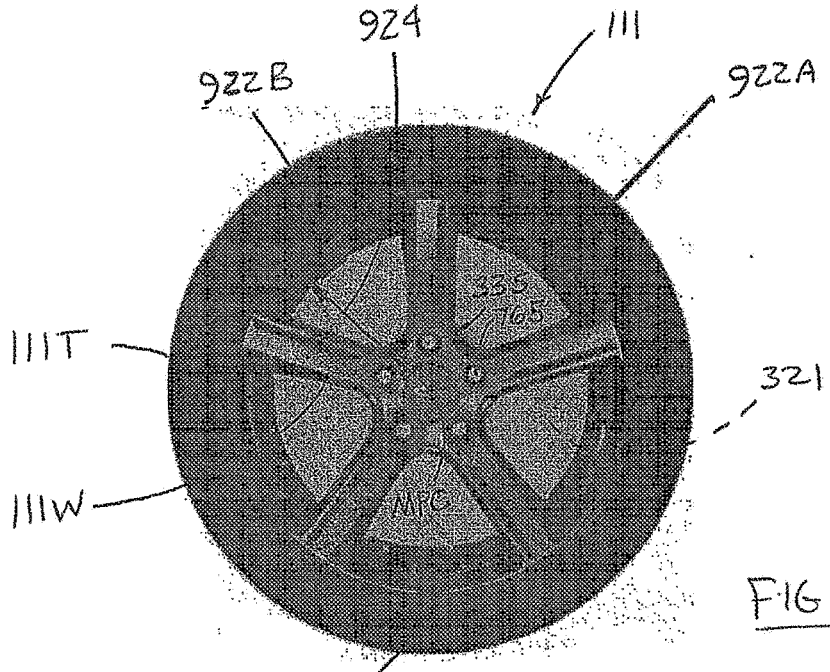


FIG. 22B

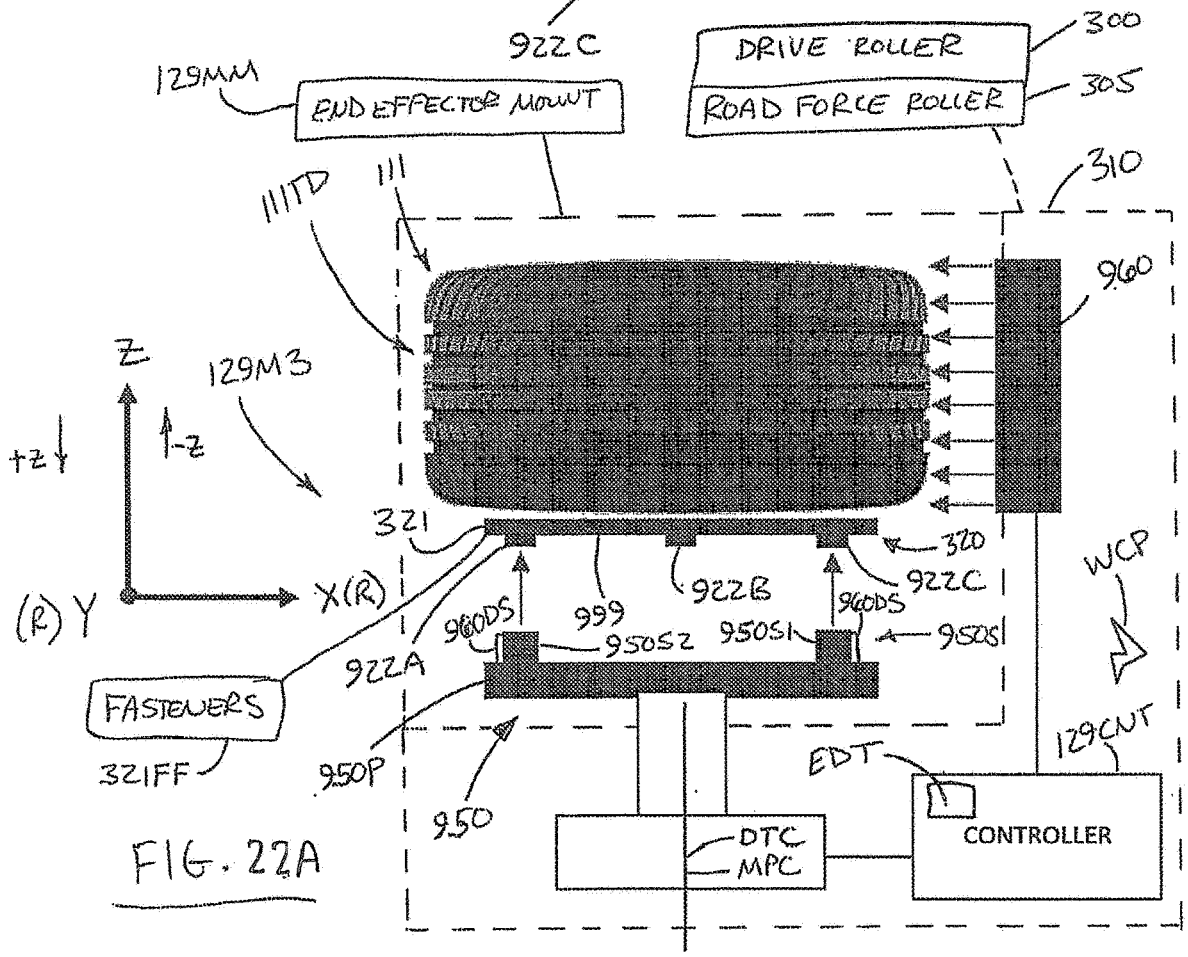


FIG. 22A

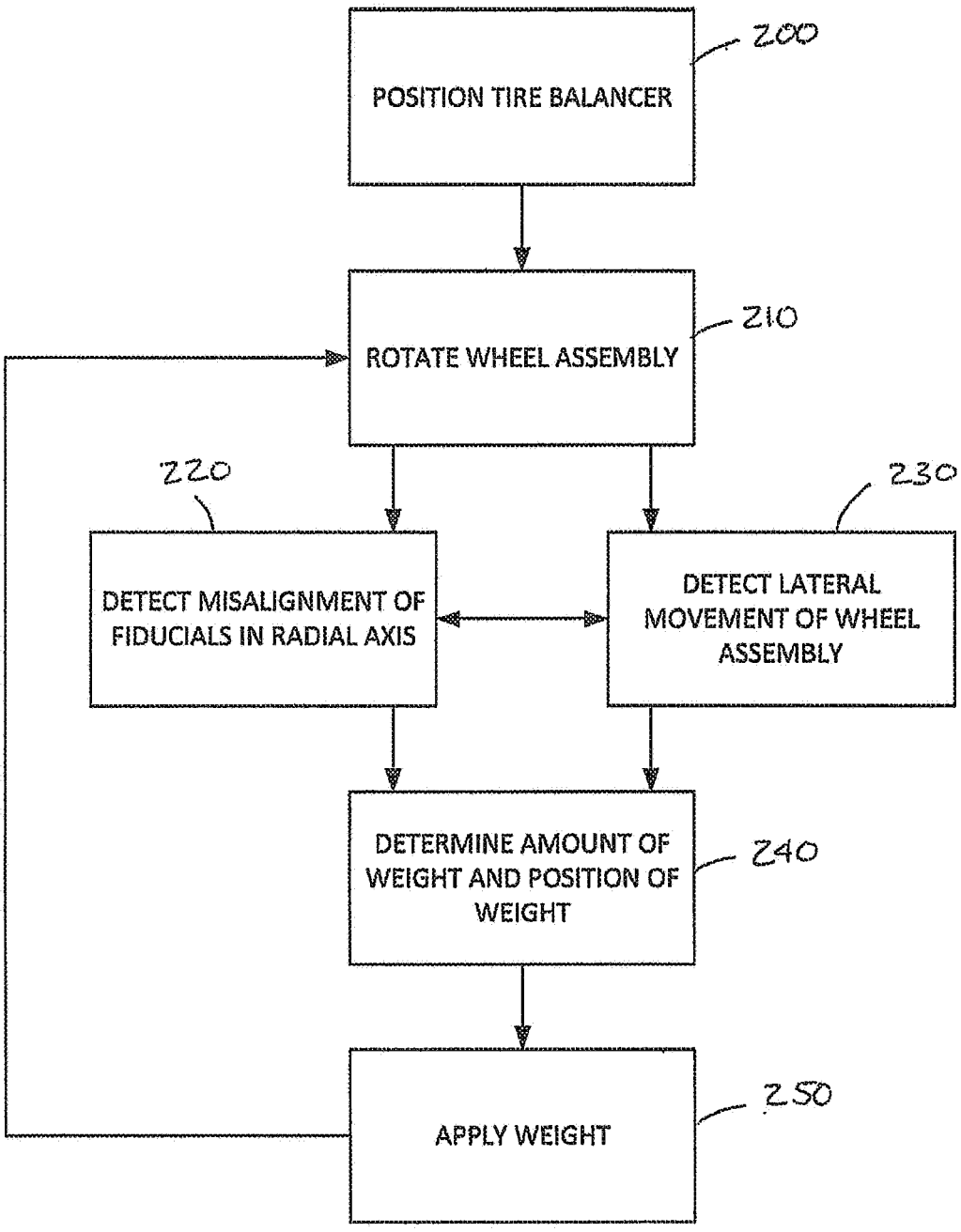

POSITION TIRE BALANCER
200
ROTATE WHEEL ASSEMBLY
210
220
230
DETECT MISALIGNMENT OF FIDUCIALS IN RADIAL AXIS
DETECT LATERAL MOVEMENT OF WHEEL ASSEMBLY
DETERMINE AMOUNT OF WEIGHT AND POSITION OF WEIGHT
240
APPLY WEIGHT
250

FIG. 23

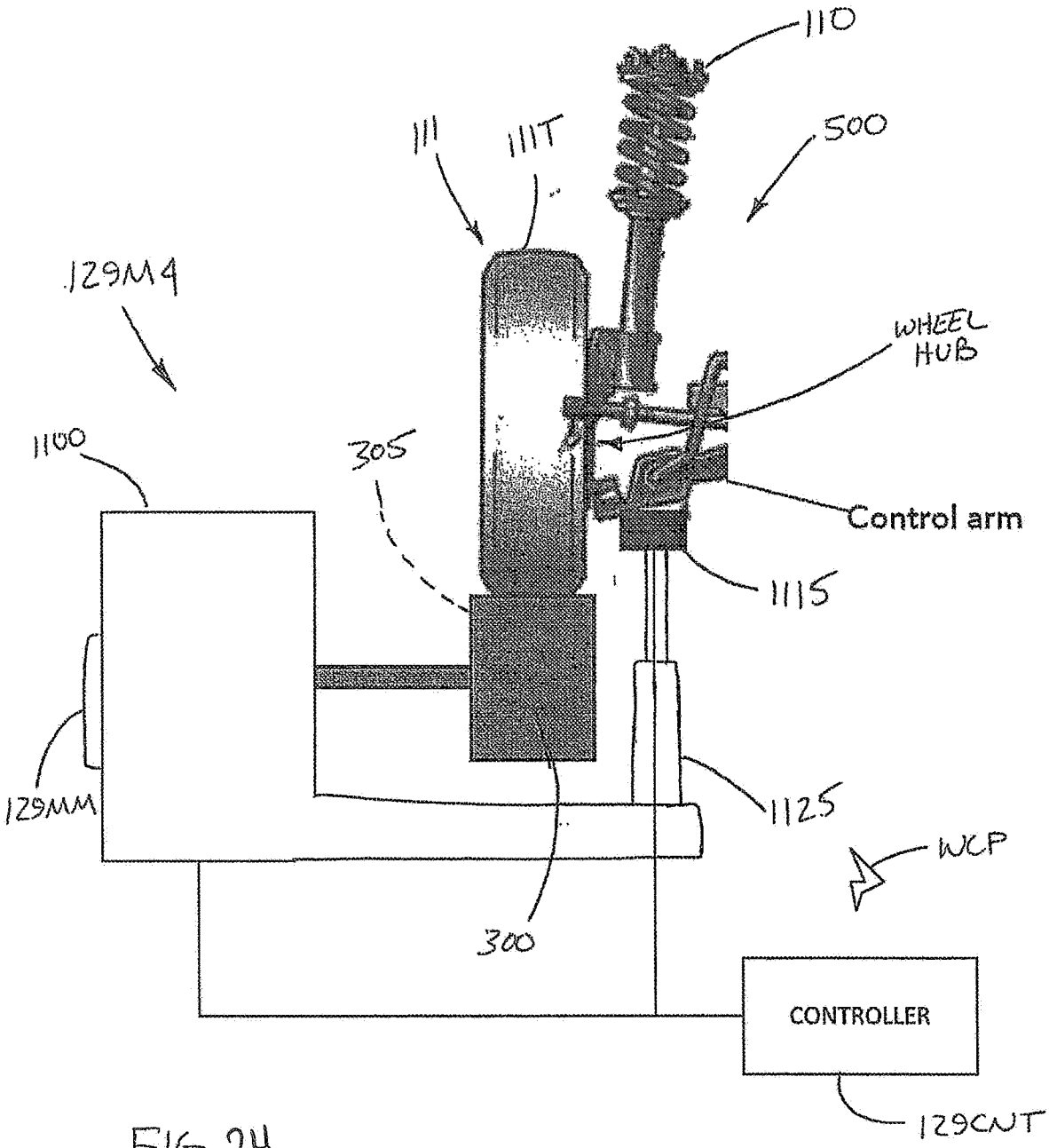

110
111
111T
500
129M4
WHEEL HUB
1100
305
Control arm
1115
129MM
1125
WCP
300
CONTROLLER
129CNT

FIG. 24

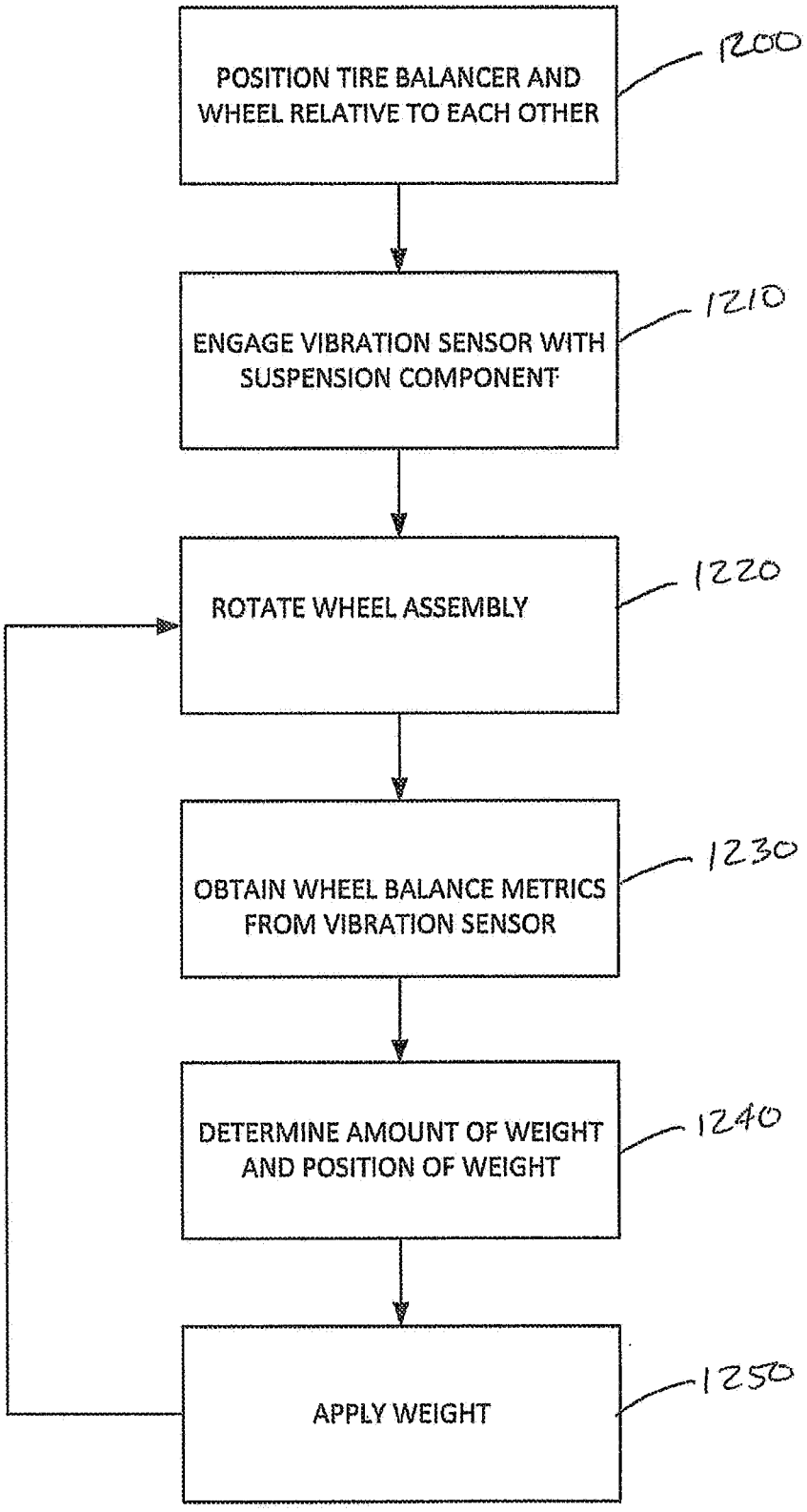

POSITION TIRE BALANCER AND WHEEL RELATIVE TO EACH OTHER
1200
ENGAGE VIBRATION SENSOR WITH SUSPENSION COMPONENT
1210
ROTATE WHEEL ASSEMBLY
1220
OBTAIN WHEEL BALANCE METRICS FROM VIBRATION SENSOR
1230
DETERMINE AMOUNT OF WEIGHT AND POSITION OF WEIGHT
1240
APPLY WEIGHT
1250

FIG. 25

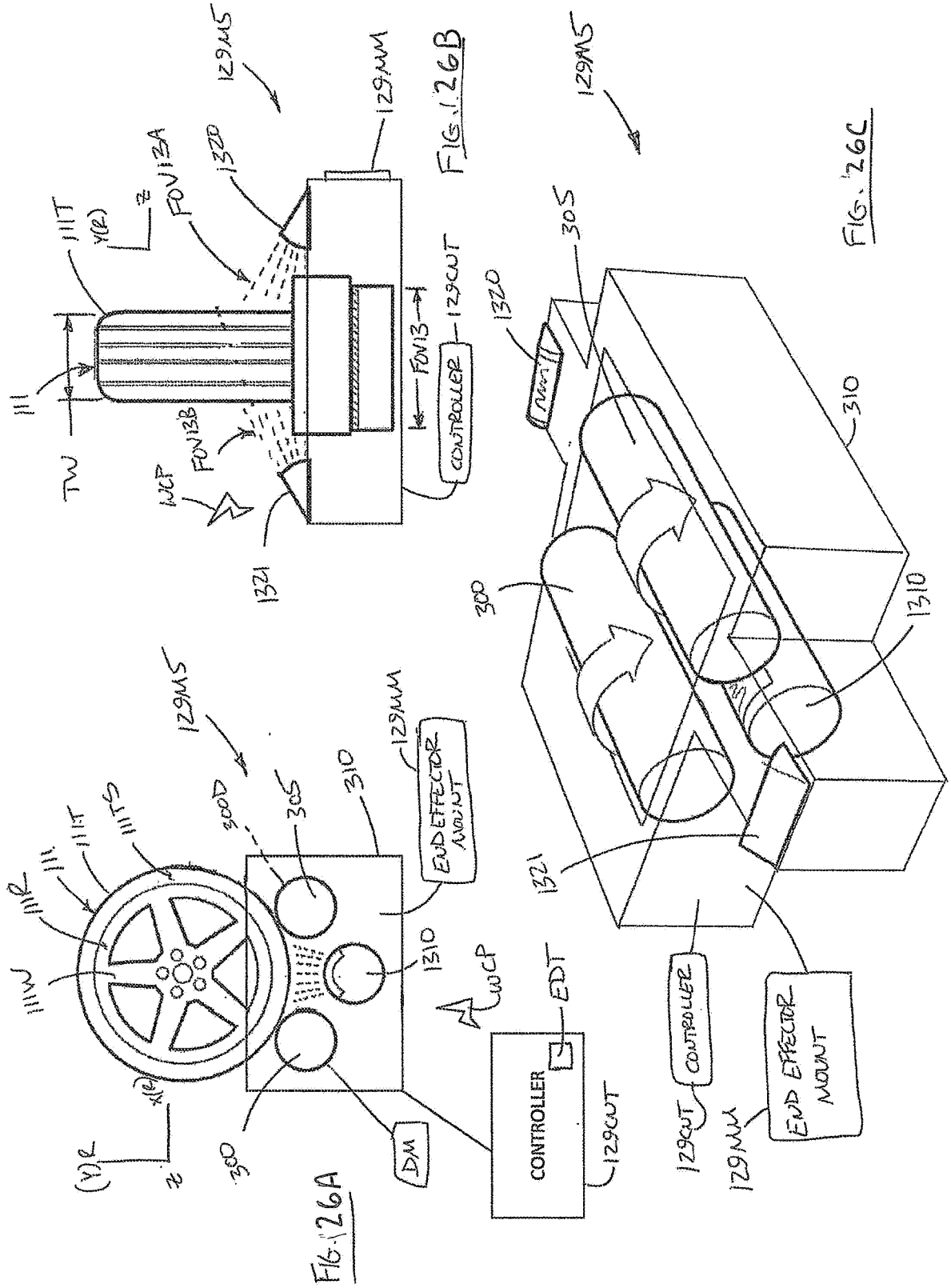


FIG. 126A

FIG. 126B

FIG. 126C

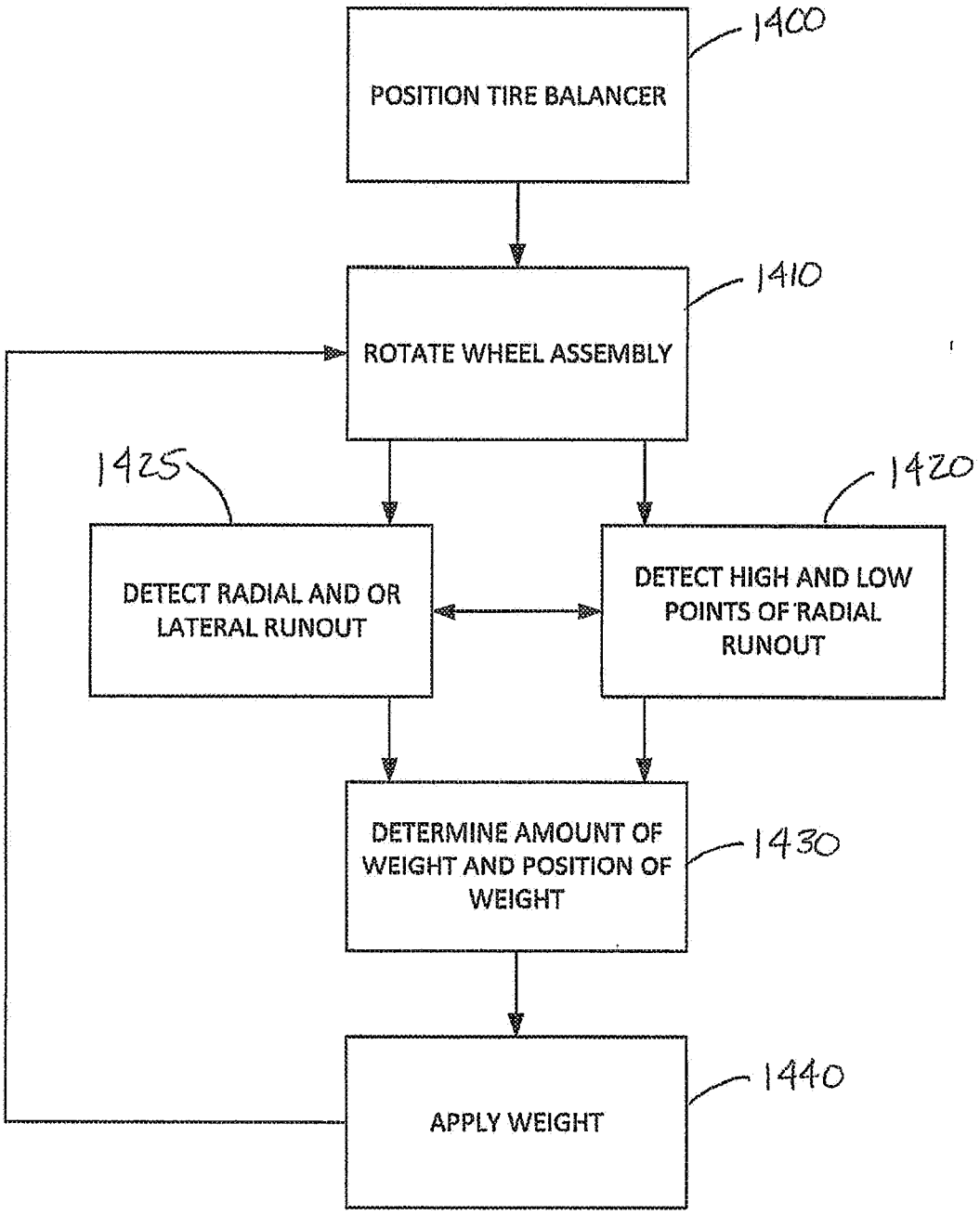

POSITION TIRE BALANCER
1400
ROTATE WHEEL ASSEMBLY
1410
1425
1420
DETECT RADIAL AND OR LATERAL RUNOUT
DETECT HIGH AND LOW POINTS OF RADIAL RUNOUT
DETERMINE AMOUNT OF WEIGHT AND POSITION OF WEIGHT
1430
APPLY WEIGHT
1440

FIG. 27

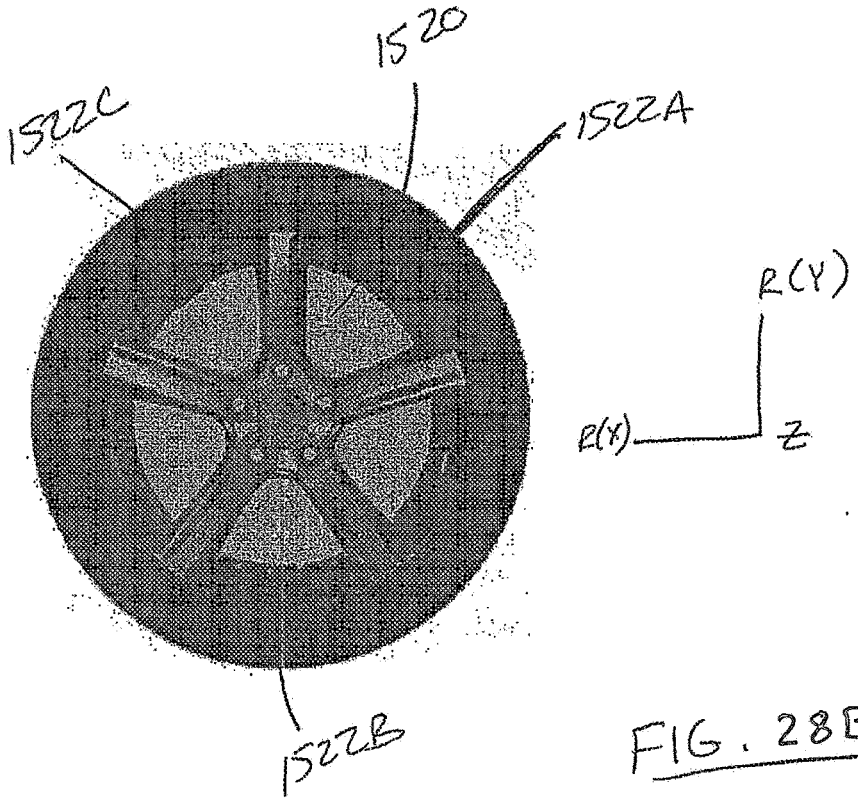


FIG. 28B

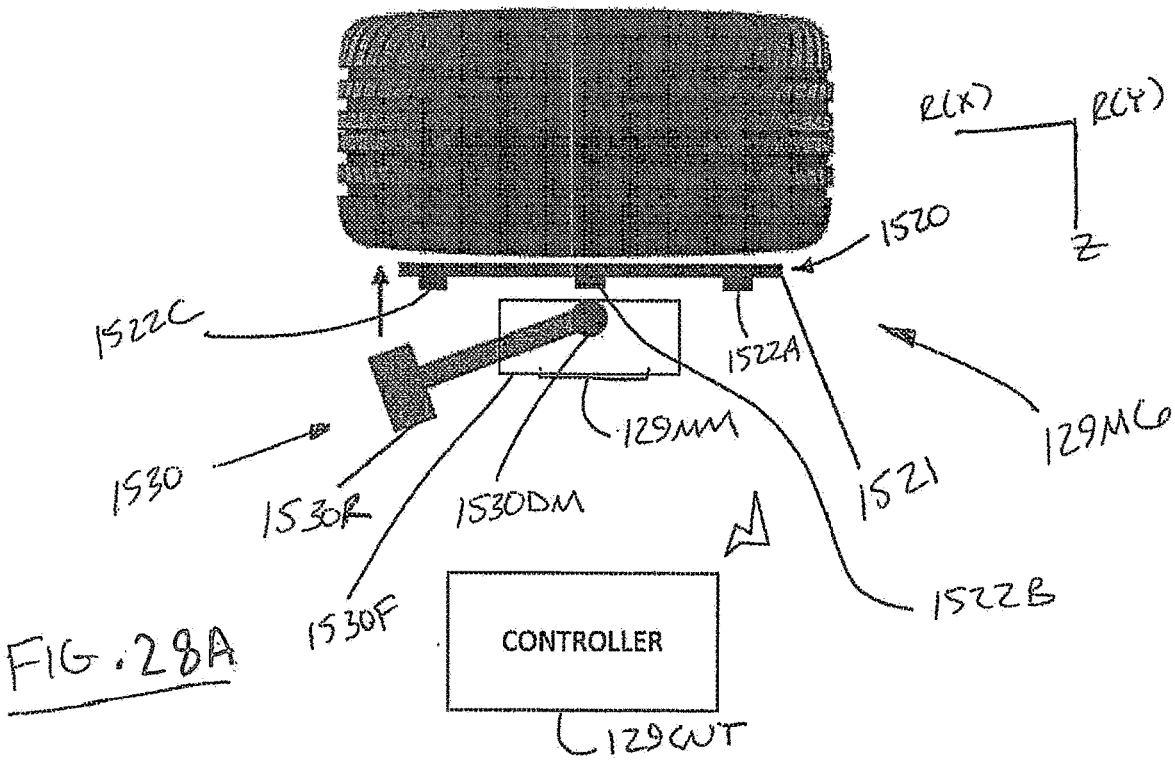


FIG. 28A

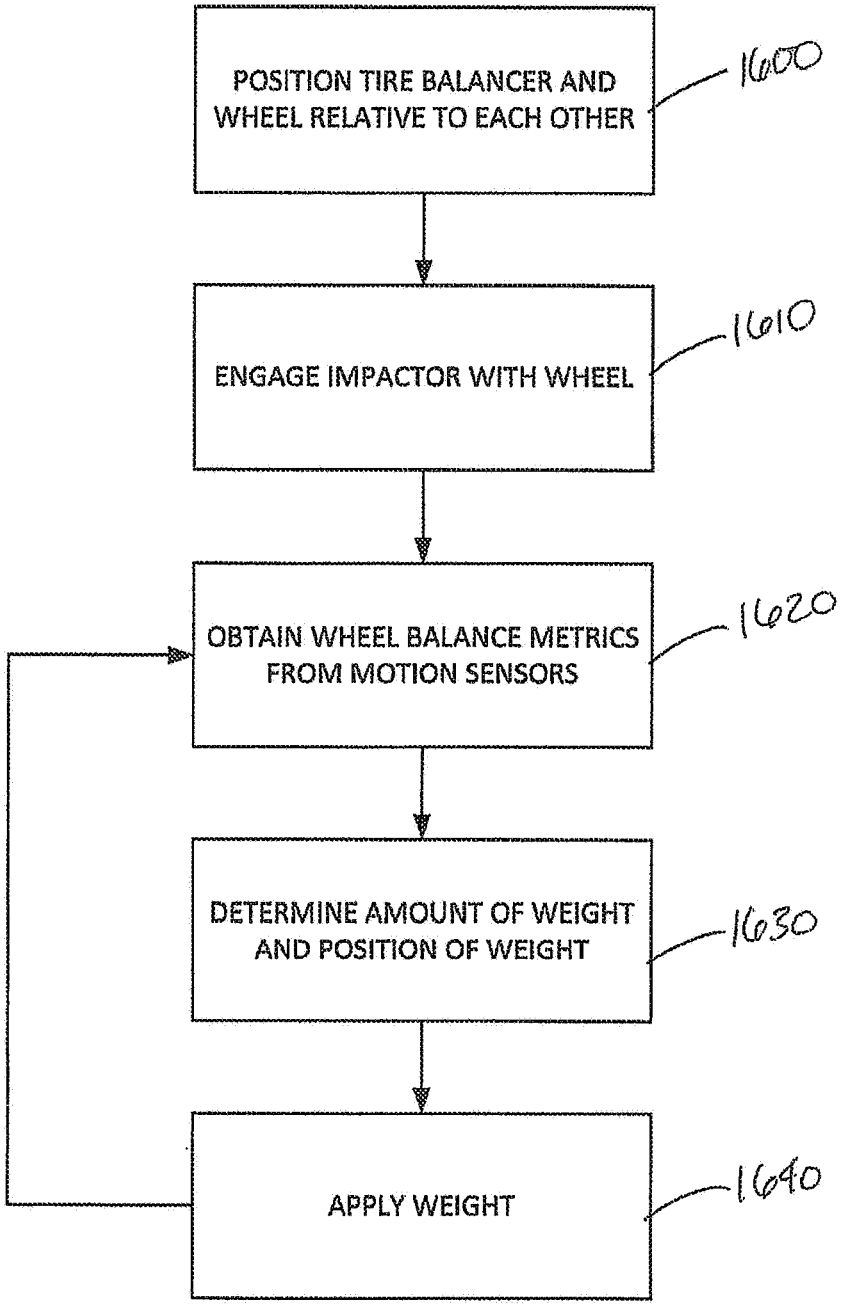

POSITION TIRE BALANCER AND WHEEL RELATIVE TO EACH OTHER
1600
ENGAGE IMPACTOR WITH WHEEL
1610
OBTAIN WHEEL BALANCE METRICS FROM MOTION SENSORS
1620
DETERMINE AMOUNT OF WEIGHT AND POSITION OF WEIGHT
1630
APPLY WEIGHT
1640

FIG 29

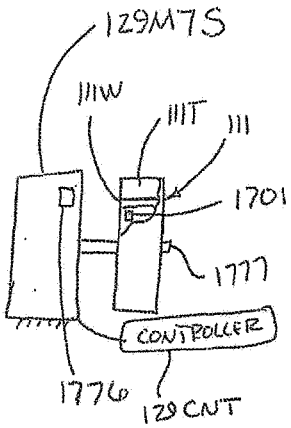


FIG. 30D

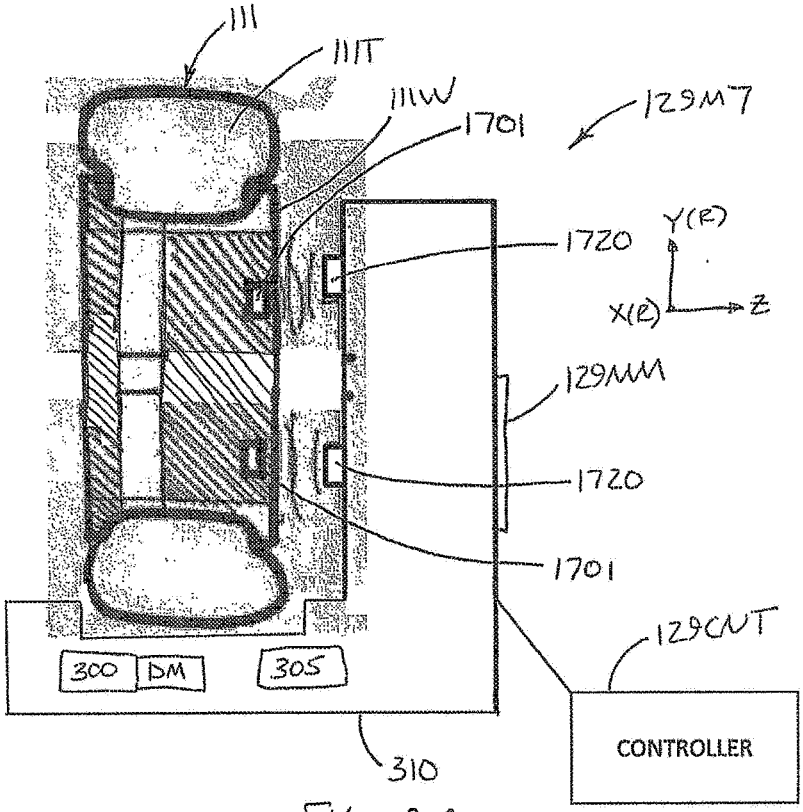


FIG. 30A

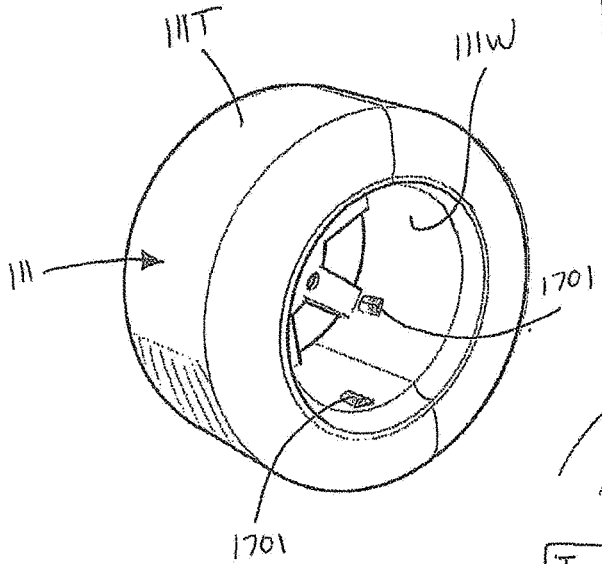


FIG. 30B

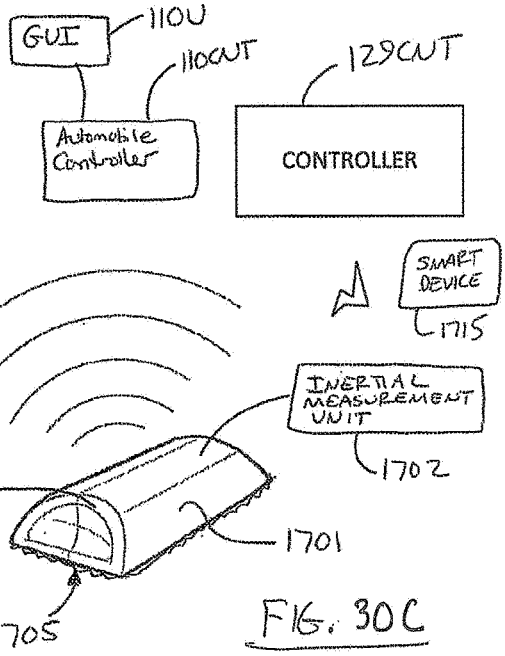


FIG. 30C

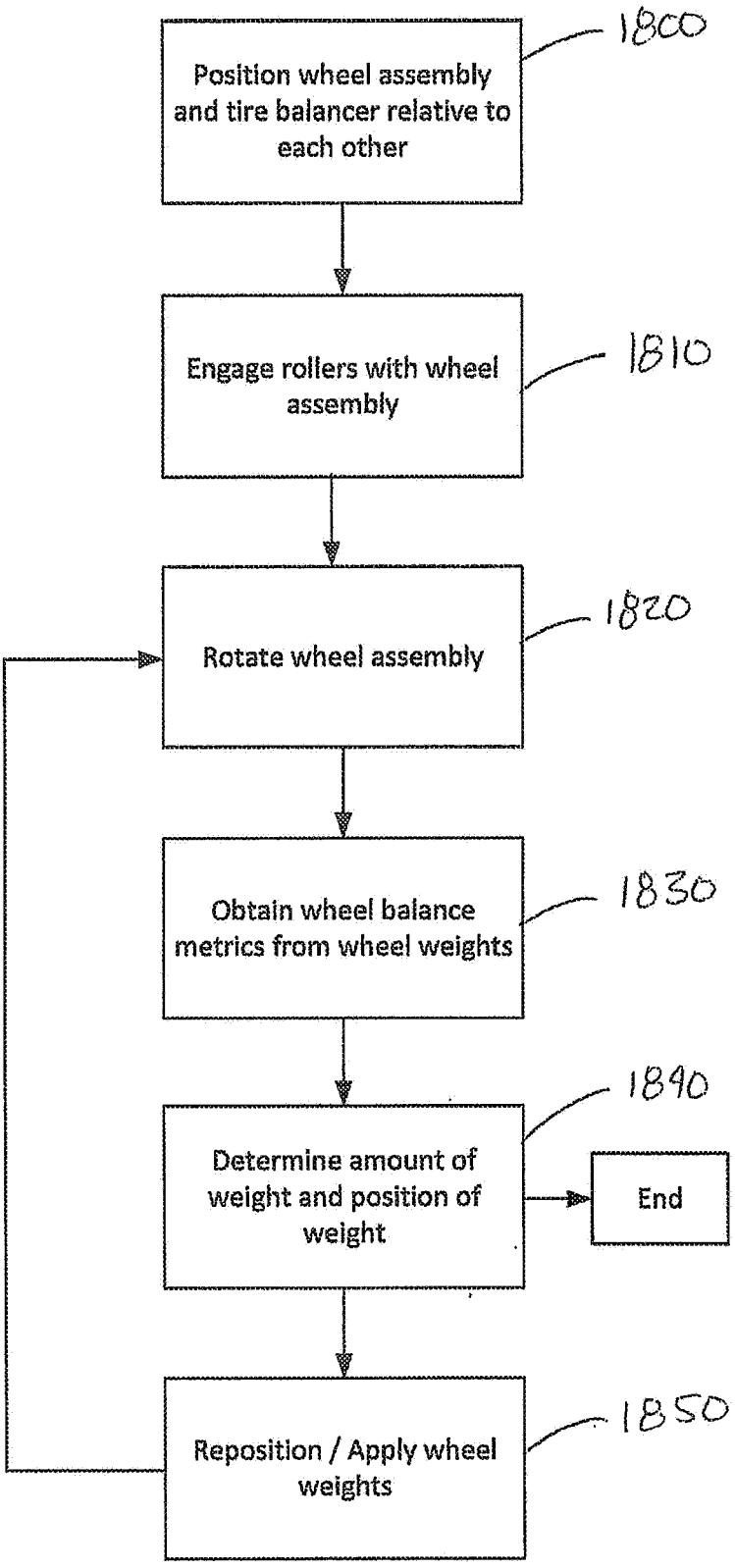

Position wheel assembly and tire balancer relative to each other
1800
Engage rollers with wheel assembly
1810
Rotate wheel assembly
1820
Obtain wheel balance metrics from wheel weights
1830
Determine amount of weight and position of weight
1840
End
Reposition / Apply wheel weights
1850

FIG 31

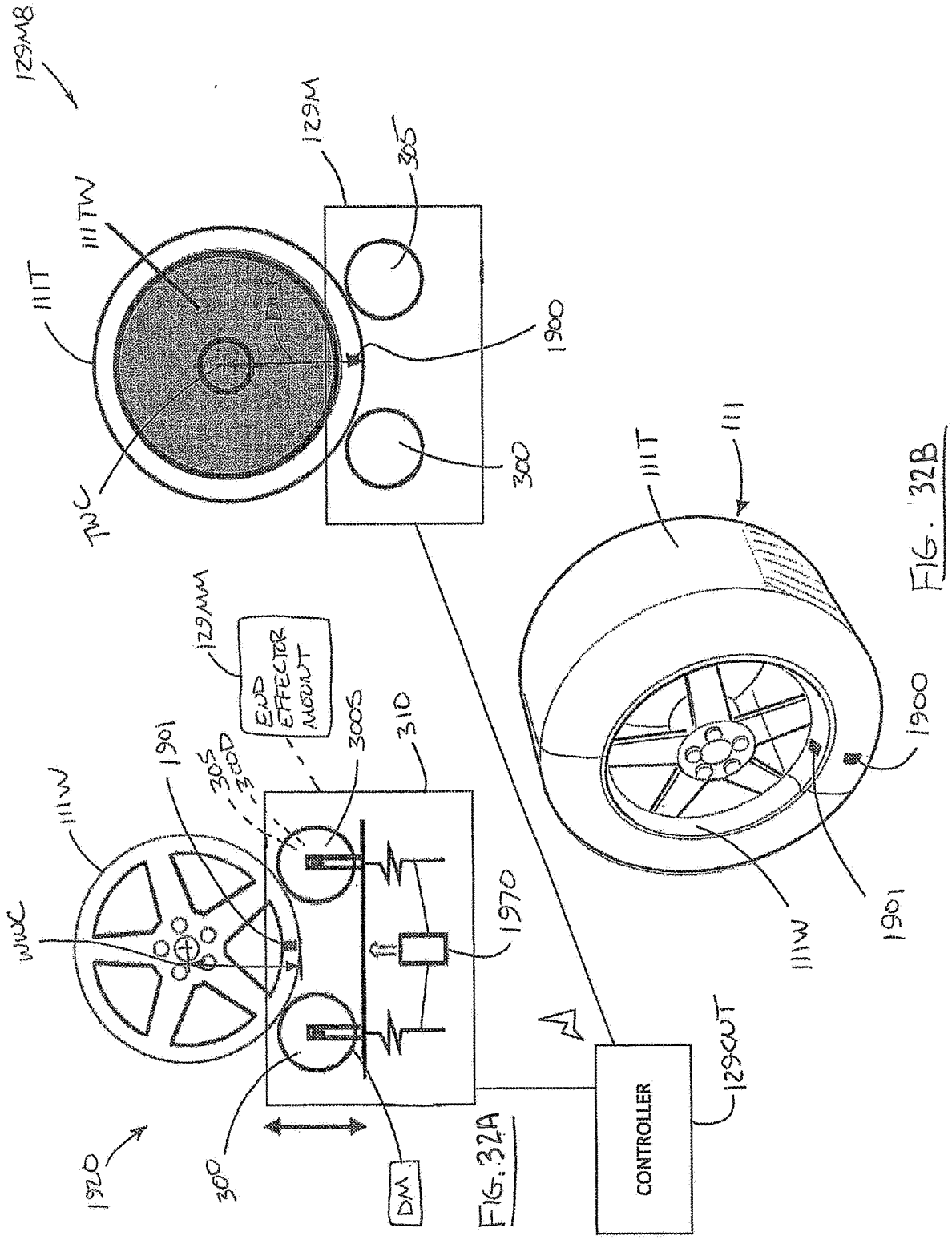


FIG. 32A

FIG. 32B

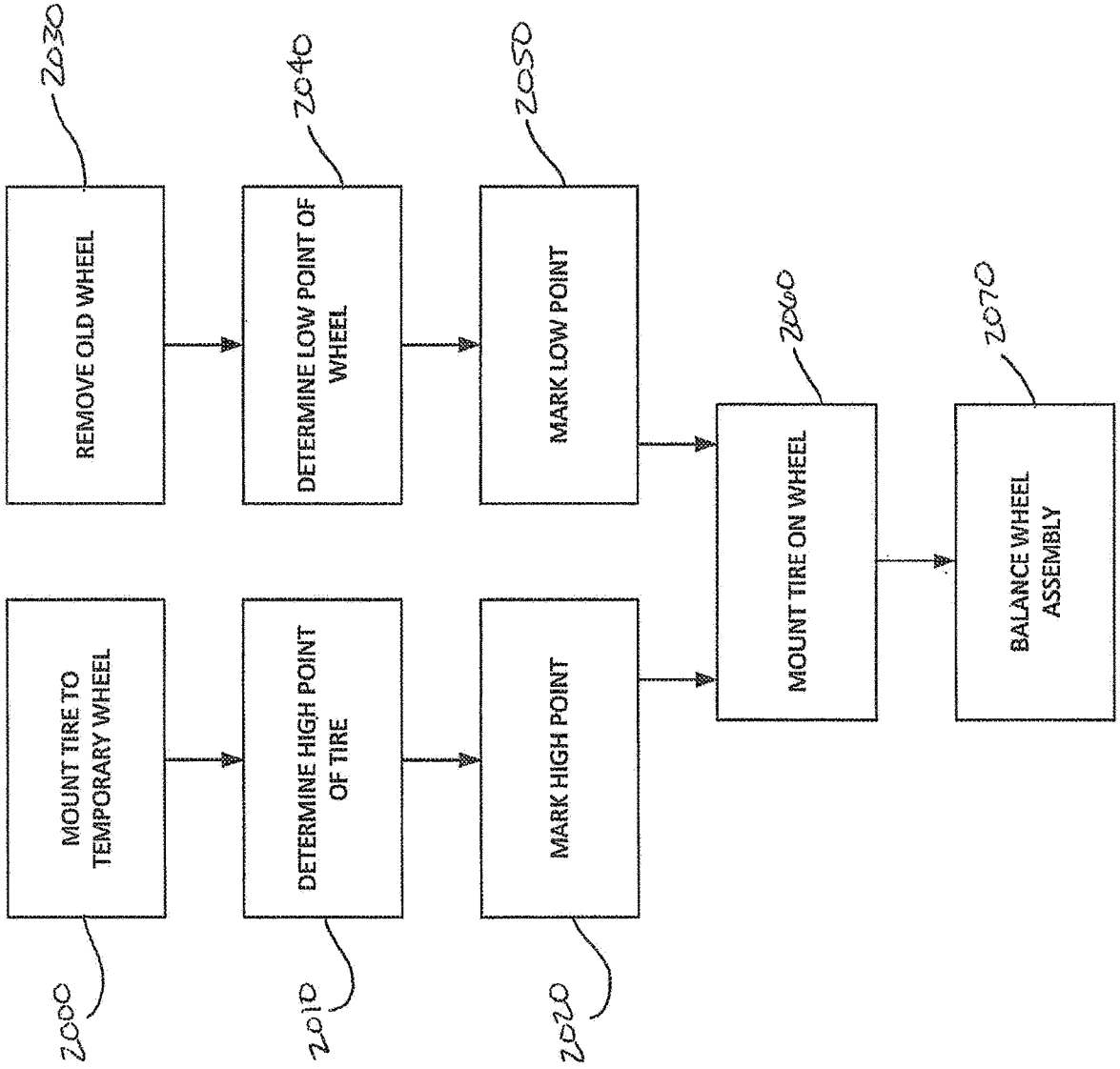

MOUNT TIRE TO TEMPORARY WHEEL
2000
DETERMINE HIGH POINT OF TIRE
2010
MARK HIGH POINT
2020
REMOVE OLD WHEEL
2030
DETERMINE LOW POINT OF WHEEL
2040
MARK LOW POINT
2050
MOUNT TIRE ON WHEEL
2060
BALANCE WHEEL ASSEMBLY
2070

FIG. 33

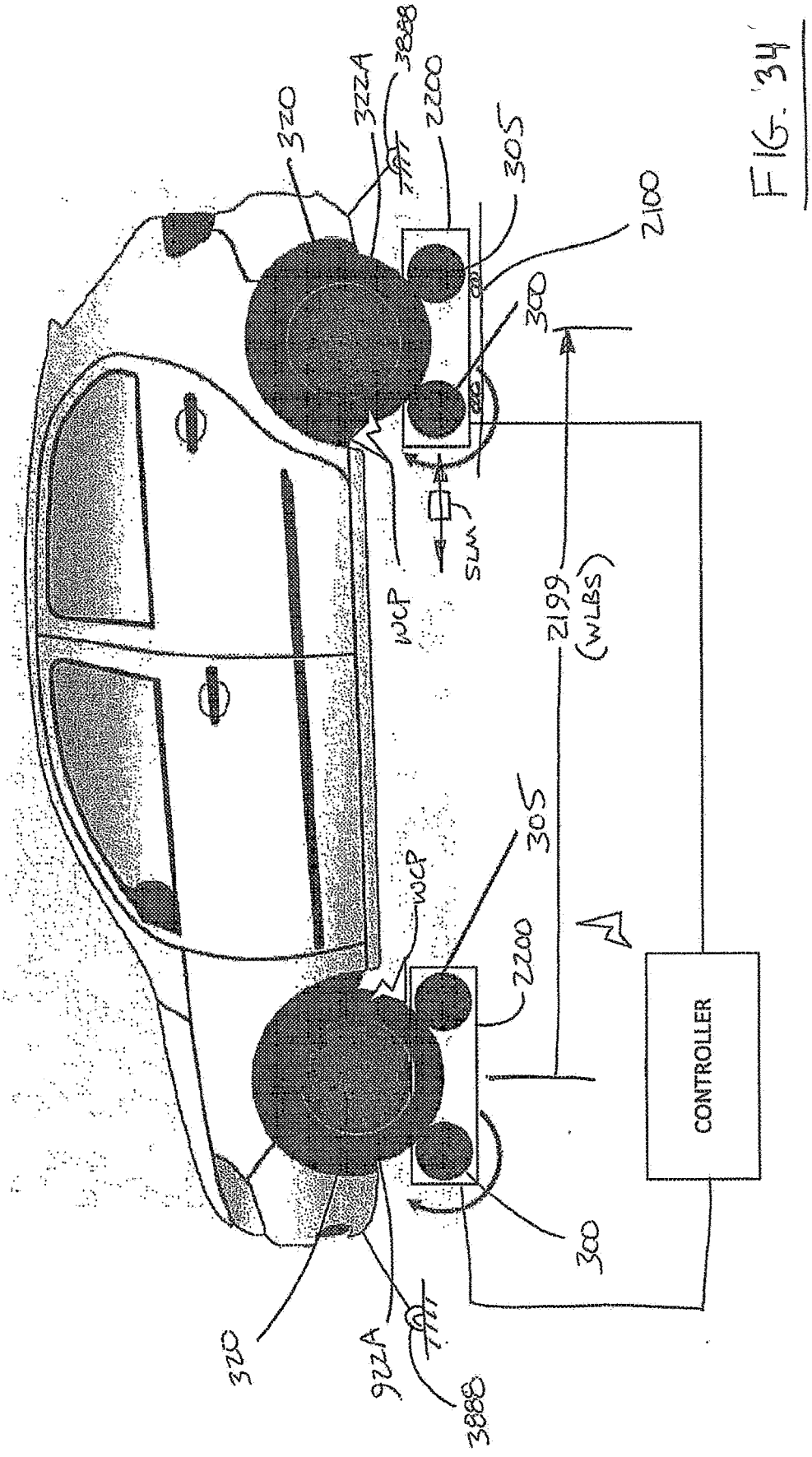

320
3224
3888
2200
305
2100
300
WCP
SLM
2199
(WLBS)
305
WCP
2200
CONTROLLER
300
320
922A
3888

FIG. 34

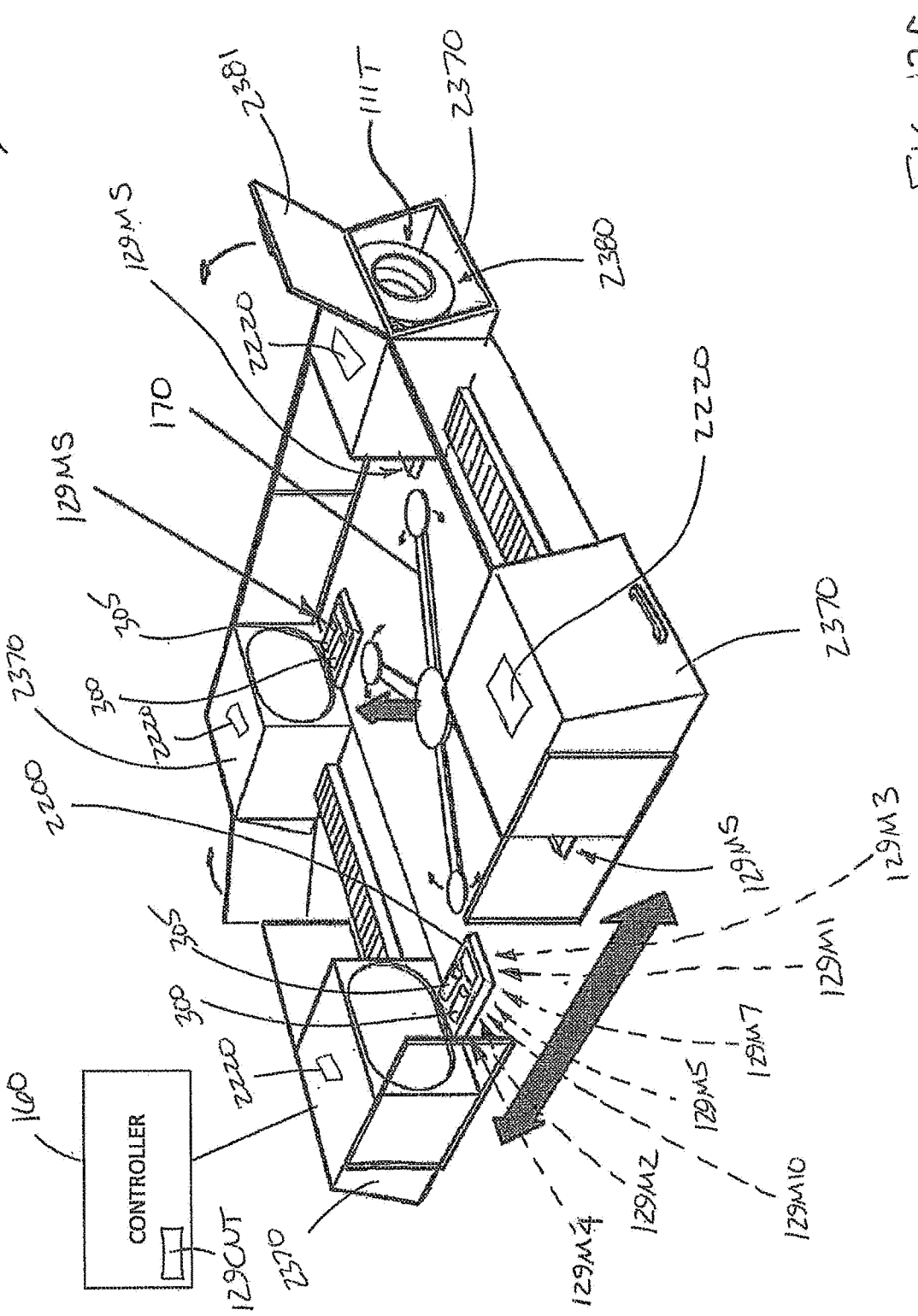

100A
2381
111T
2370
129MS
2380
2220
170
2220
129MS
305
2370
300
2220
2200
2370
305
129MS
129M3
129M1
300
2220
129M7
160
CONTROLLER
129MS
129M2
129M10
129CUT
2370
129M4

FIG. 135

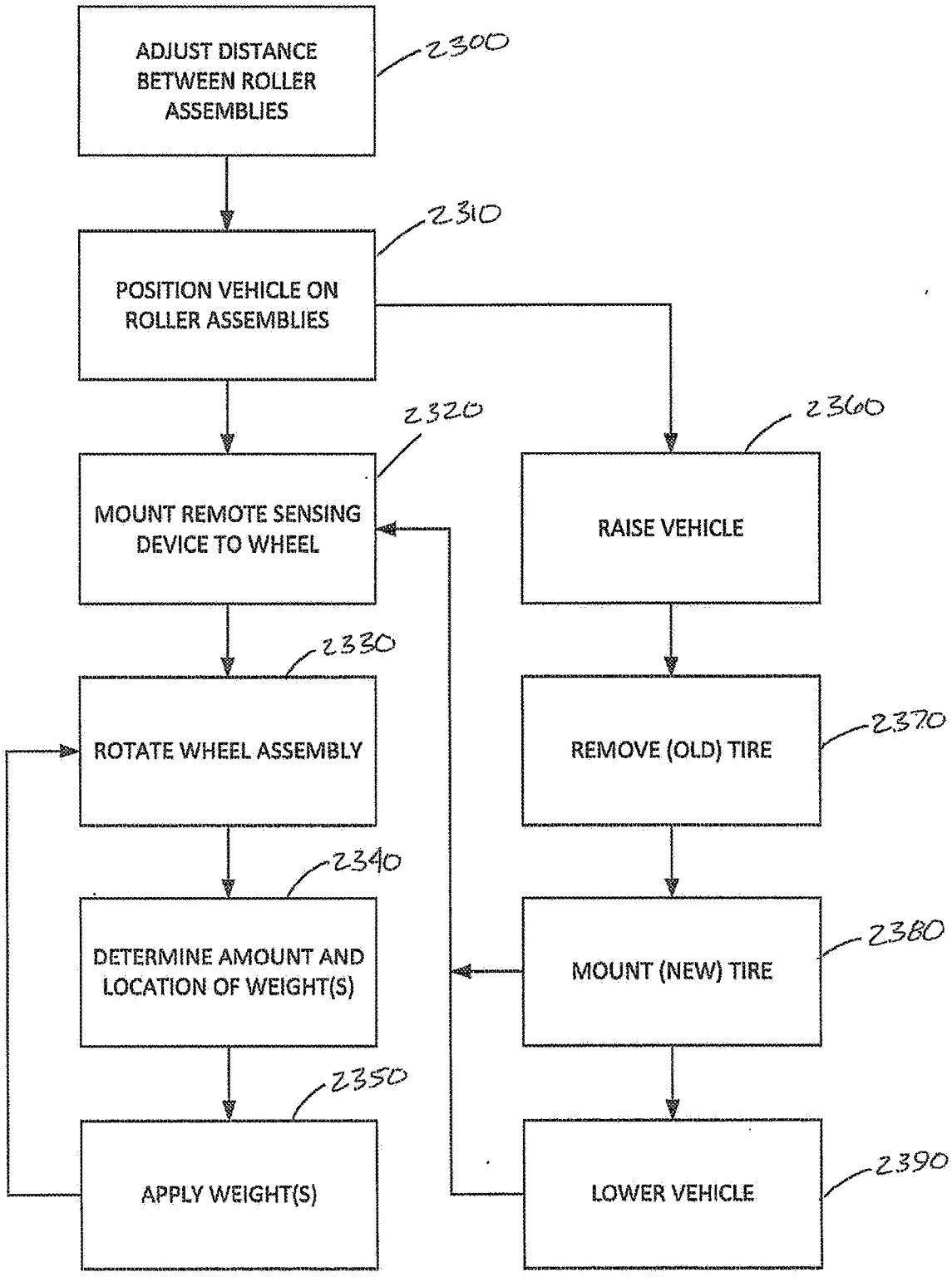

ADJUST DISTANCE BETWEEN ROLLER ASSEMBLIES
2300
POSITION VEHICLE ON ROLLER ASSEMBLIES
2310
MOUNT REMOTE SENSING DEVICE TO WHEEL
2320
ROTATE WHEEL ASSEMBLY
2330
DETERMINE AMOUNT AND LOCATION OF WEIGHT(S)
2340
APPLY WEIGHT(S)
2350
RAISE VEHICLE
2360
REMOVE (OLD) TIRE
2370
MOUNT (NEW) TIRE
2380
LOWER VEHICLE
2390

FIG. 36

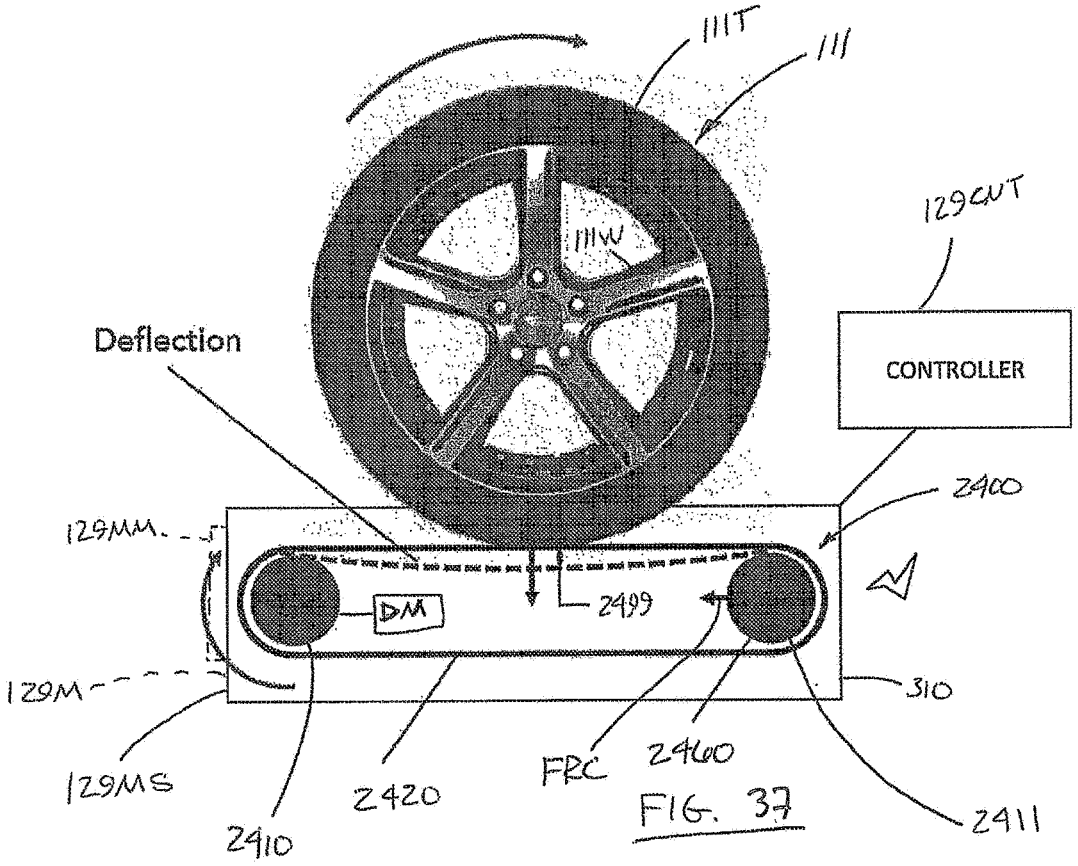


FIG. 37

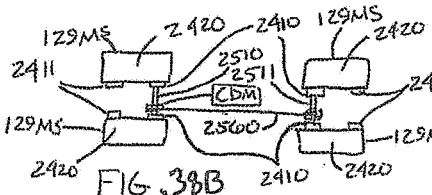


FIG. 38B

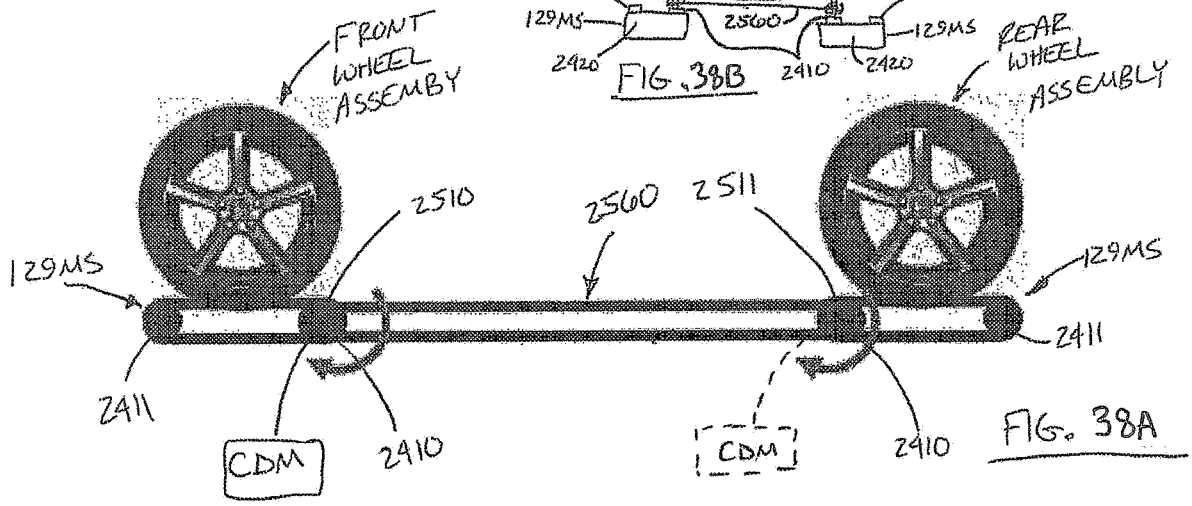


FIG. 38A

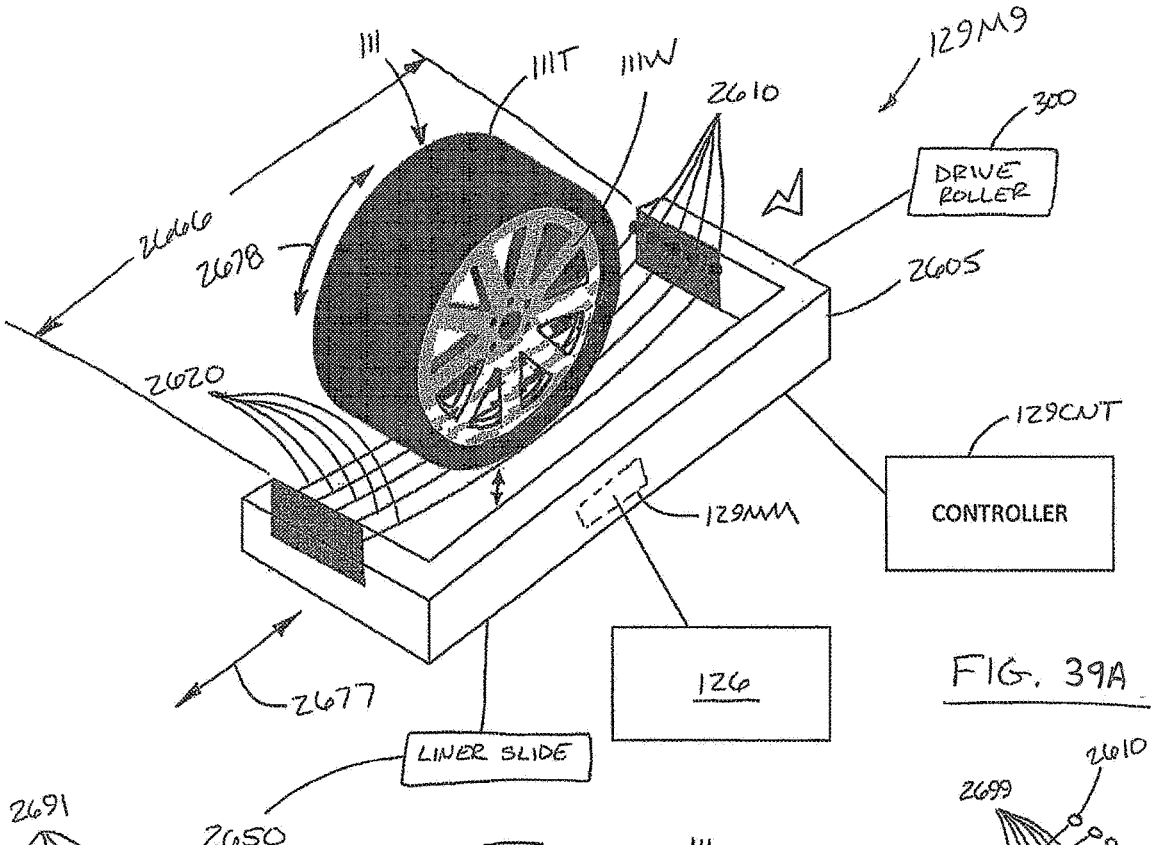


FIG. 39A

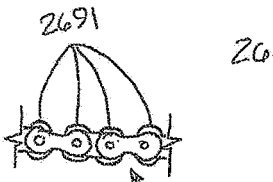


Fig. 39D

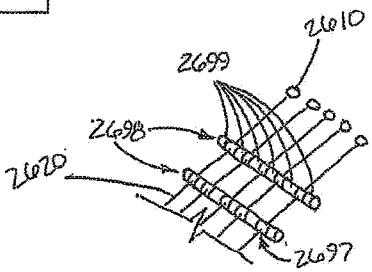


FIG. 39C

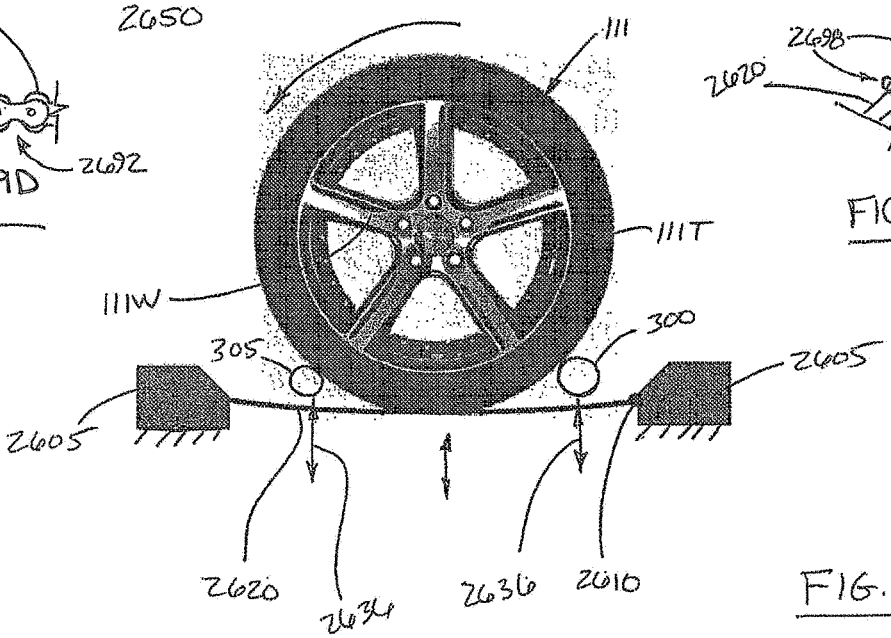


FIG. 39B

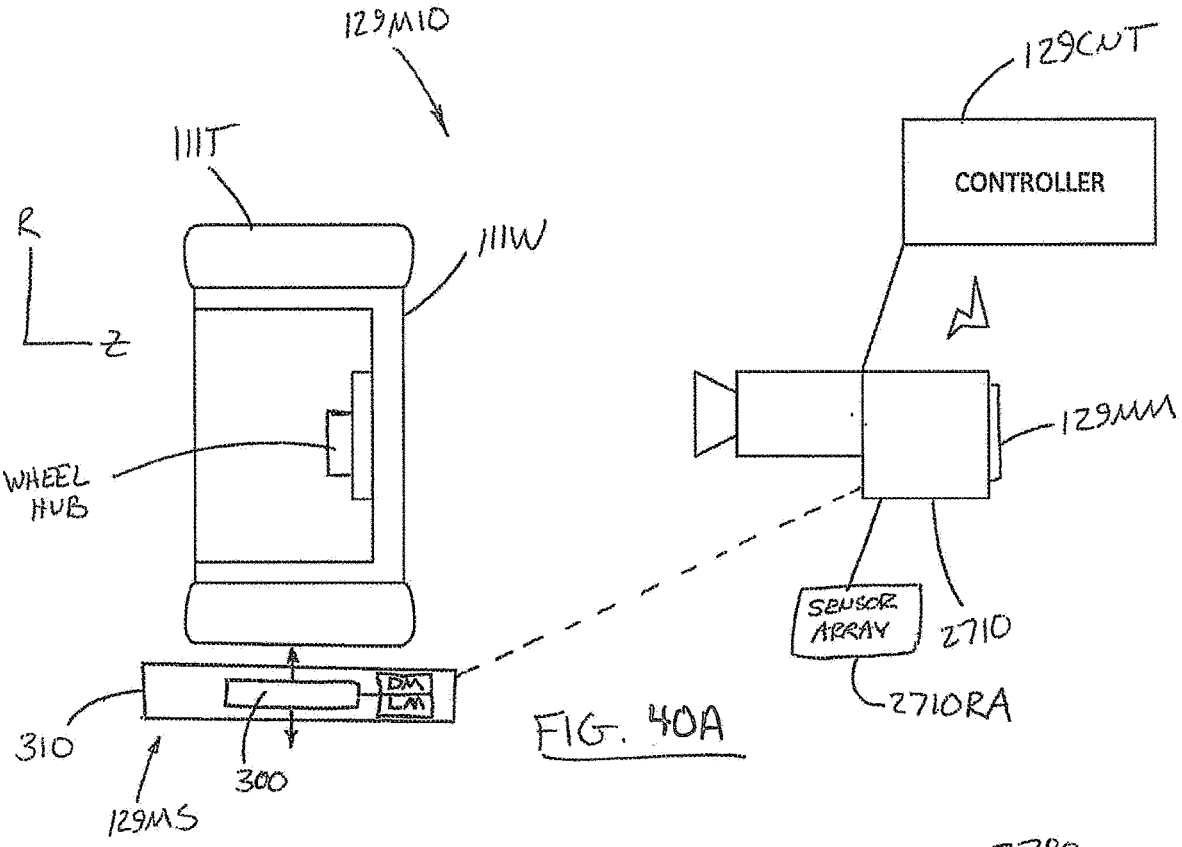


FIG. 40A

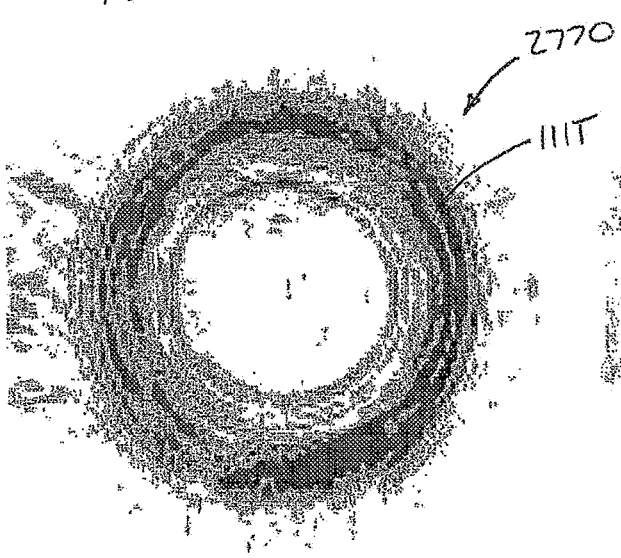


FIG. 40B

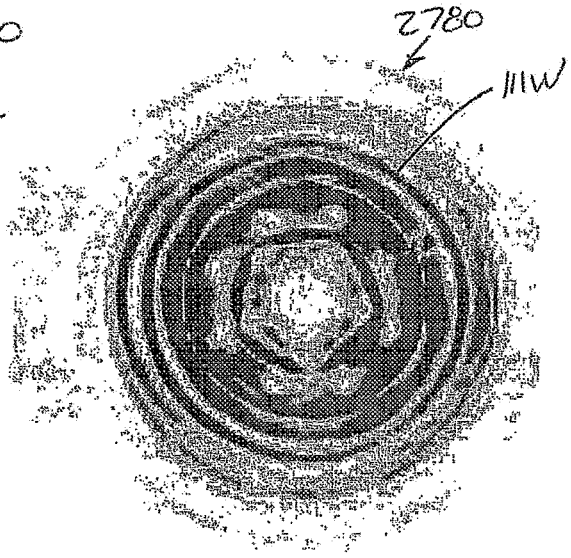


FIG. 40C

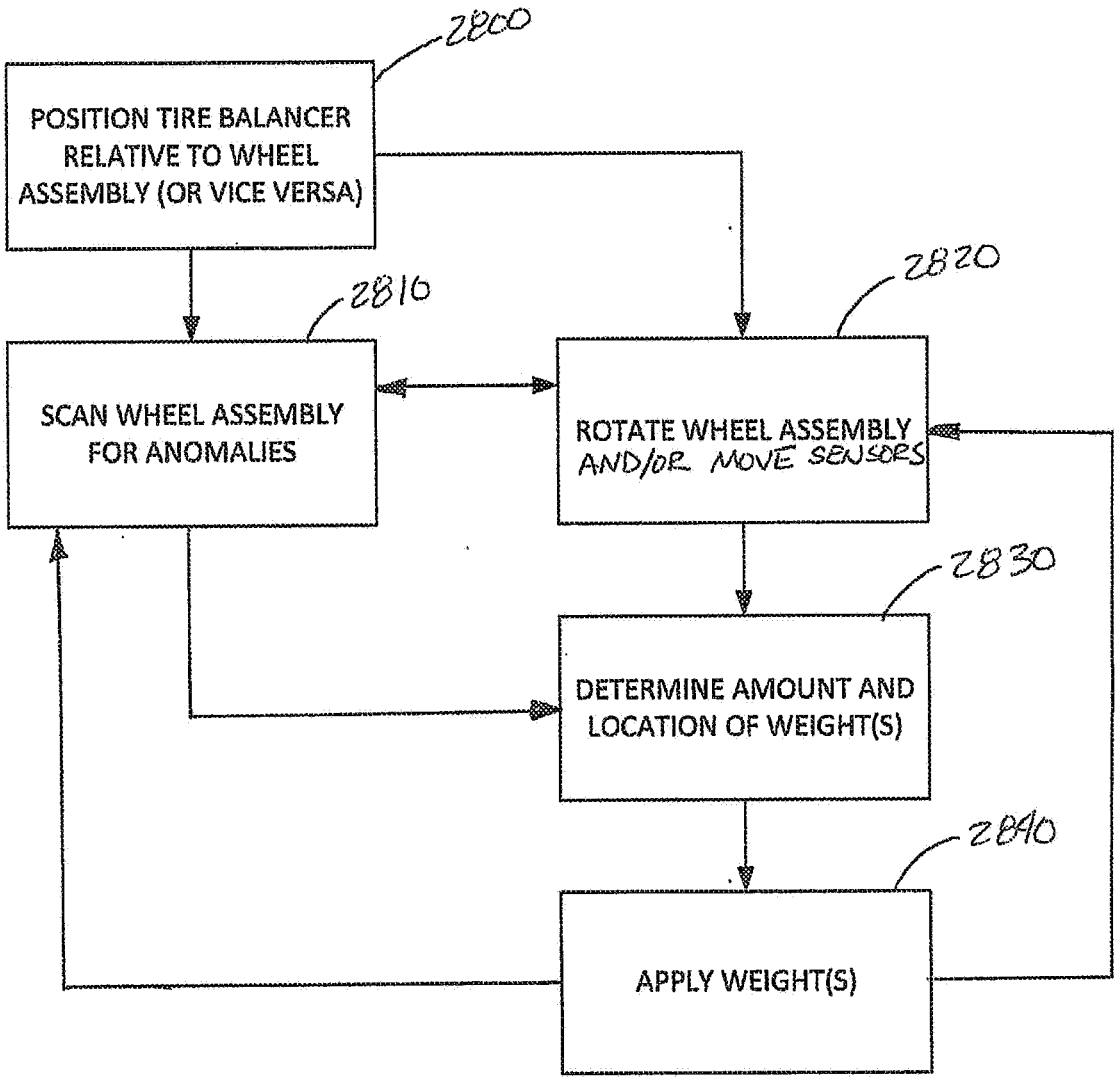

2800
POSITION TIRE BALANCER RELATIVE TO WHEEL ASSEMBLY (OR VICE VERSA)
2810
SCAN WHEEL ASSEMBLY FOR ANOMALIES
2820
ROTATE WHEEL ASSEMBLY AND/OR MOVE SENSORS
2830
DETERMINE AMOUNT AND LOCATION OF WEIGHT(S)
2840
APPLY WEIGHT(S)

FIG. 41

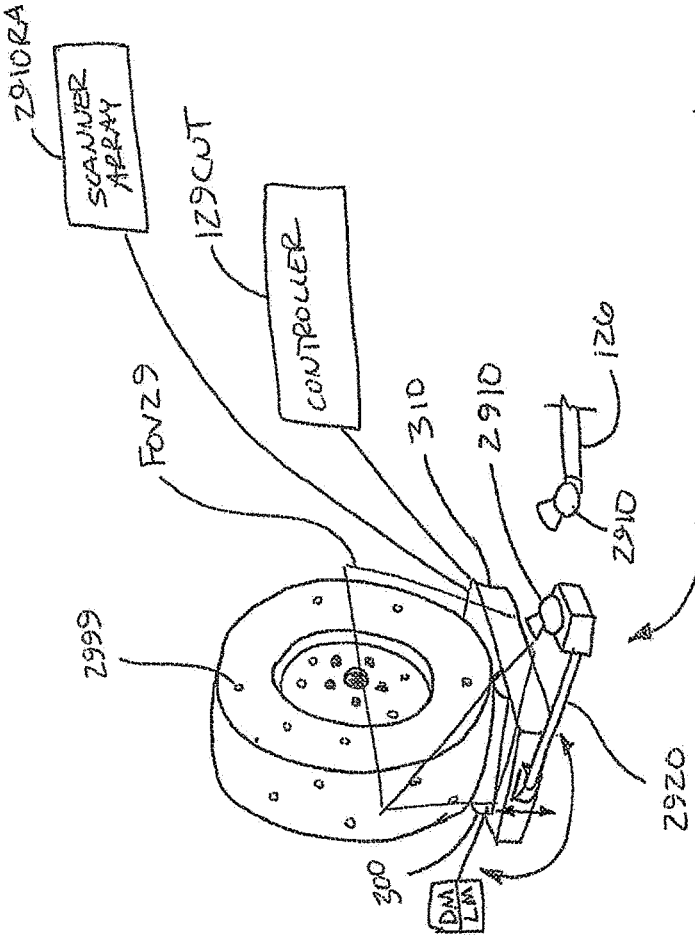


FIG. 42A

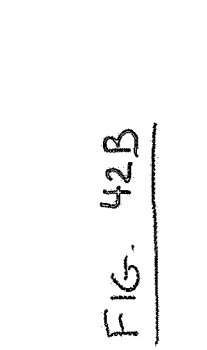


FIG. 42B

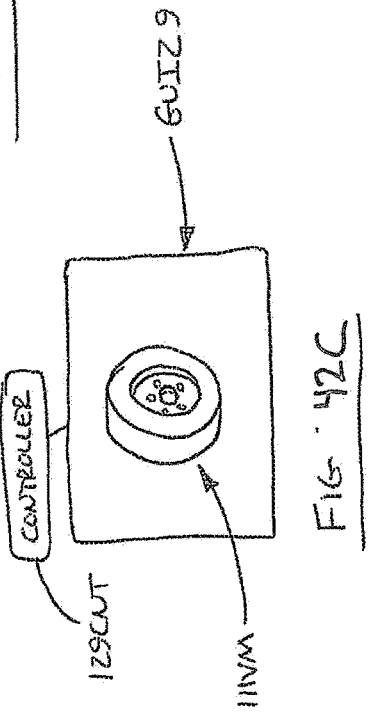


FIG. 42C

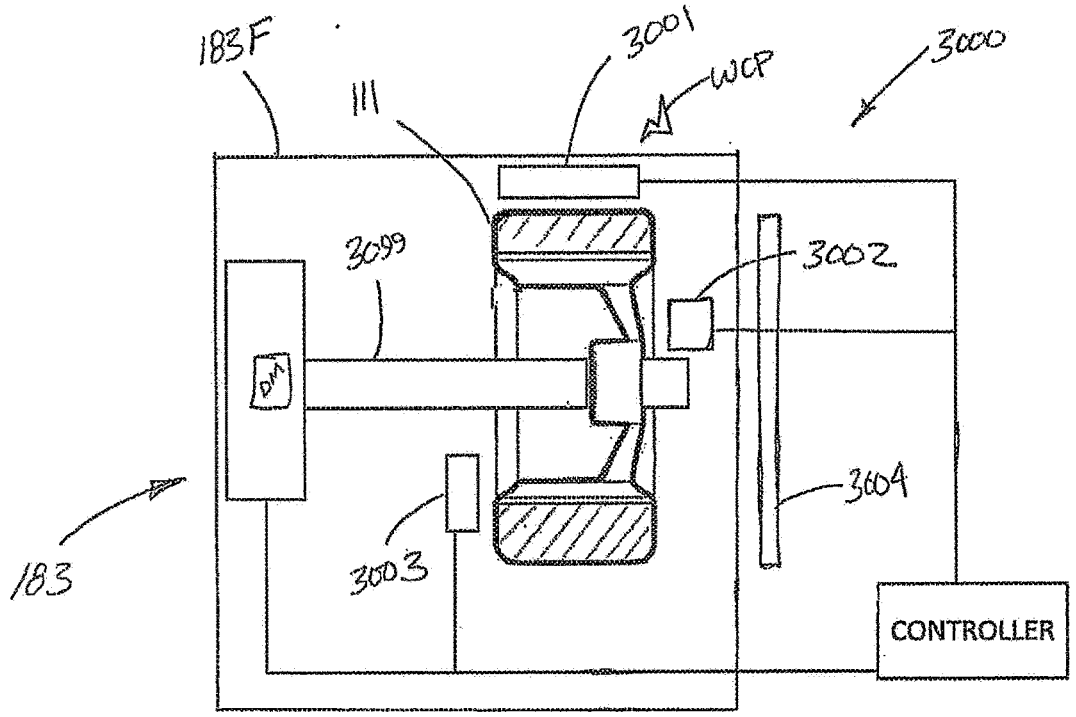


FIG. 43A

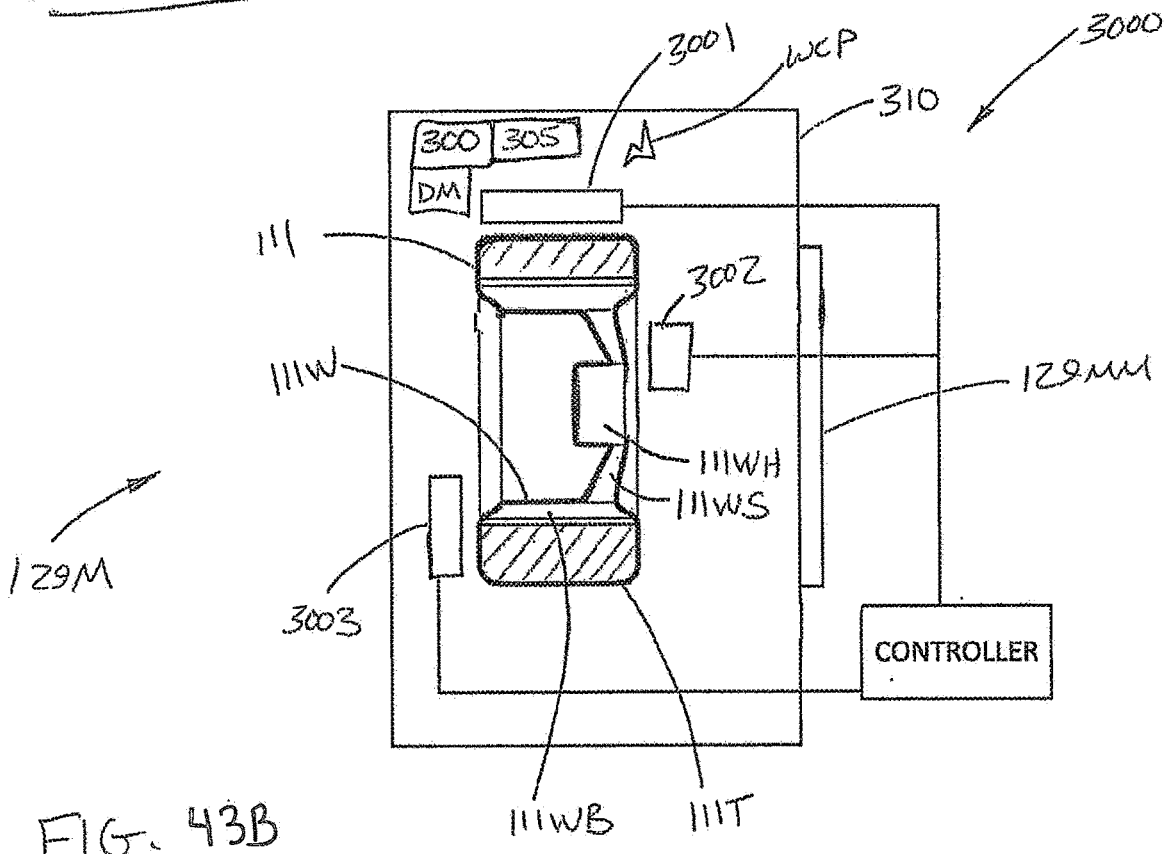


FIG. 43B

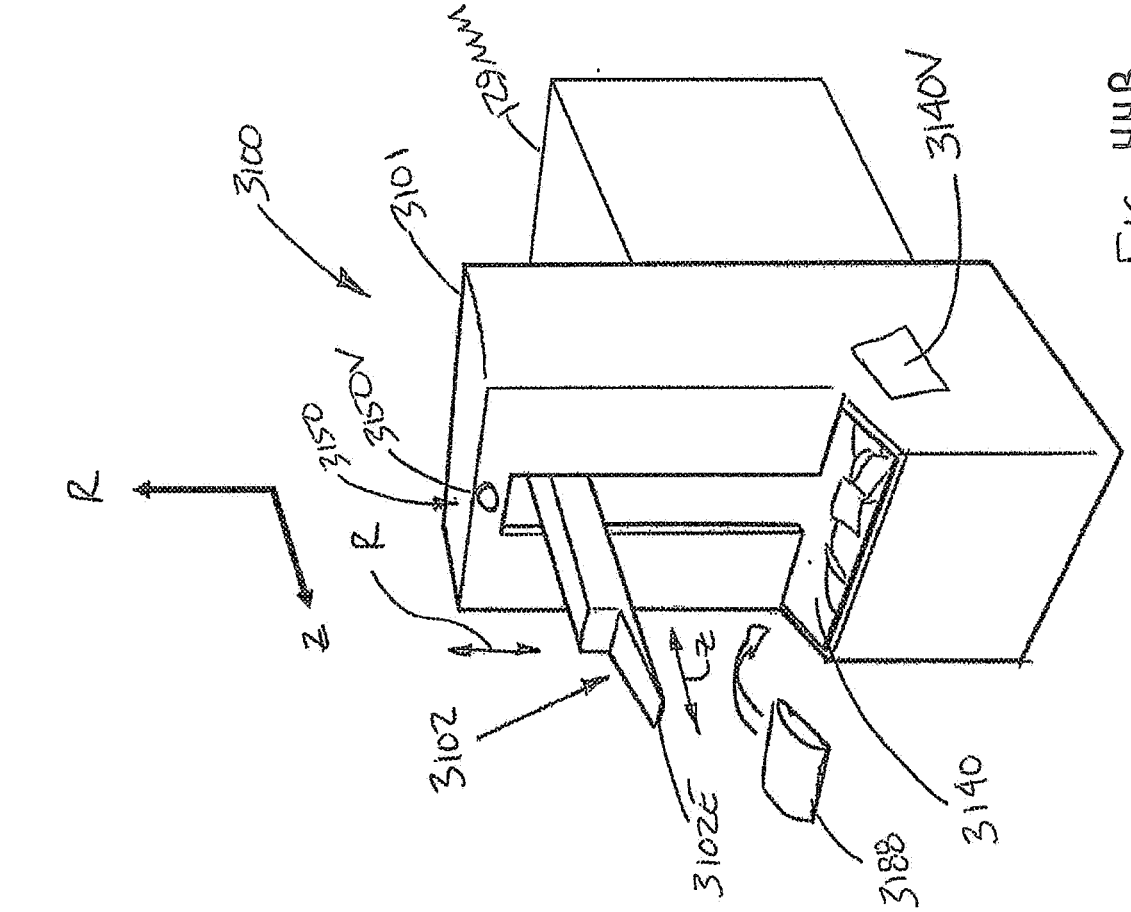


FIG. 44B

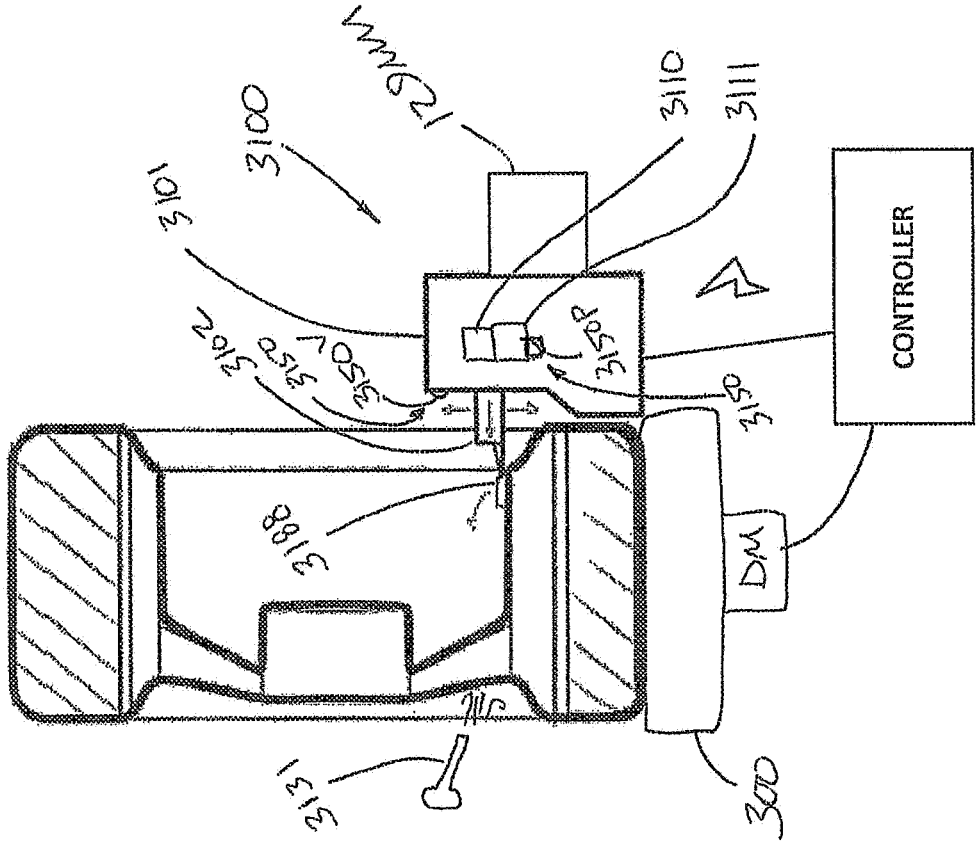


FIG. 44A

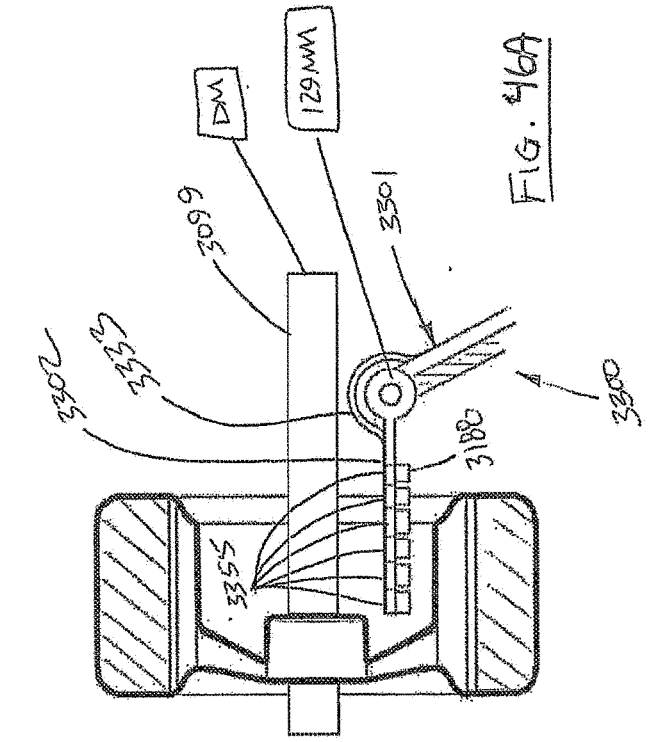


FIG. 46A

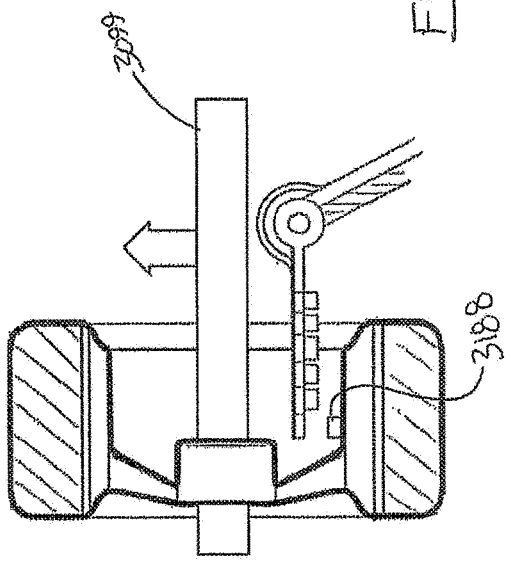


FIG. 46C

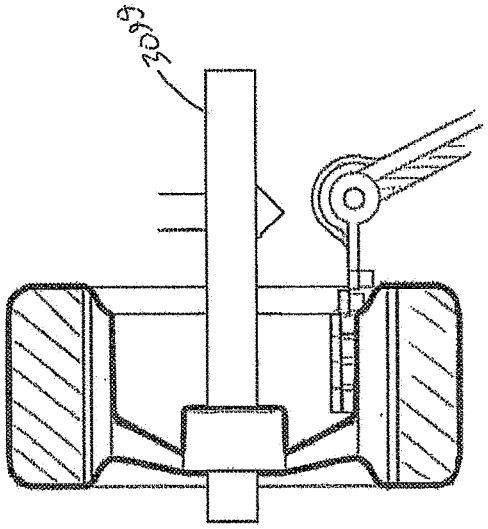


FIG. 46B

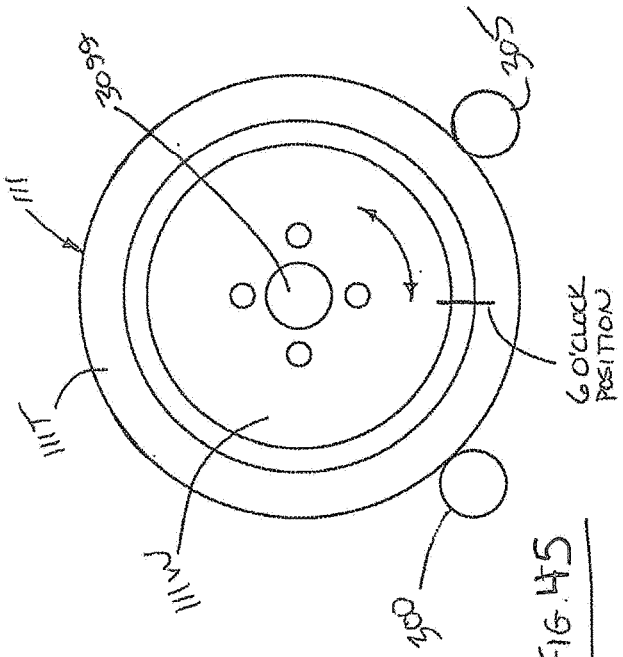


FIG. 45

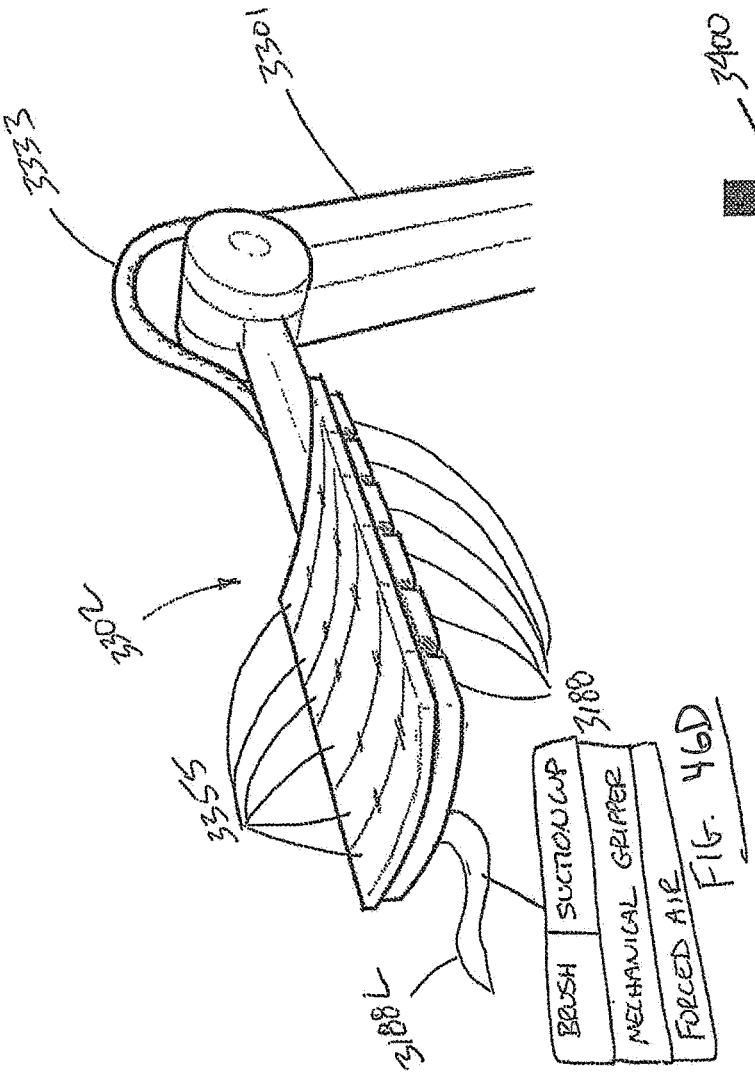


FIG. 46D

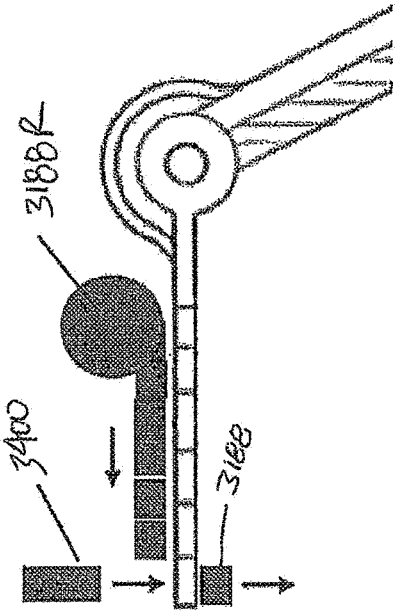


FIG. 47

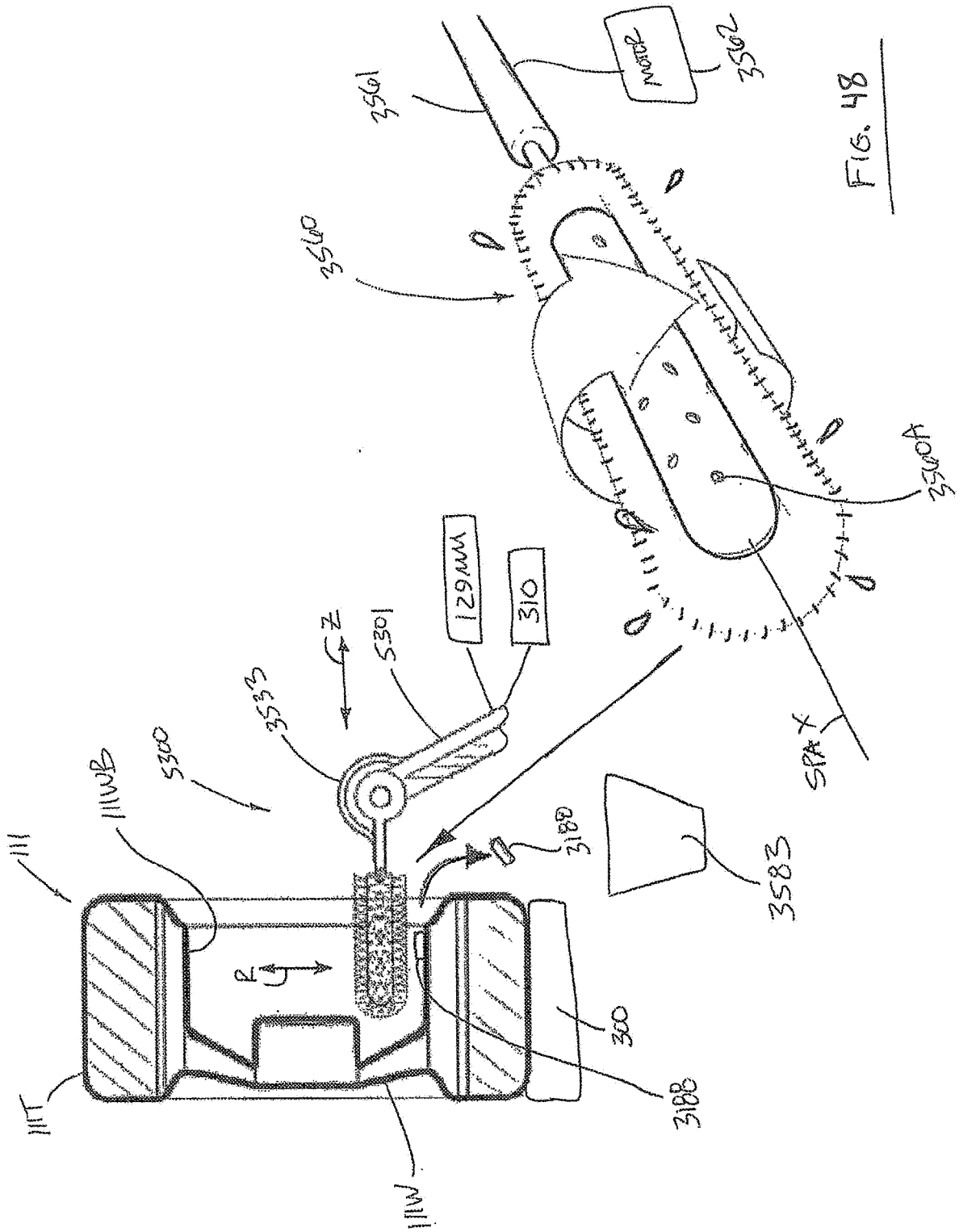

111
111WB
5300
3535
Z
5301
129MM
310
3188
3583
111W
111T
R
300
3188
SPA X
3500A
3540
3501
MOTOR
3502

FIG. 48

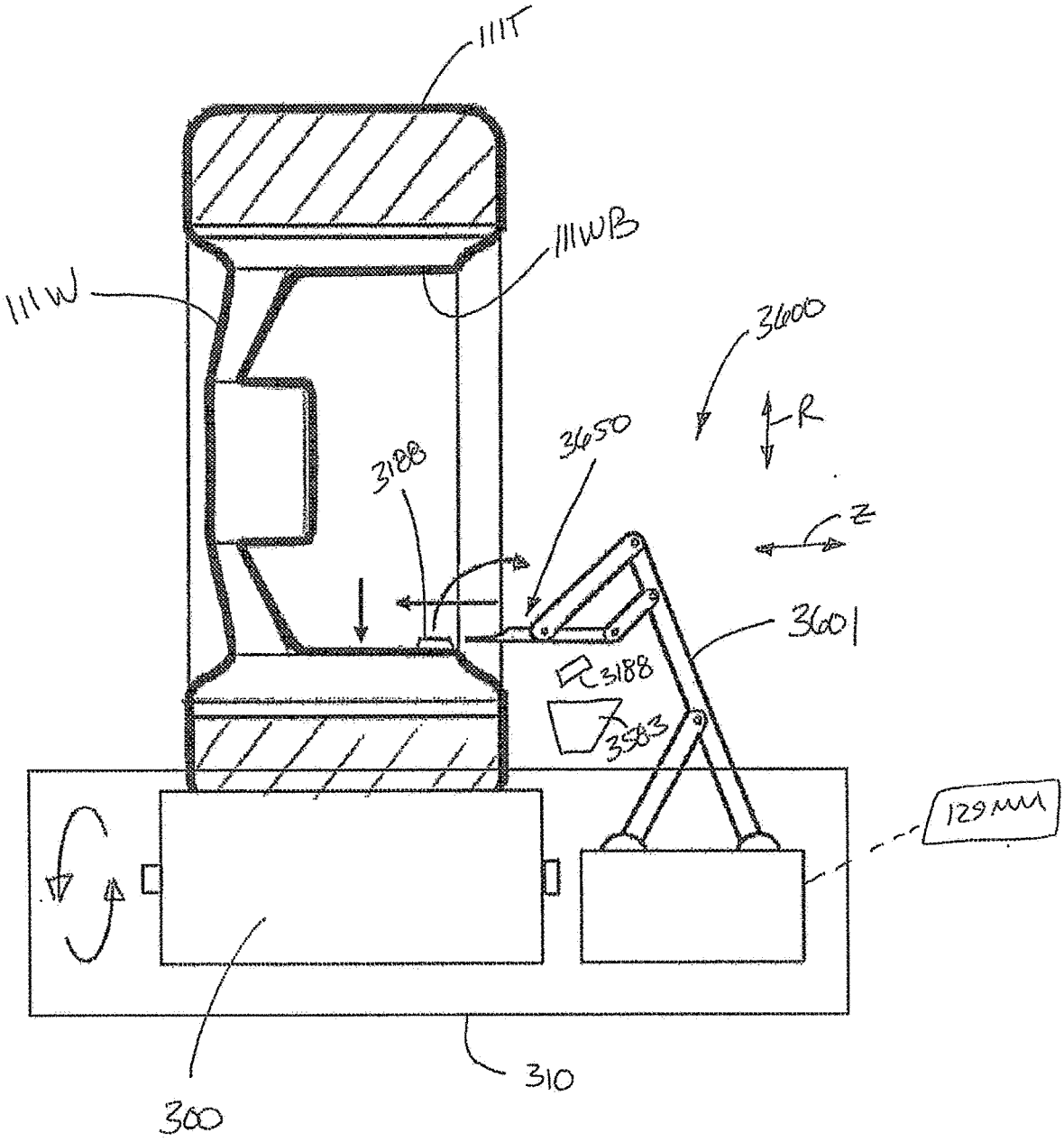
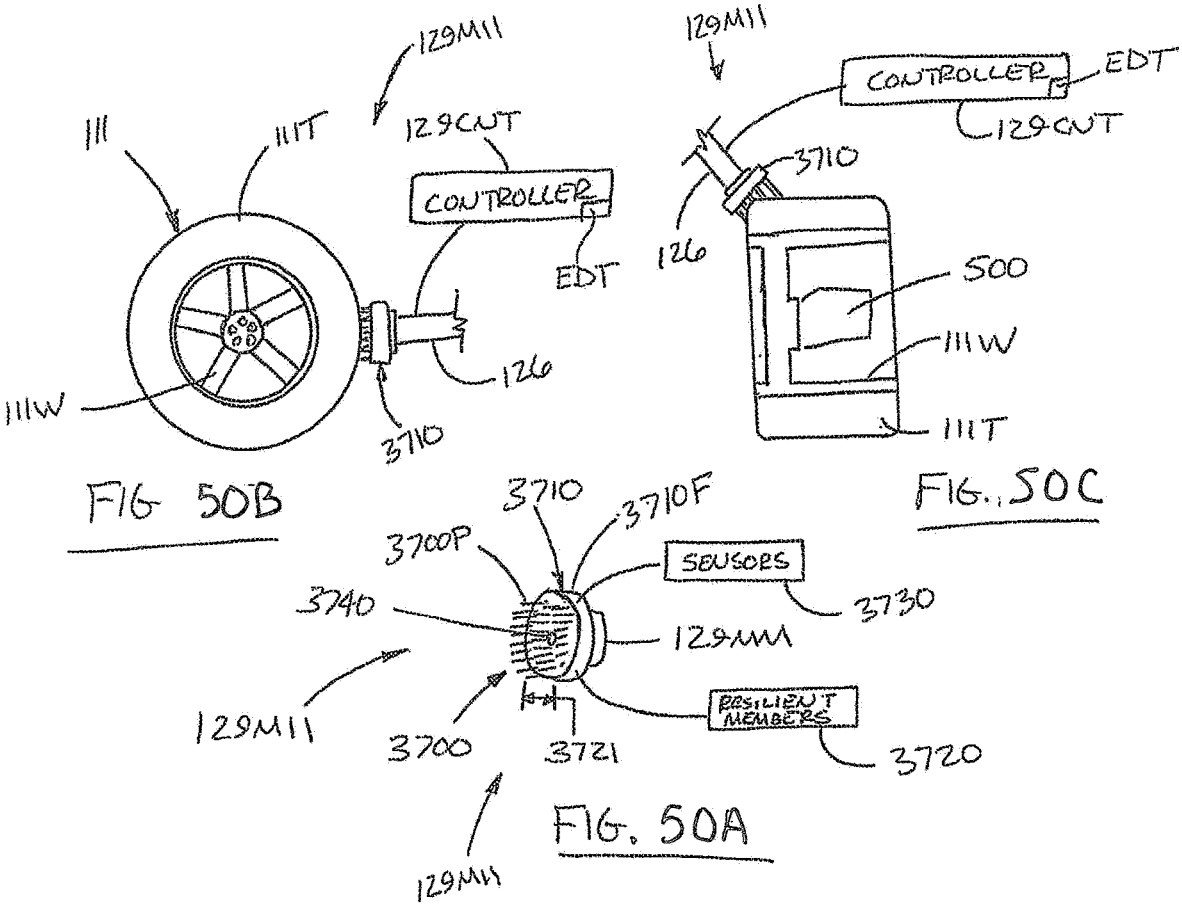

111T
111WB
111W
3600
R
Z
3650
3188
3601
3188
3383
129mm
310
300

FIG. 49


129M11
111
111T
129CNT
CONTROLLER
EDT
126
3710
111W
FIG 50B
129M11
CONTROLLER
EDT
129CNT
3710
126
500
111W
111T
FIG. 50C
3710
3710F
3700P
SENSORS
3730
3740
129MM
129M11
3700
3721
RESILIENT MEMBERS
3720
129M11
FIG. 50A

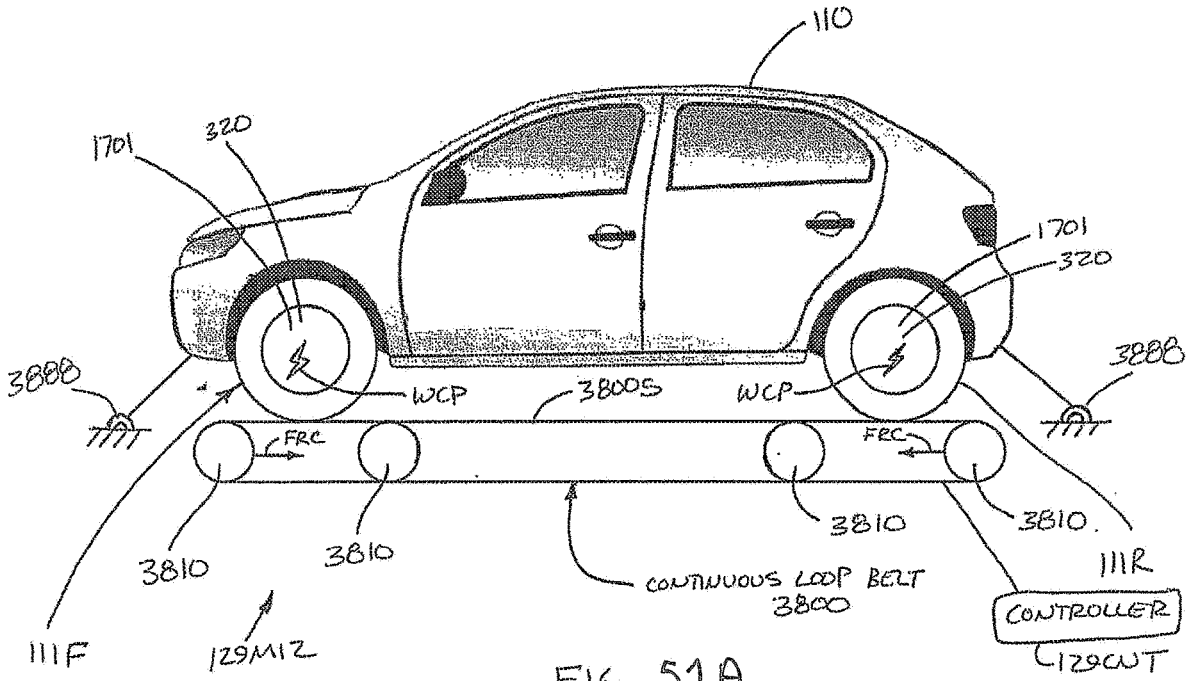


FIG. 51A

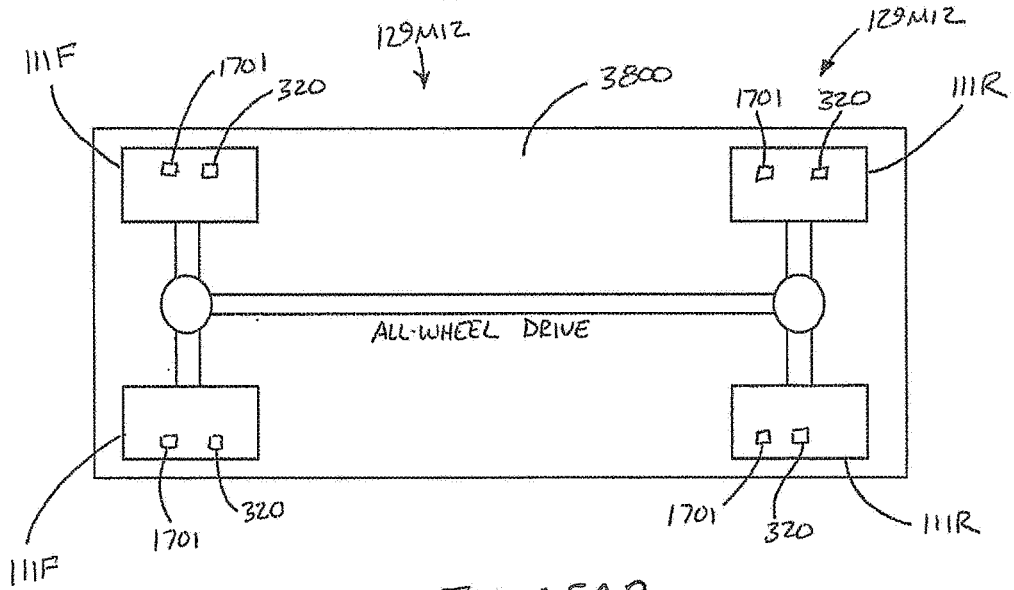


FIG. 51B

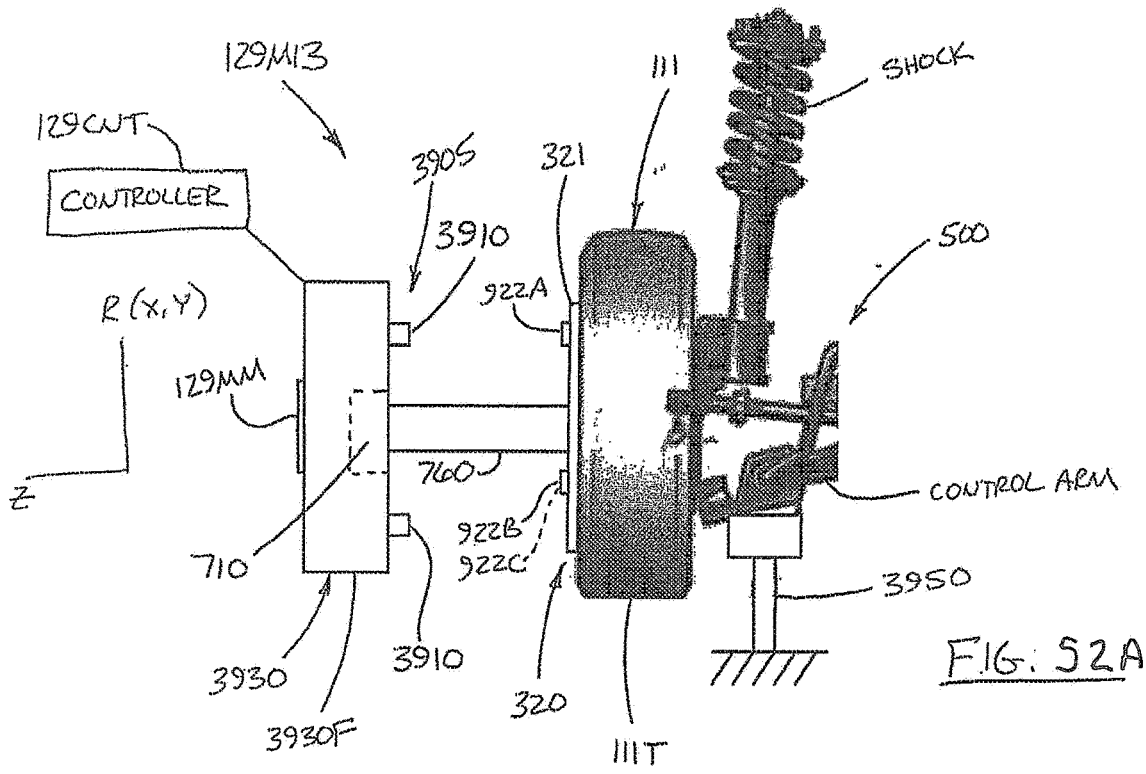


FIG. 52A

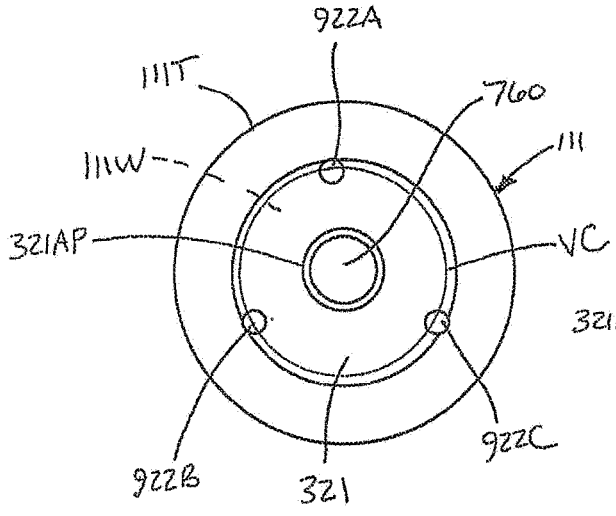


FIG. 52B

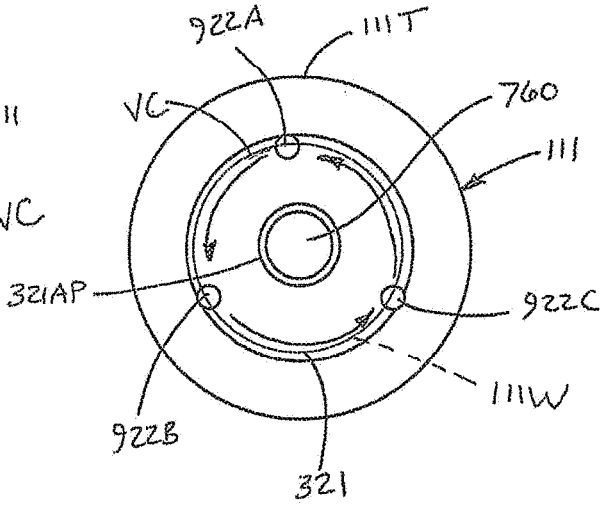


FIG. 52C

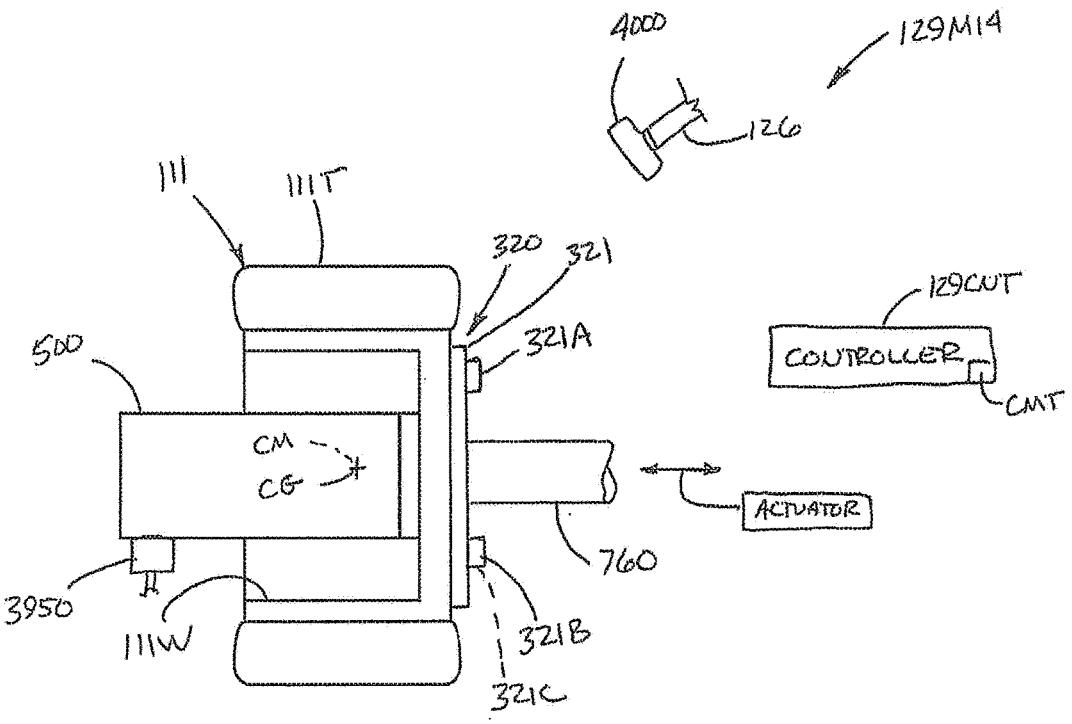


FIG. 53

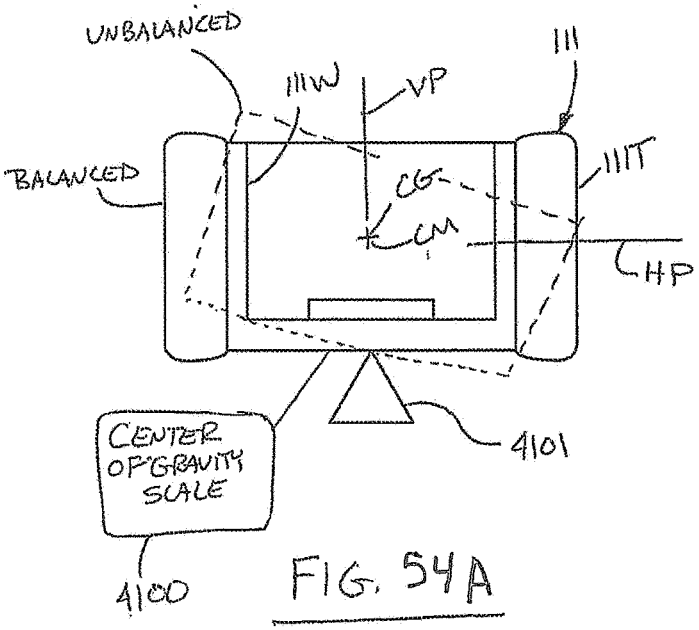


FIG. 54A

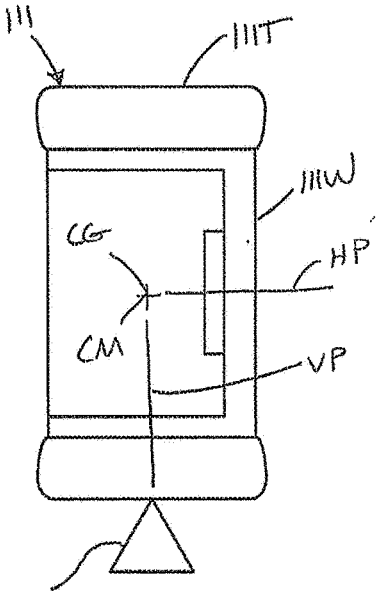


FIG. 54B

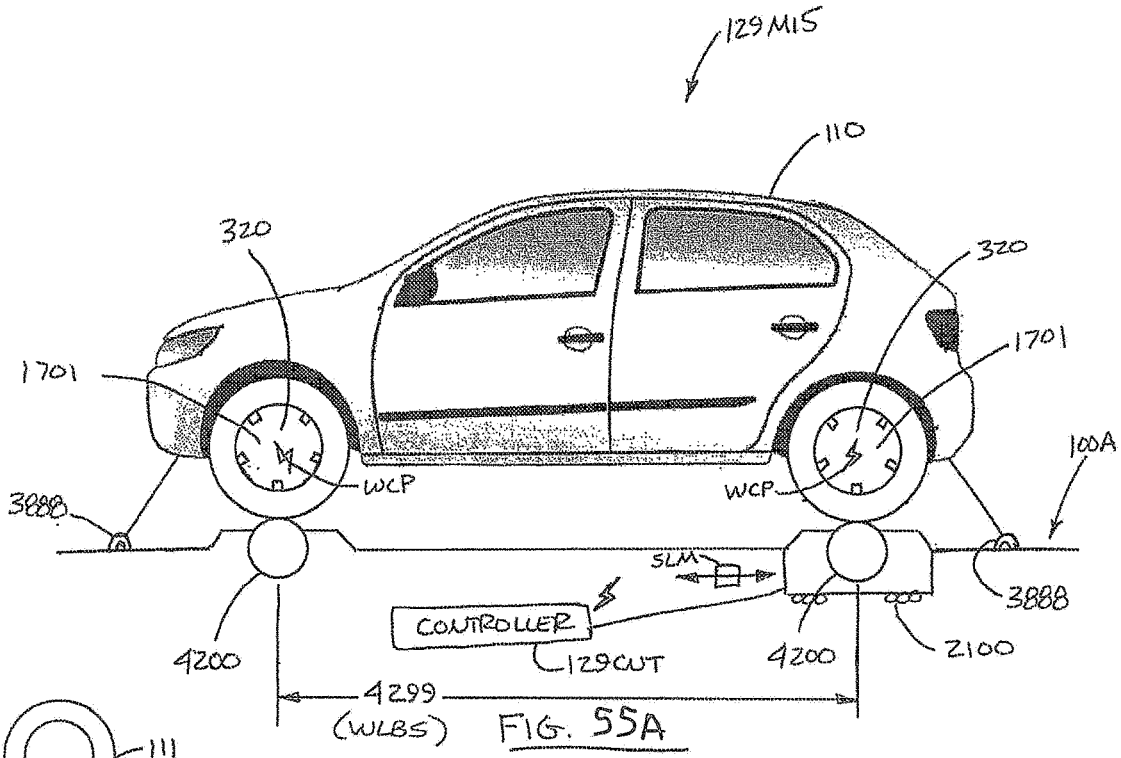


FIG. 55A



FIG. 55C

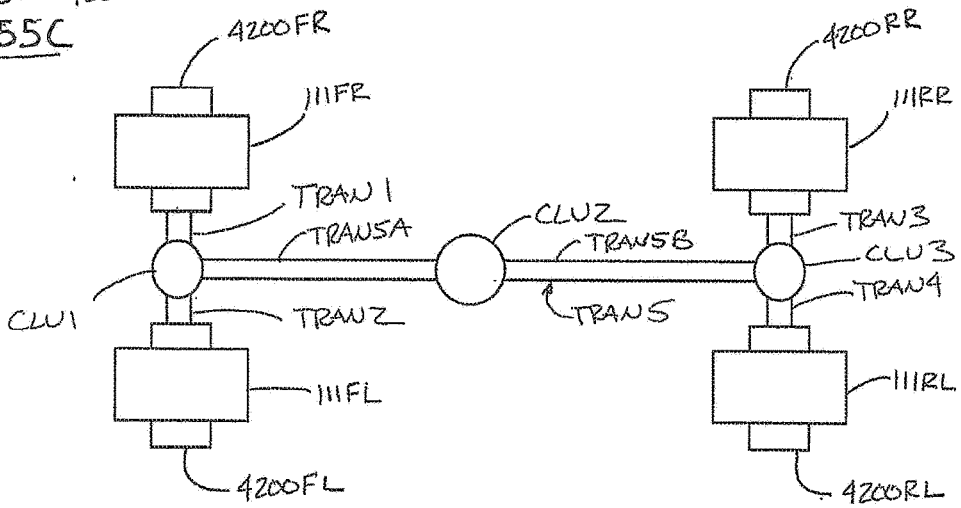


FIG. 55B

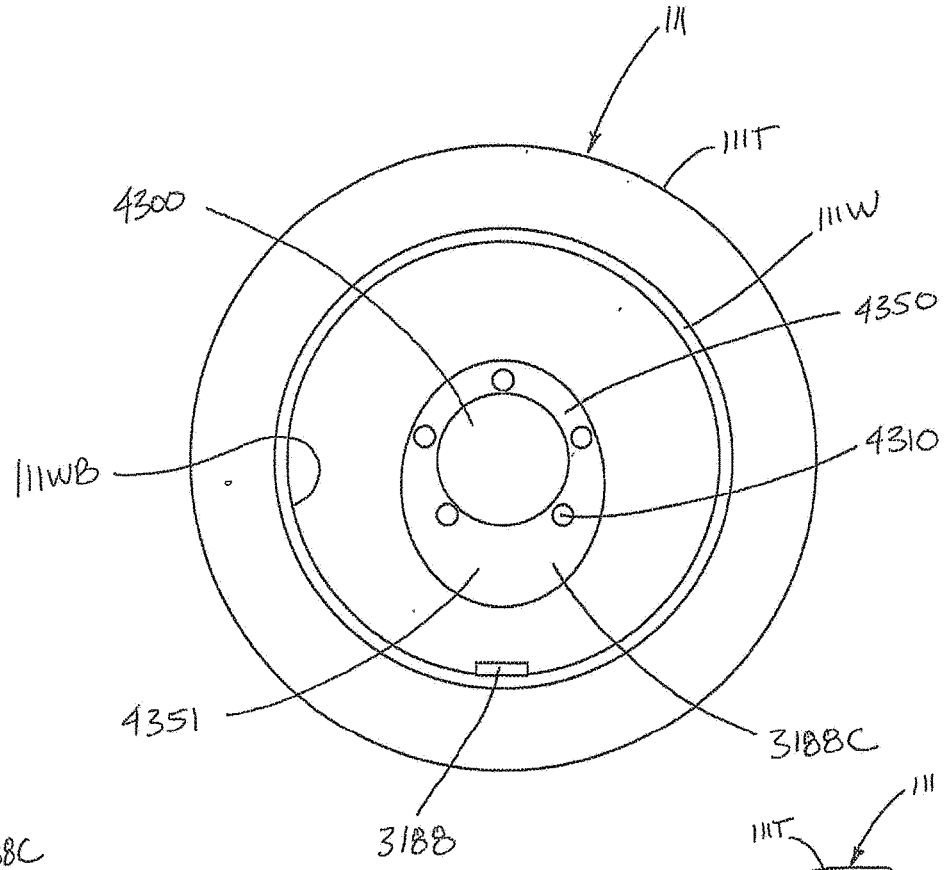


FIG 56

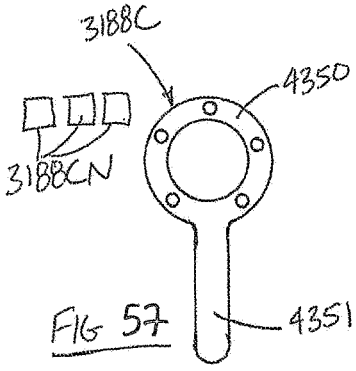


FIG 57

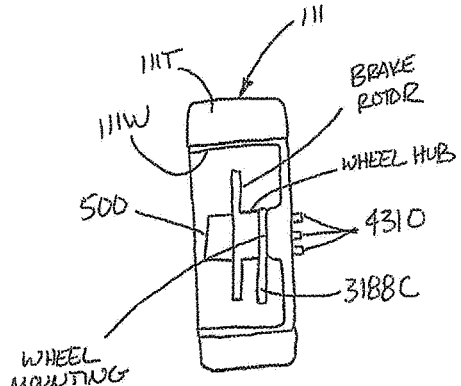


FIG. 58

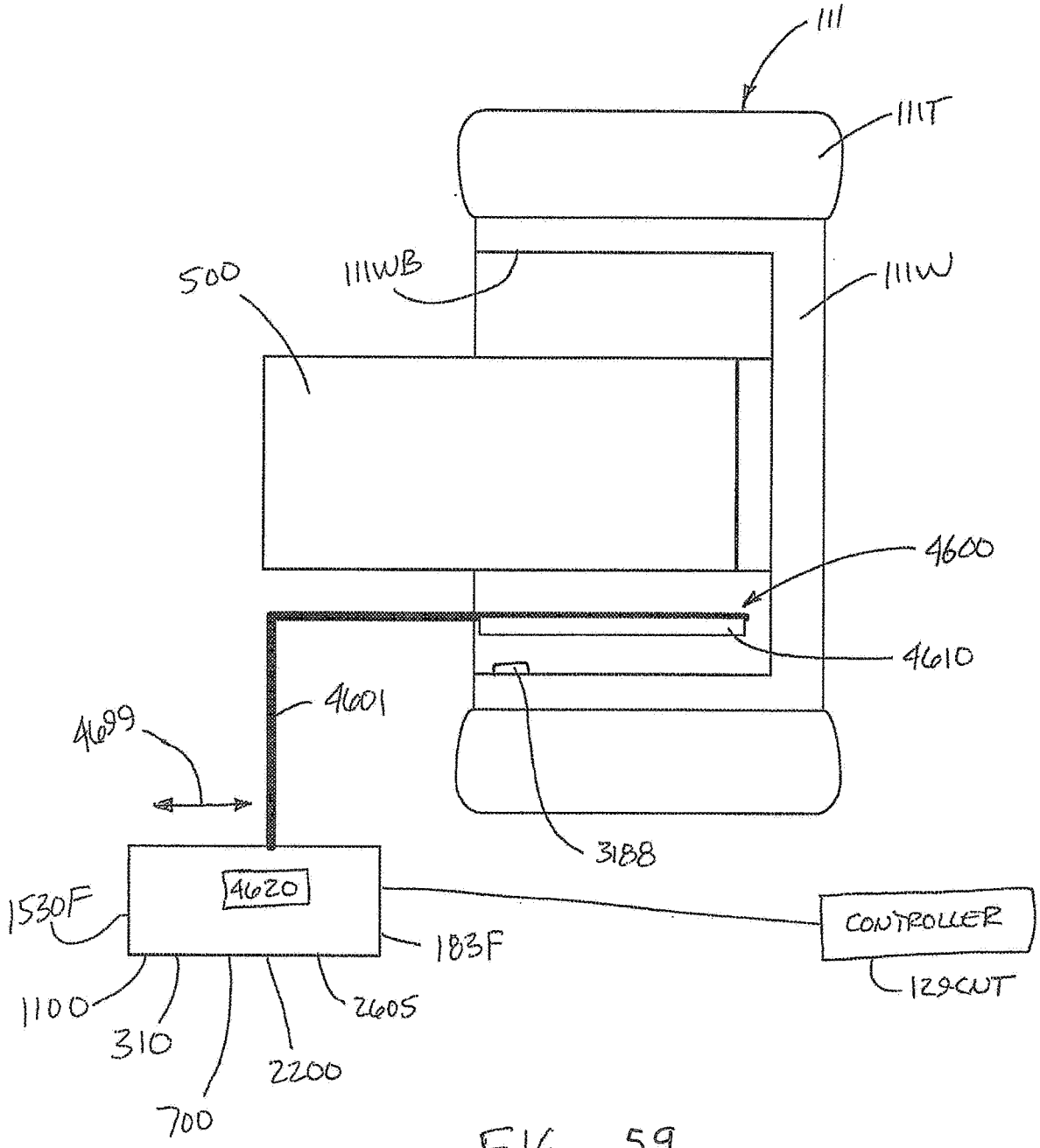

111
111T
111WB
111W
500
4600
4610
4601
4699
3188
4620
1530F
183F
CONTROLLER
129-CNT
1100
310
700
2200
2605

FIG 59

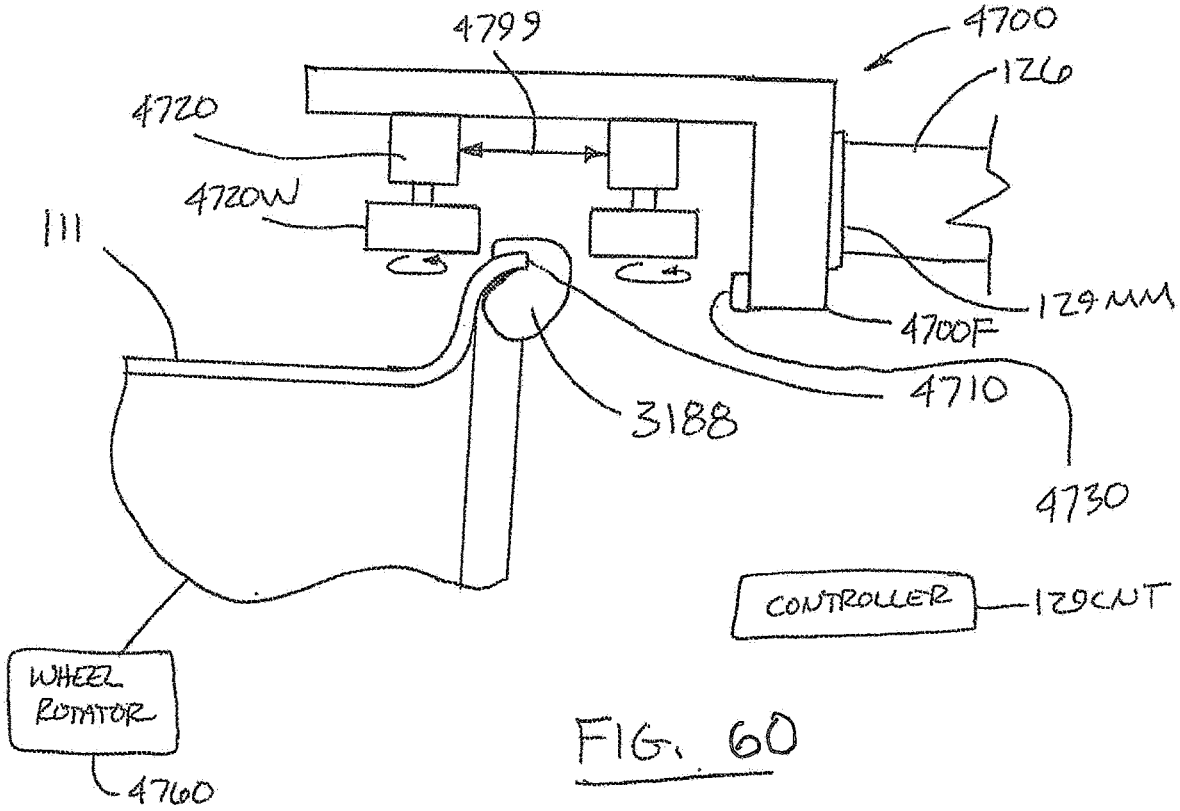

4799
4700
1260
4720
4720W
111
129MM
4700F
4710
3188
4730
CONTROLLER
129CNT
WHEEL ROTATOR
4760

FIG. 60

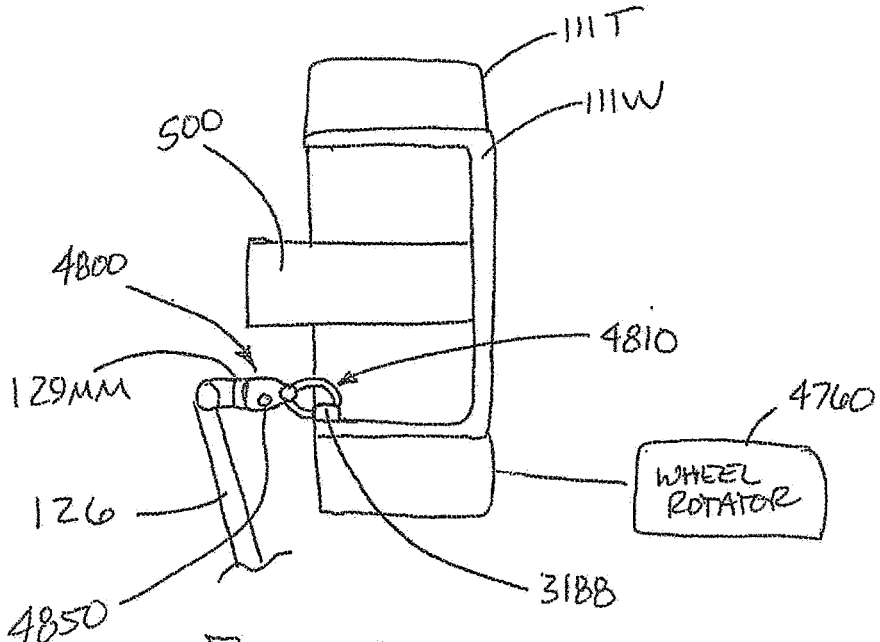

111T
111W
500
4800
4810
129MM
4760
WHEEL ROTATOR
126
3188
4850

FIG. 61

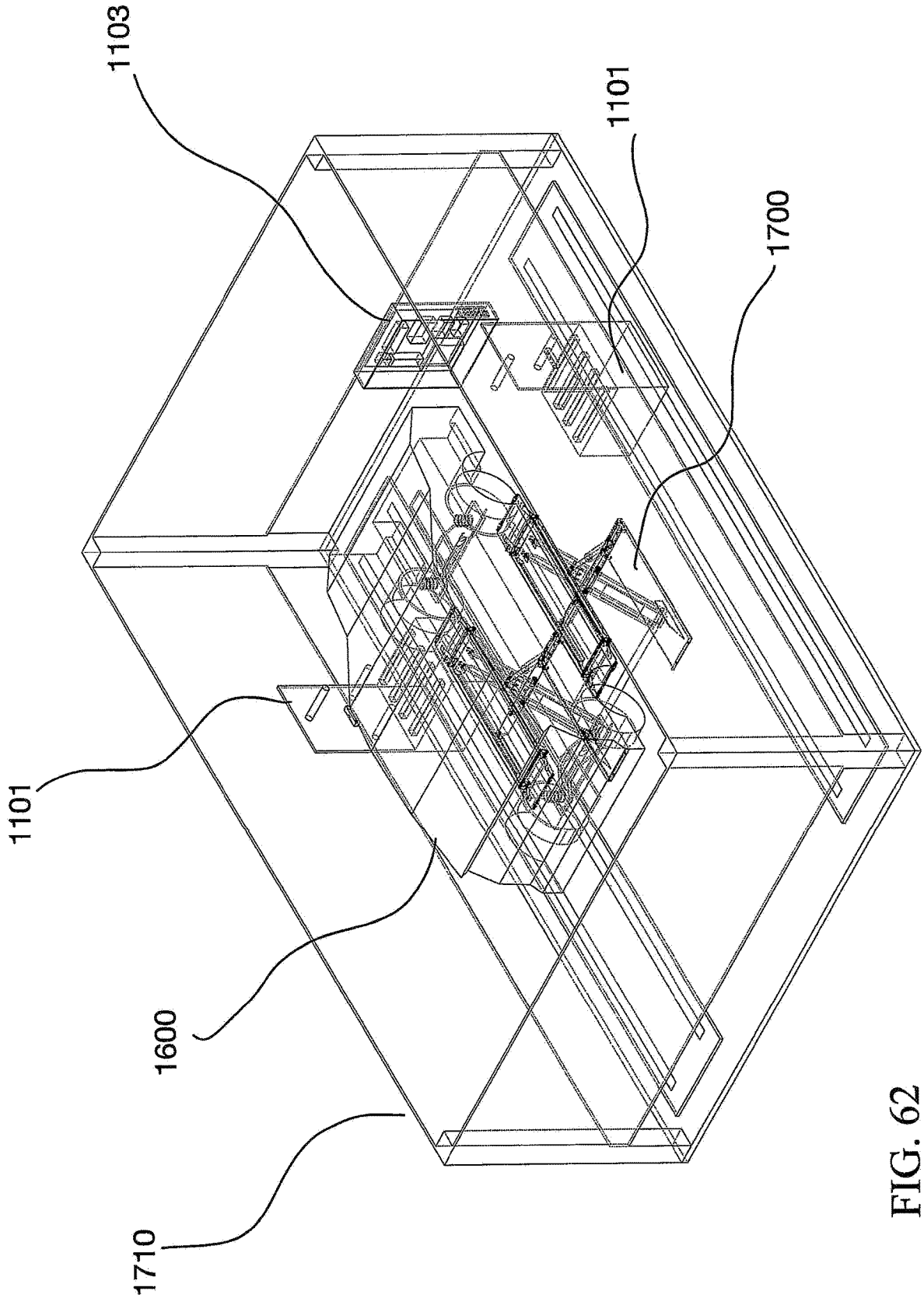


FIG. 62

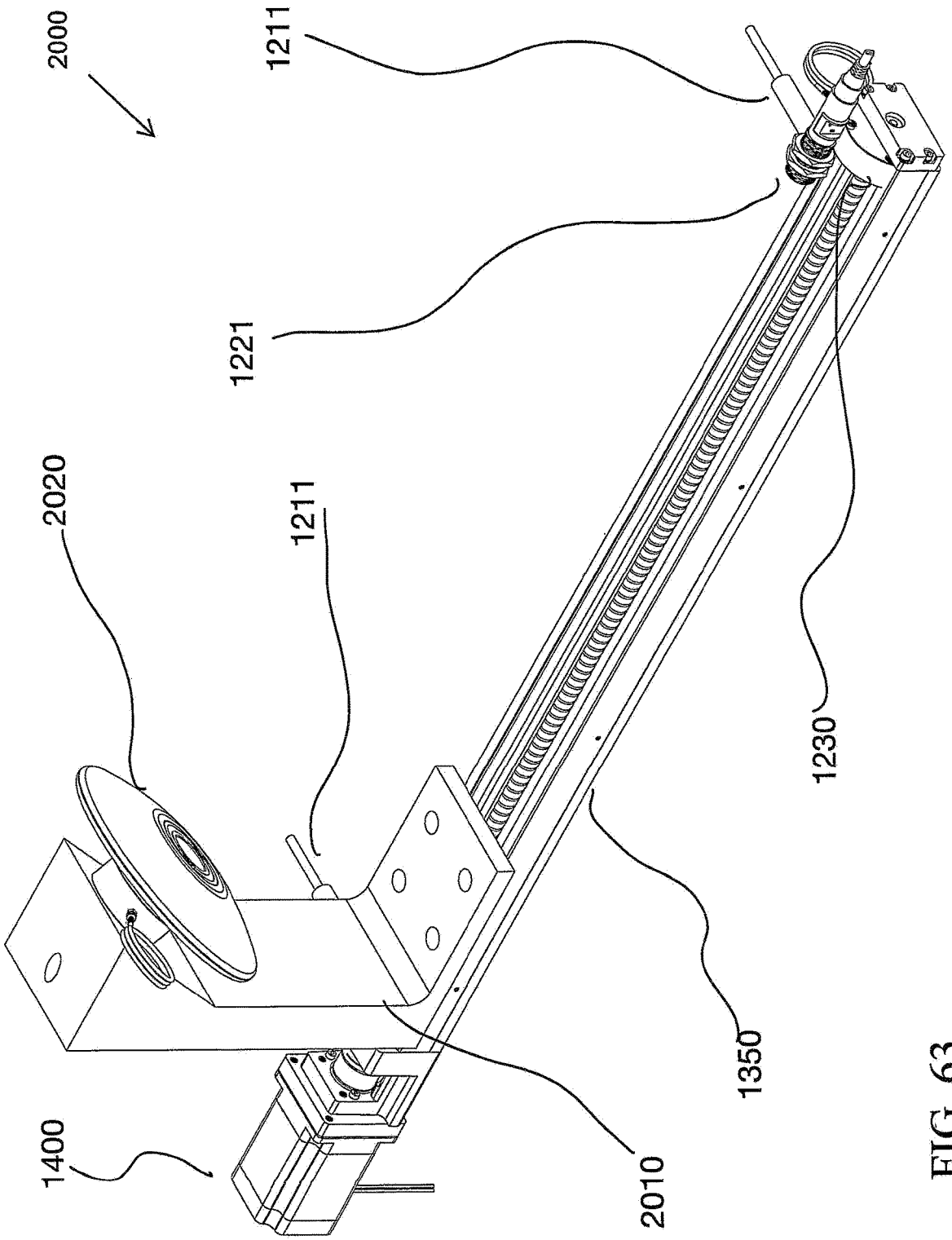


FIG. 63

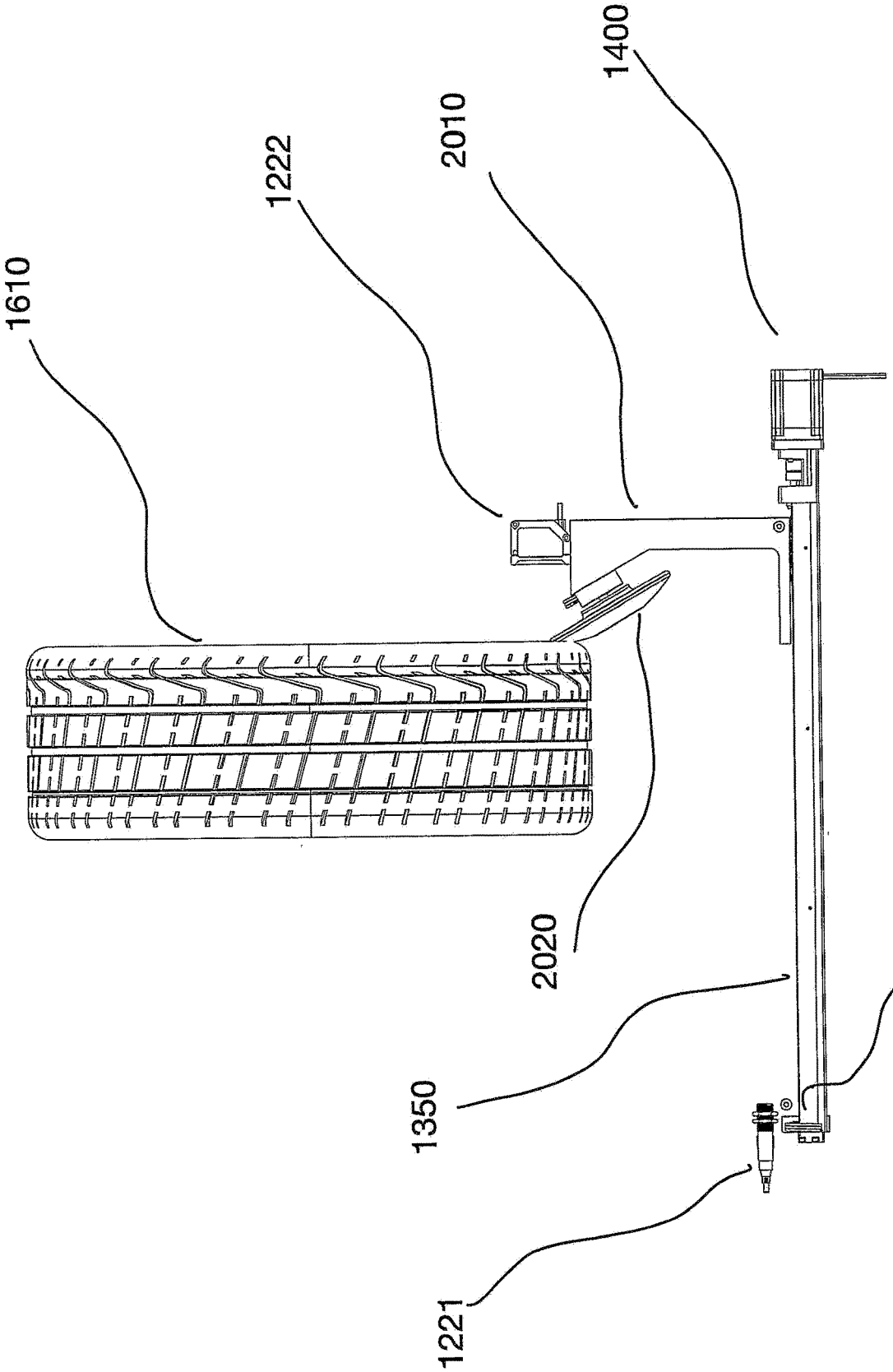


FIG. 64

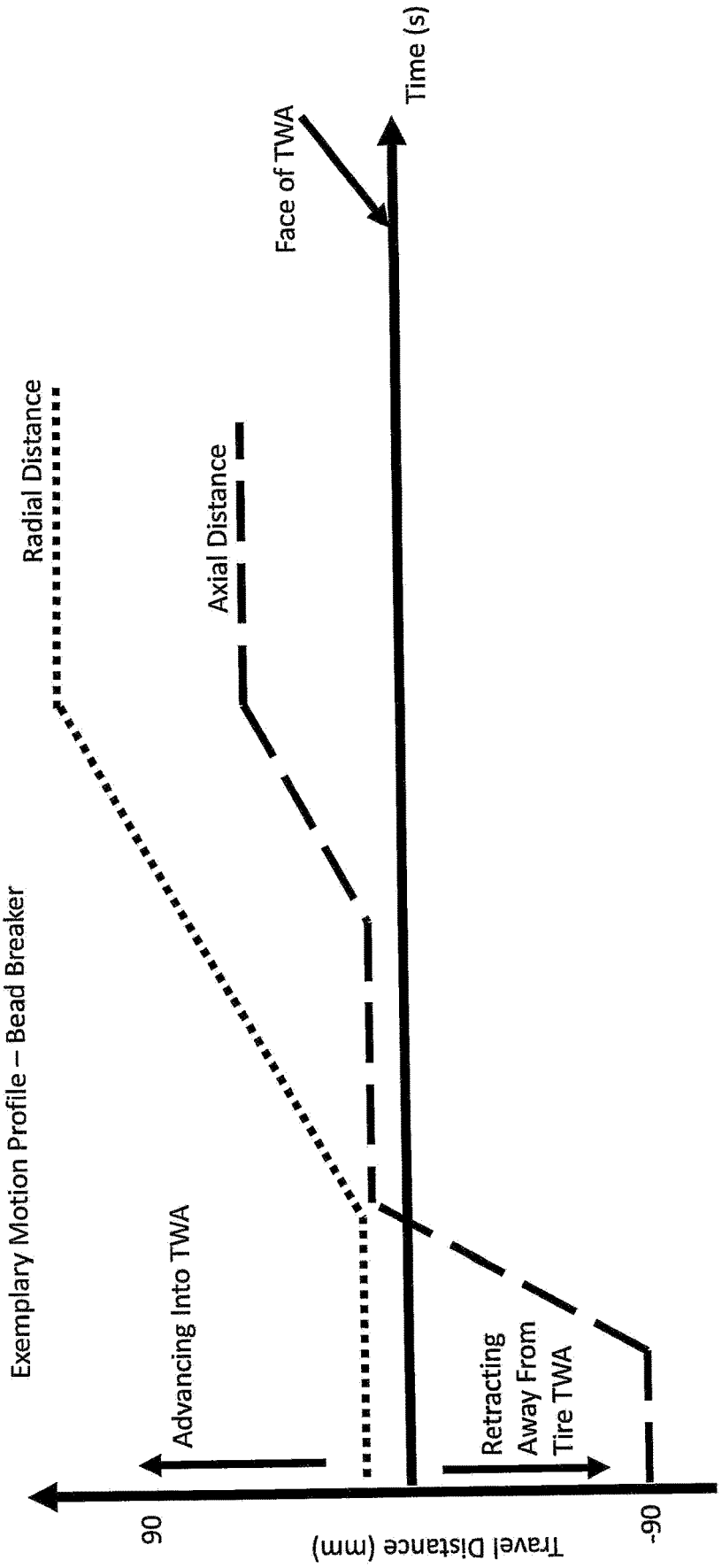

Exemplary Motion Profile – Bead Breaker
Radial Distance
Axial Distance
Face of TWA
Time (s)
Advancing Into TWA
Retracting Away From Tire TWA
90
-90
Travel Distance (mm)

FIG. 65

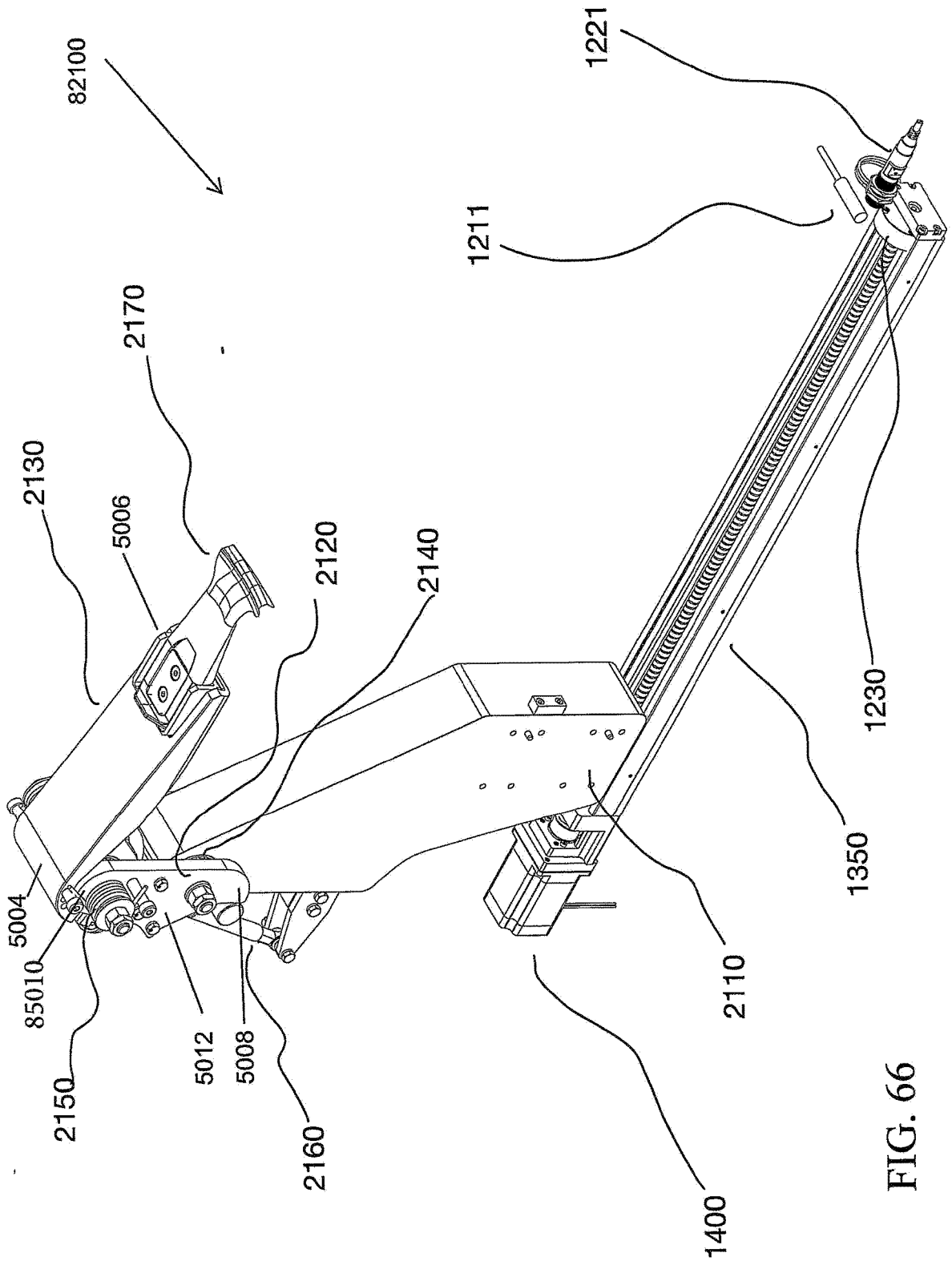

82100
1221
1211
2170
2130
5006
2120
2140
1230
1350
5004
85010
2150
5012
5008
2160
2110
1400

FIG. 66

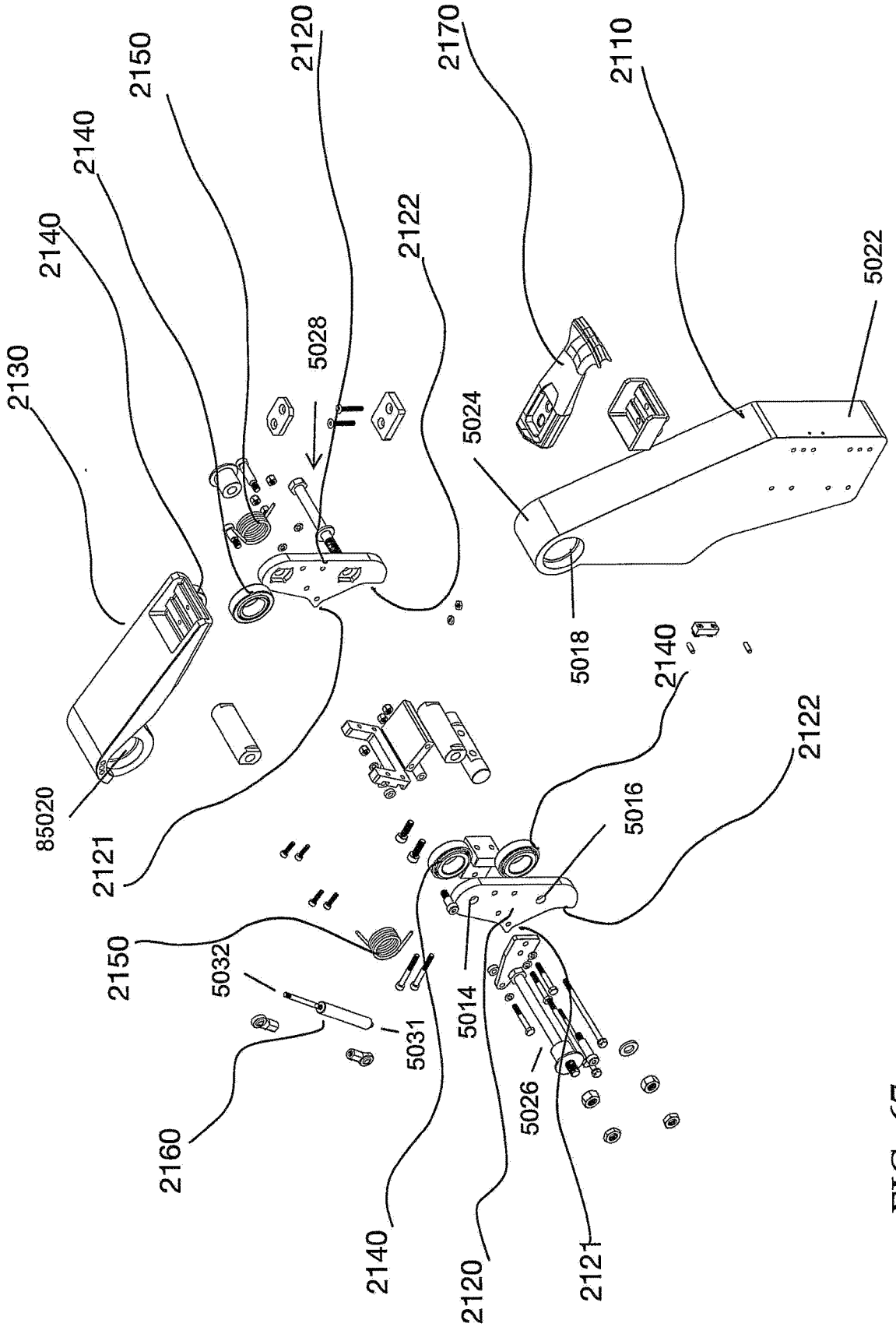

2150
2140
2140
2130
85020
2121
2120
5028
2122
2170
2110
5022
5024
5018
2140
2122
5016
2150
5032
5031
2160
5014
5026
2140
2120
2121

FIG. 67

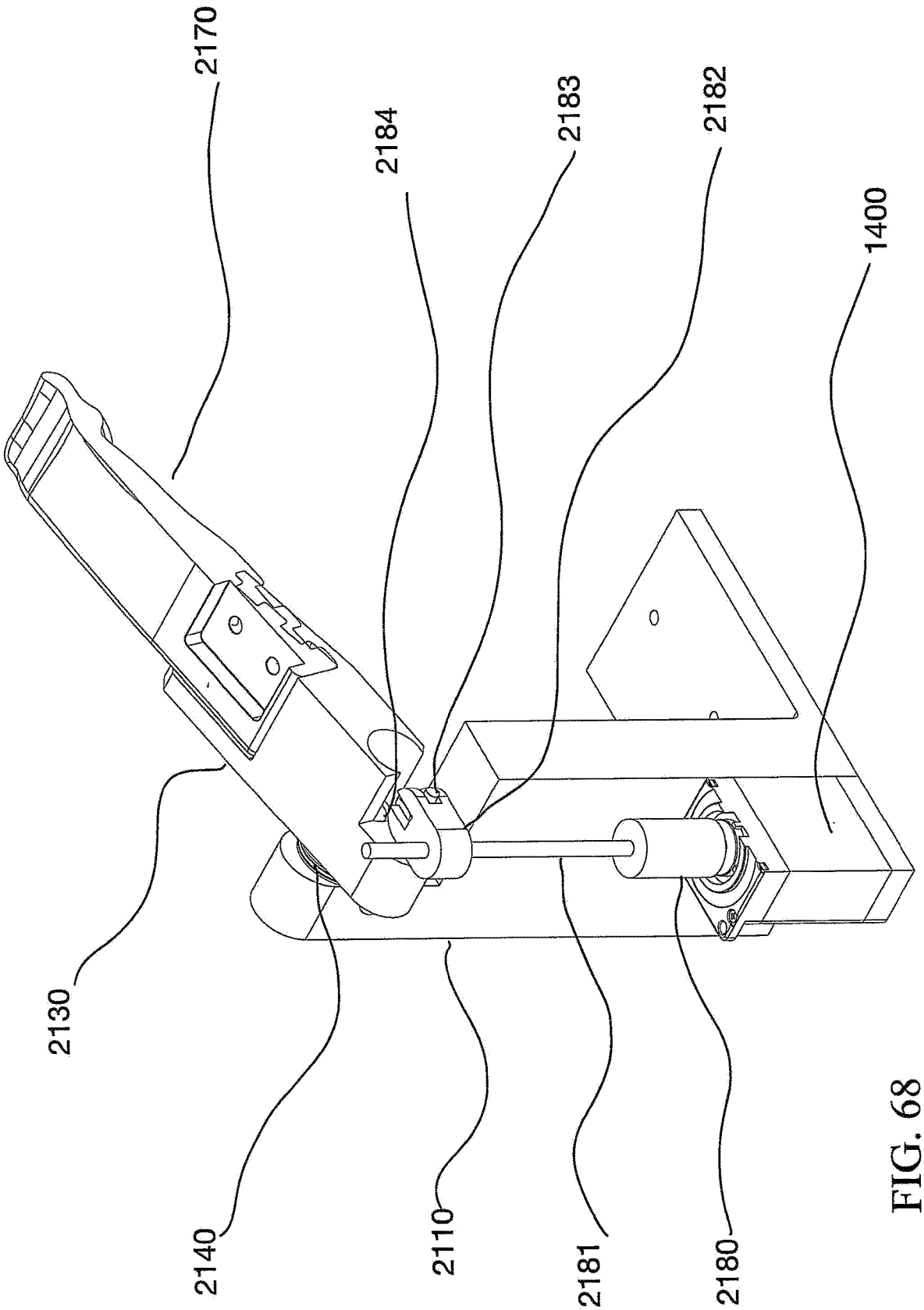


FIG. 68

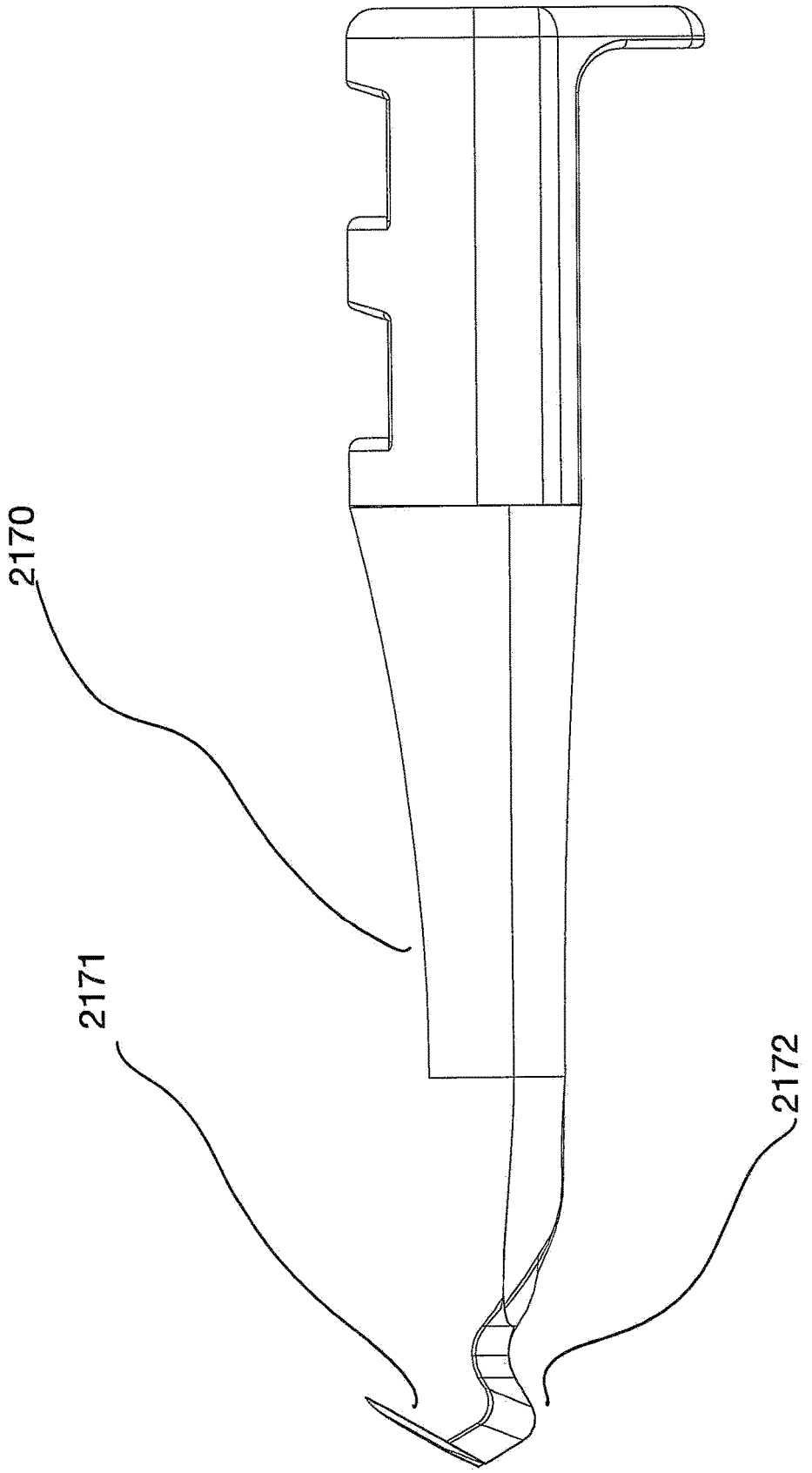


FIG. 69

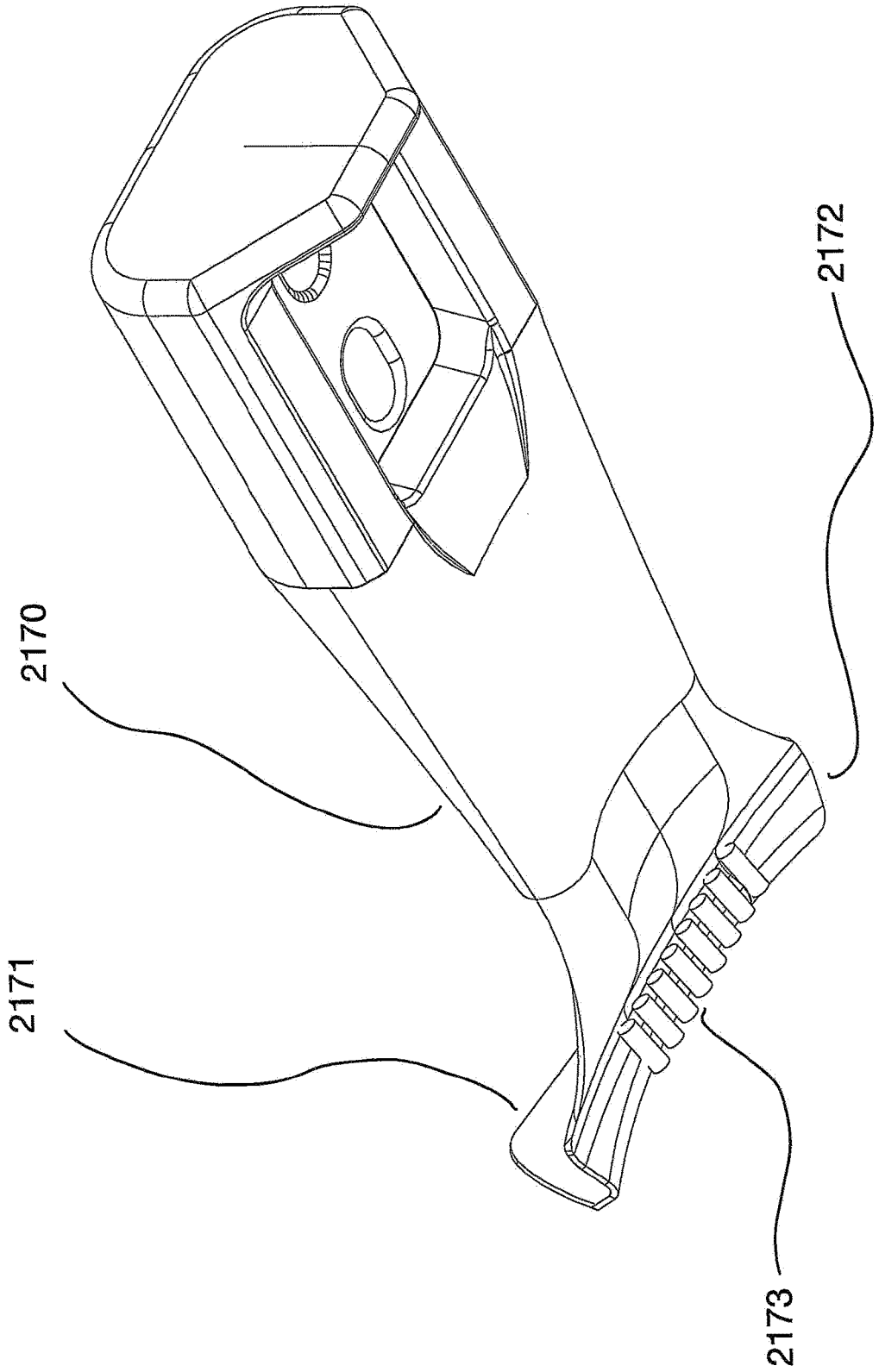


FIG. 70

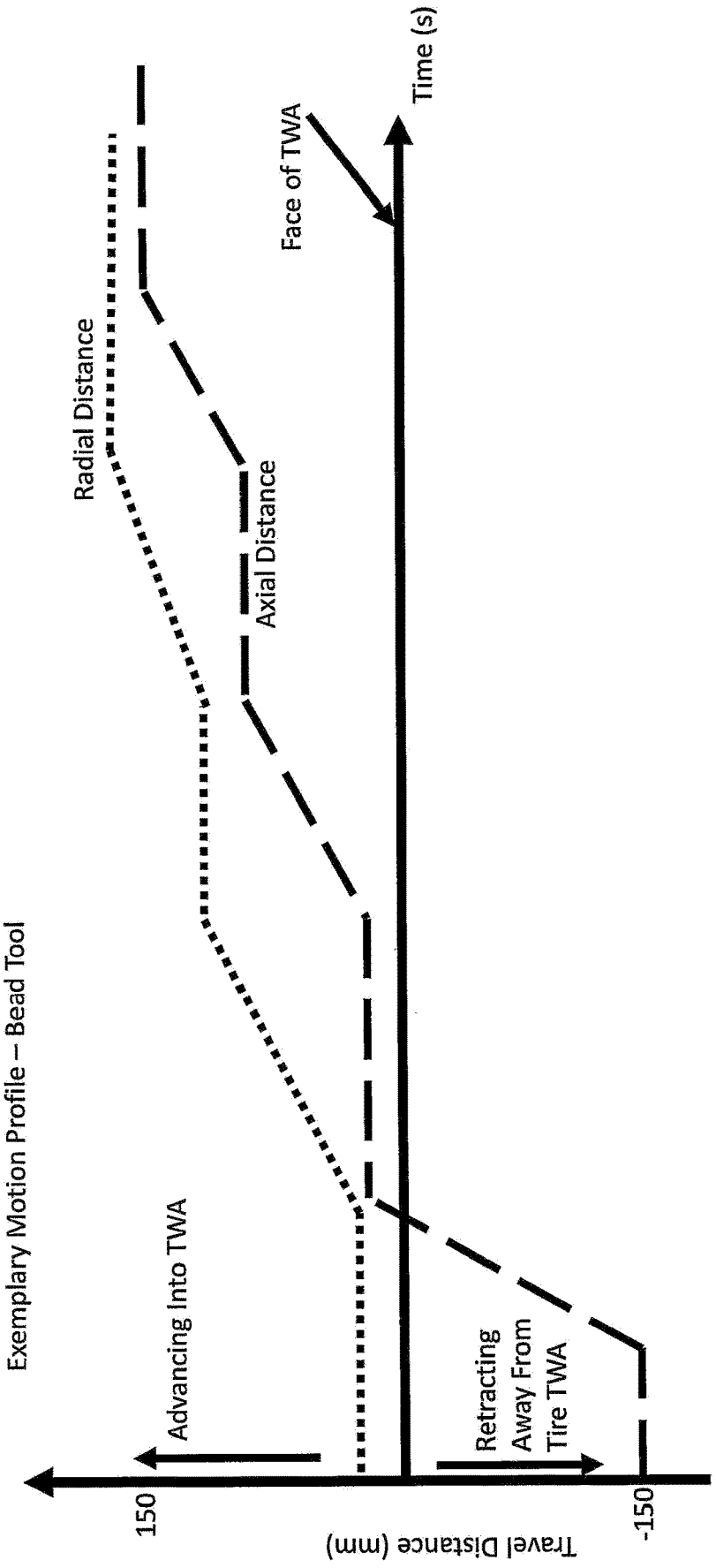

Exemplary Motion Profile – Bead Tool
Radial Distance
Axial Distance
Face of TWA
Time (s)
Advancing Into TWA
Retracting Away From Tire TWA
150
-150
Travel Distance (mm)

FIG. 71

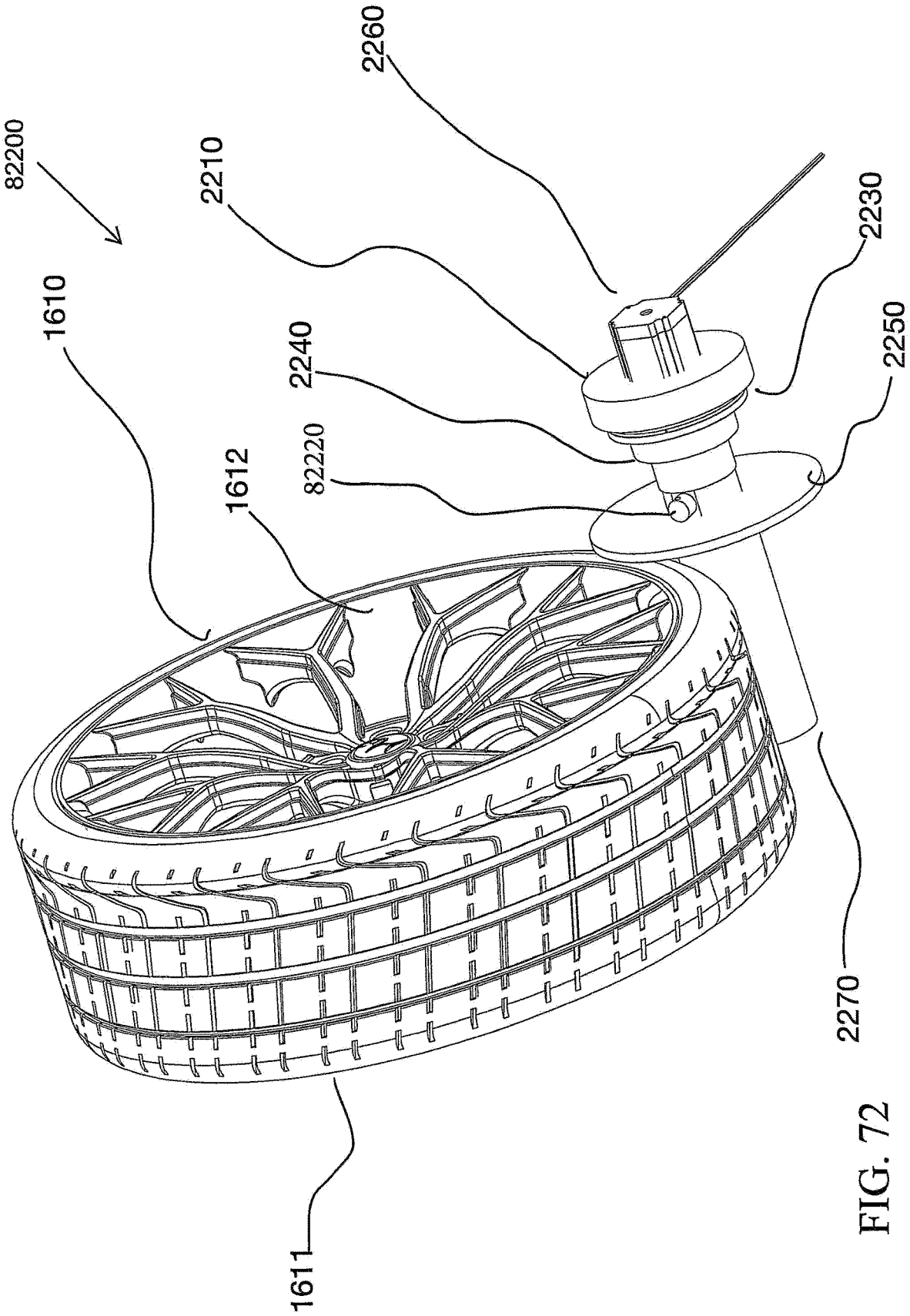


FIG. 72

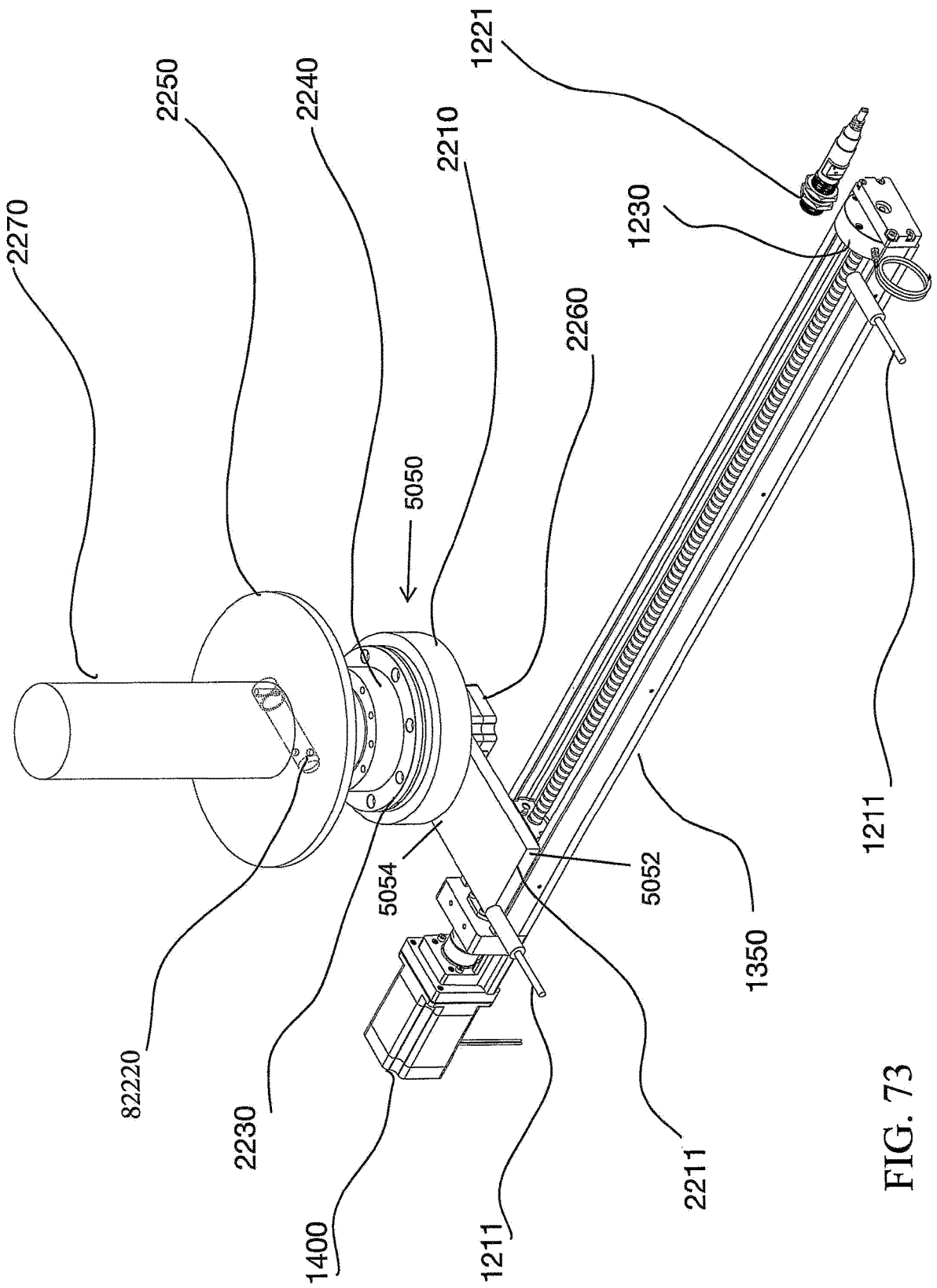

2270
2250
2240
2210
1221
1230
2260
5050
82220
2230
1400
5054
1211
5052
2211
1350
1211

FIG. 73

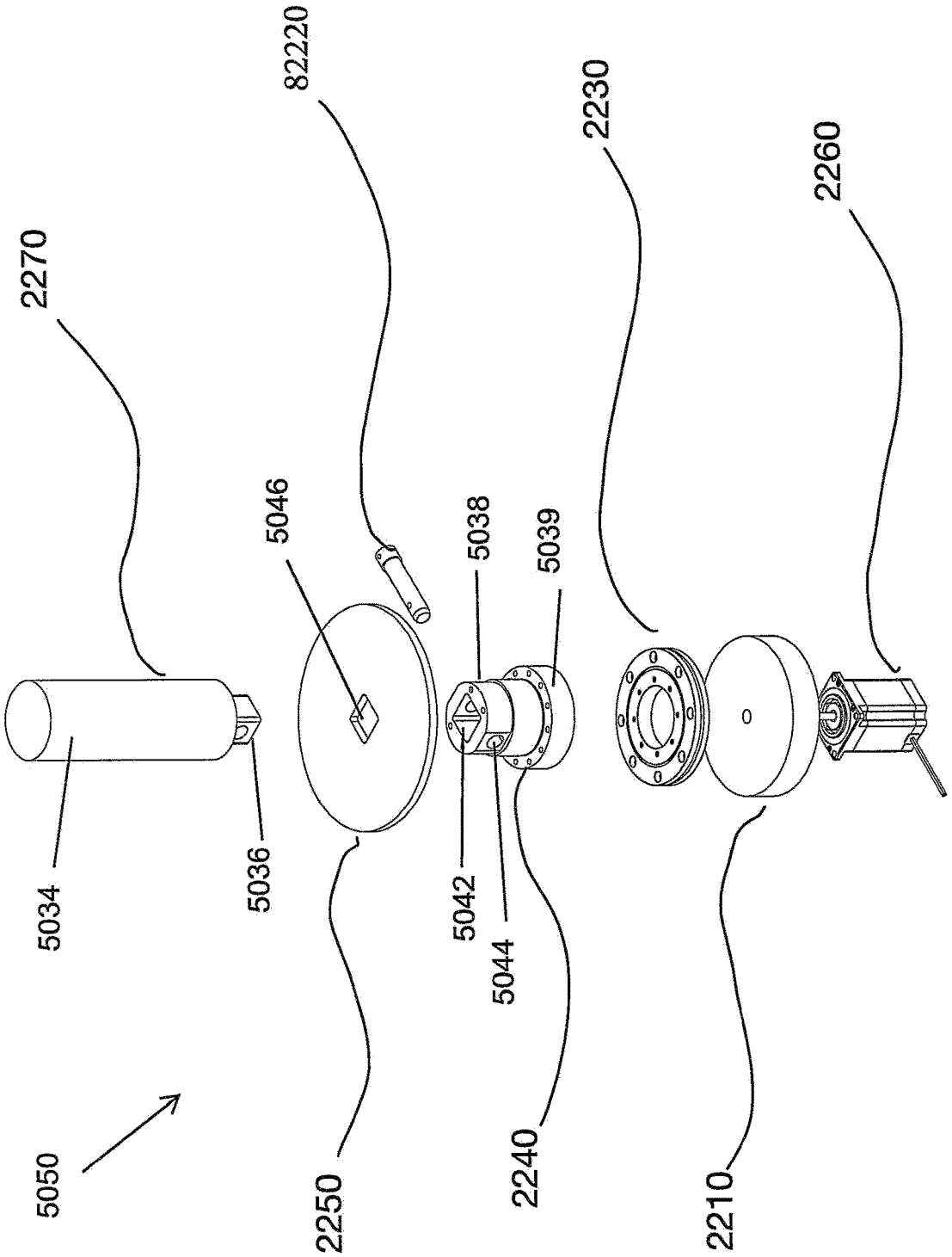

82220
2230
2260
2270
5046
5038
5039
5034
5036
5042
5044
5050
2250
2240
2210

FIG. 74

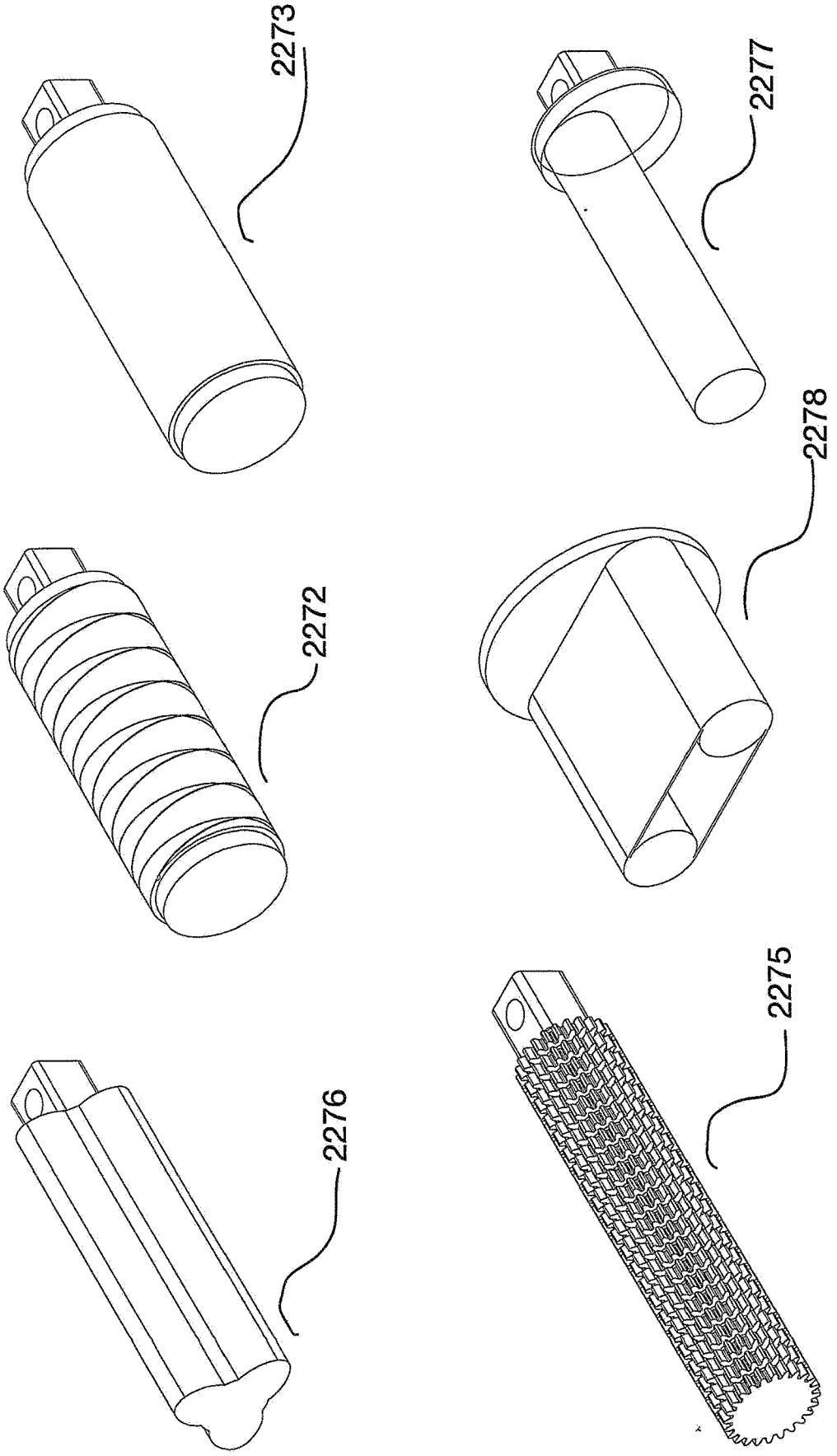


FIG. 75

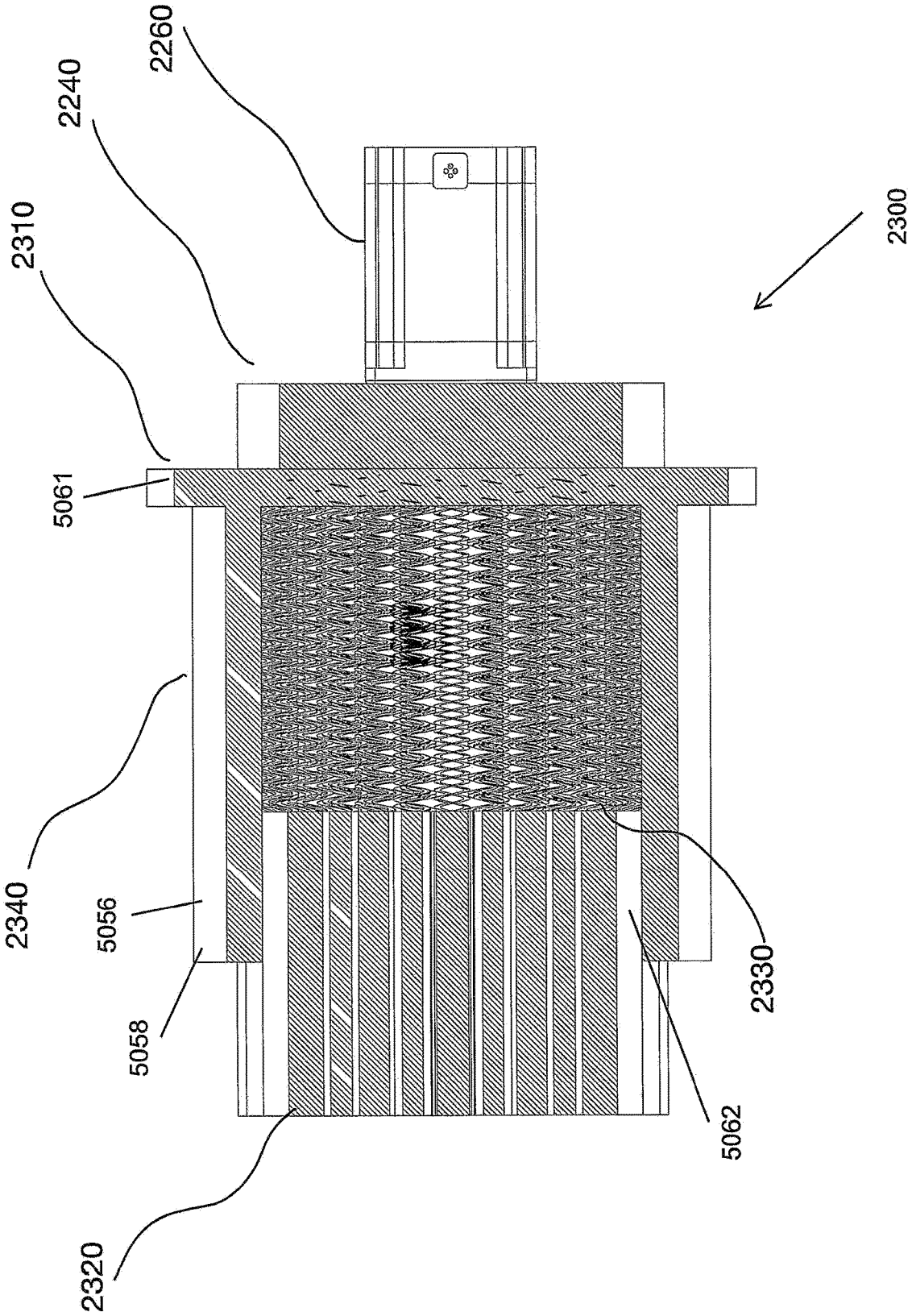


FIG. 76

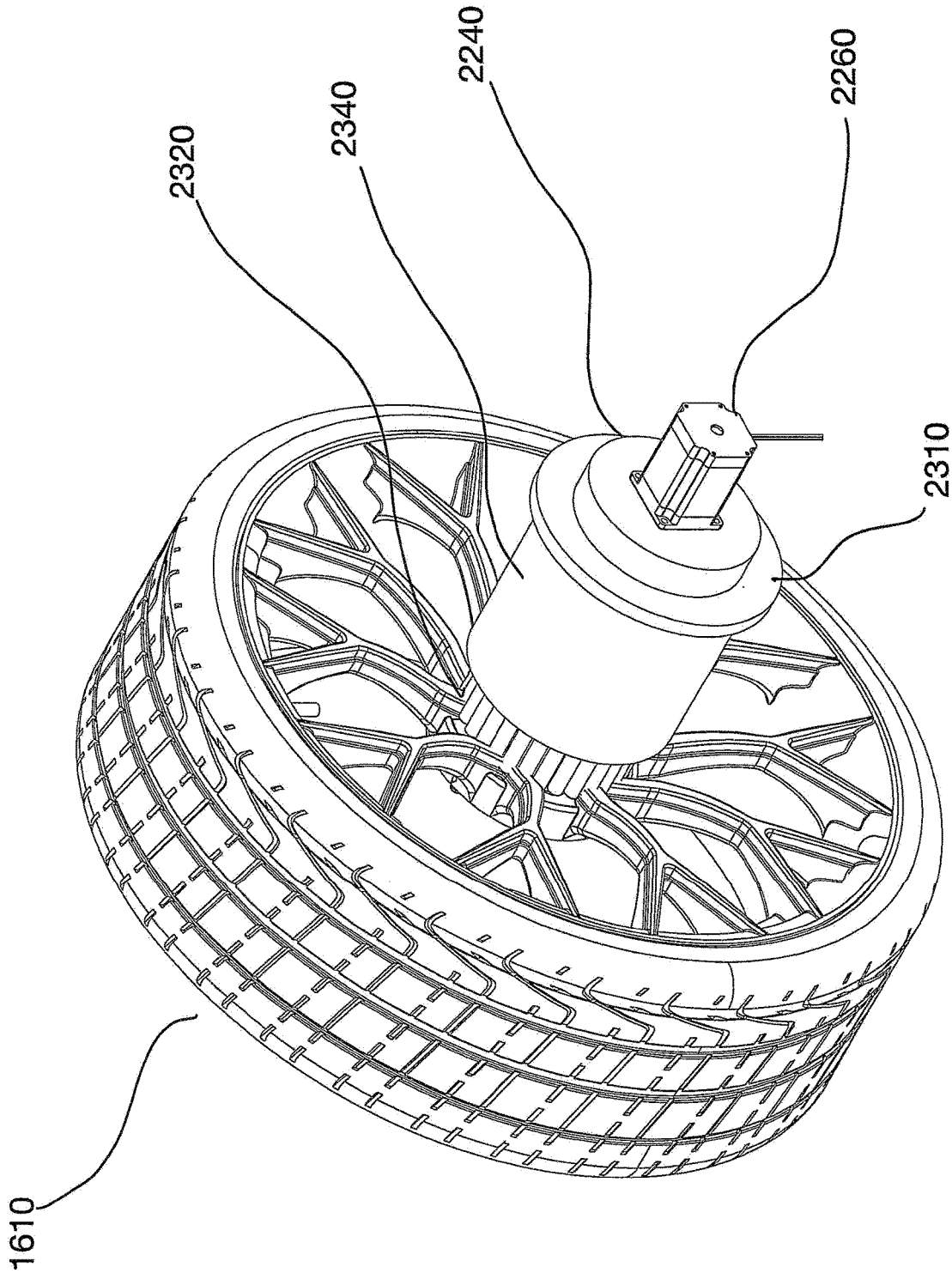


FIG. 77

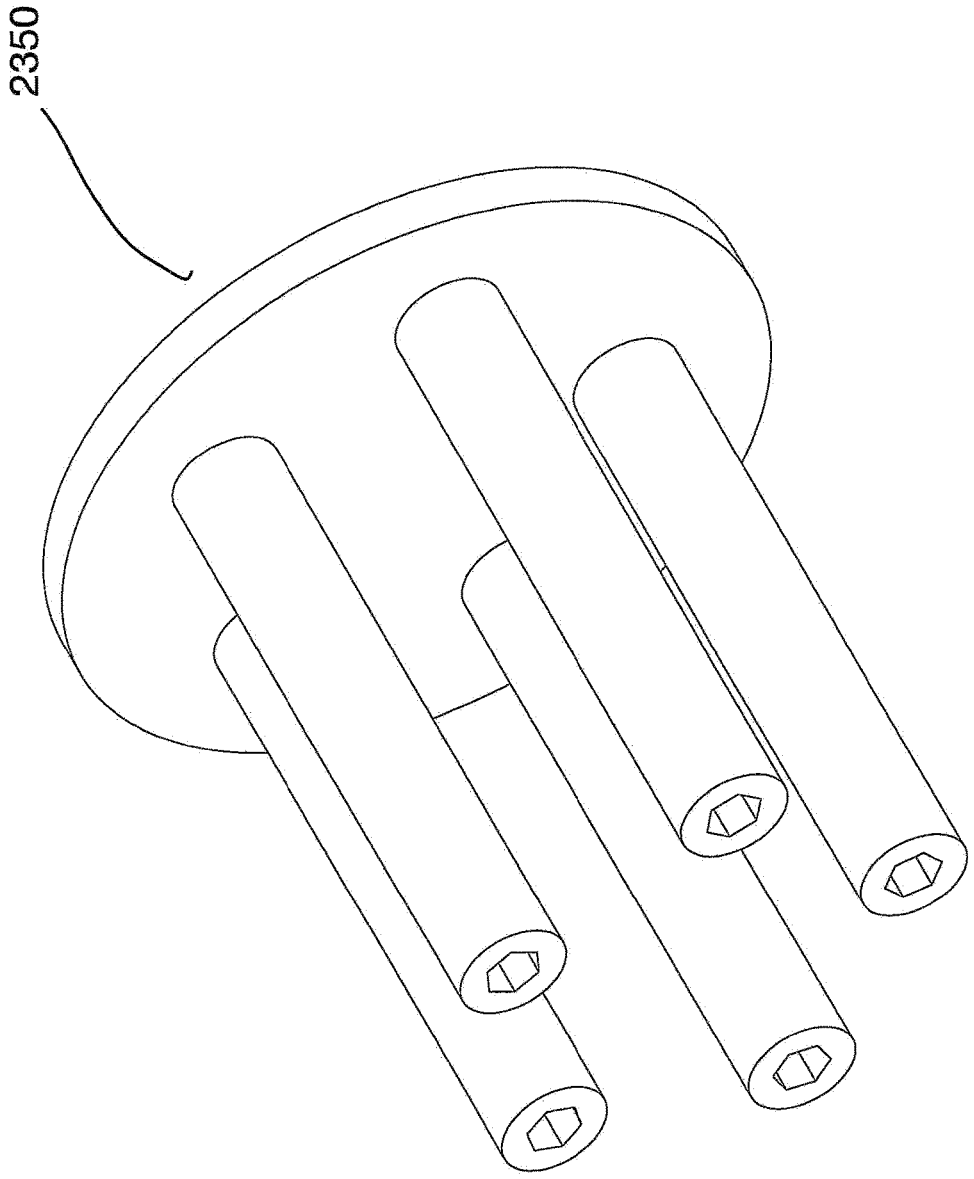


FIG. 78

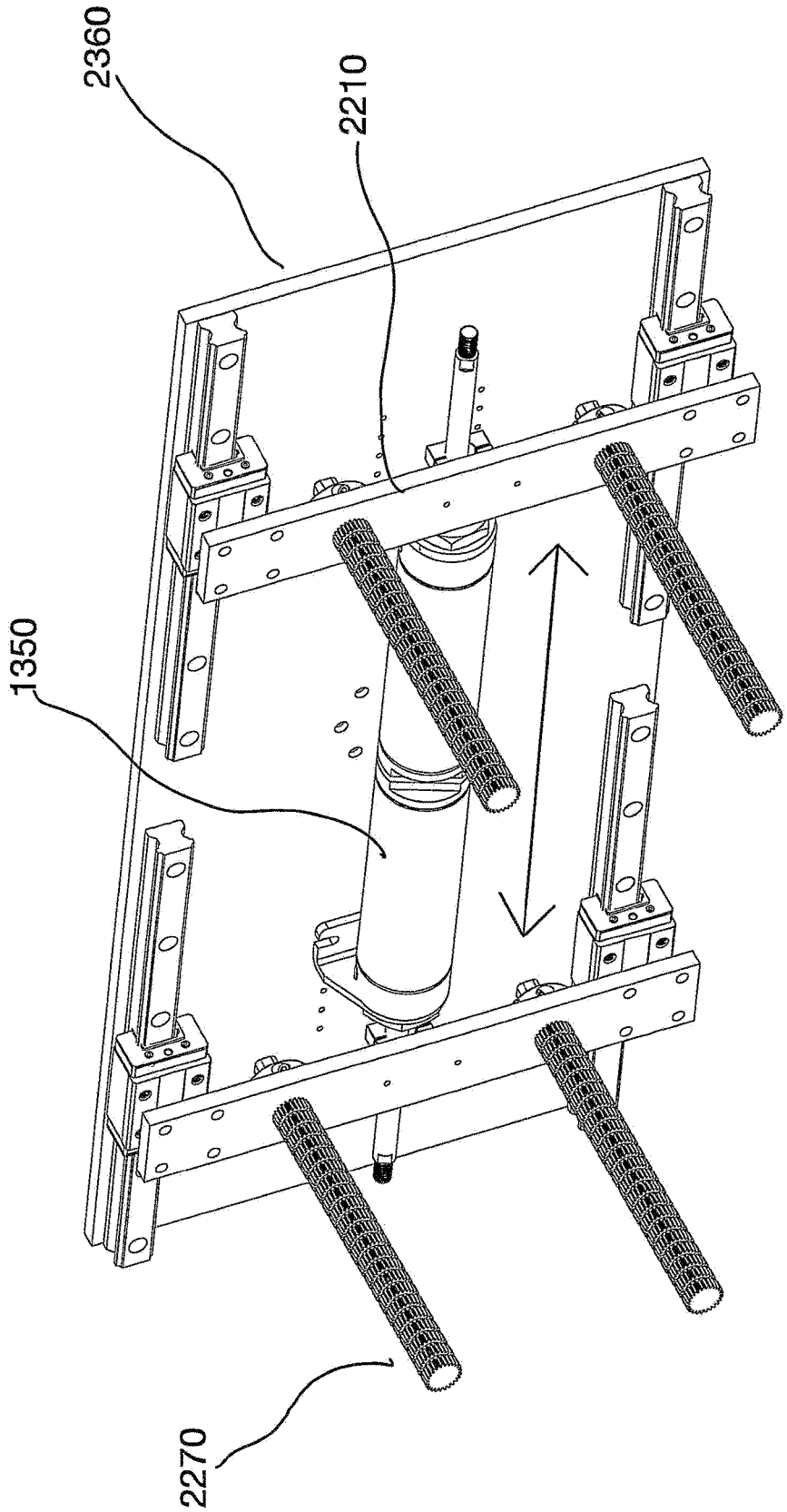


FIG. 79

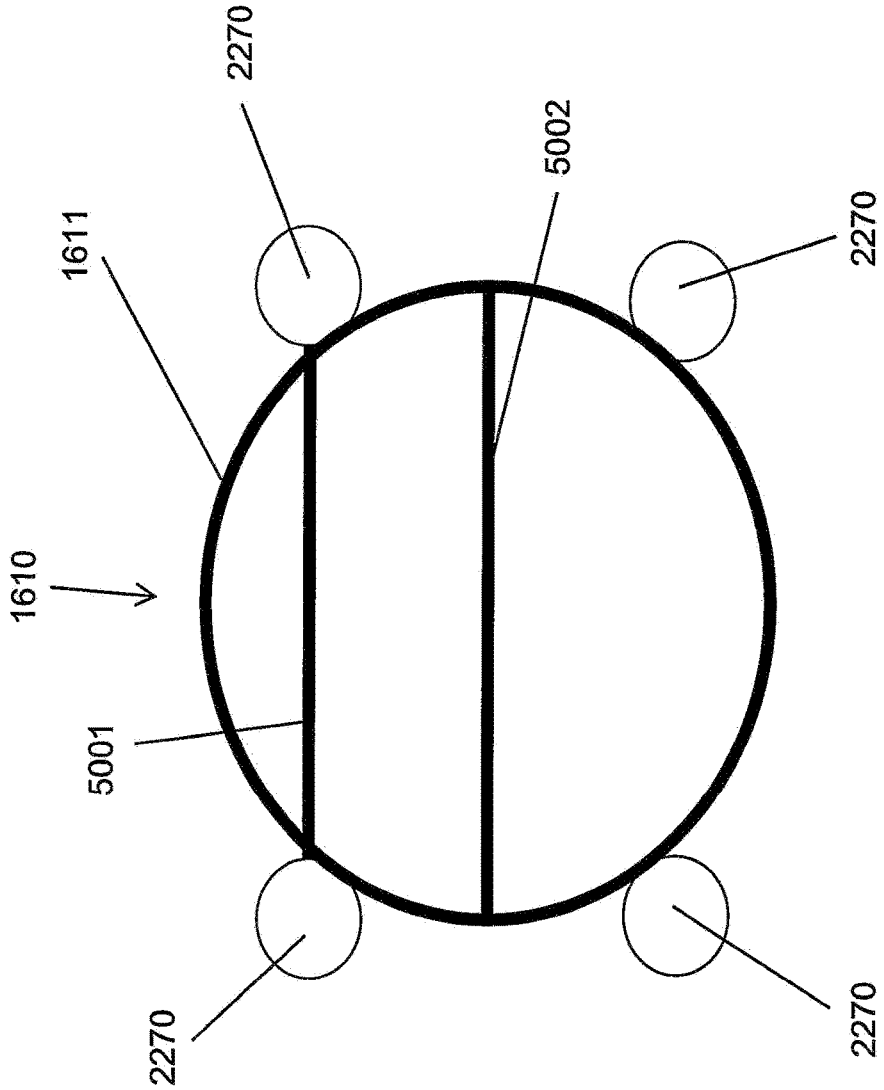


FIG. 80

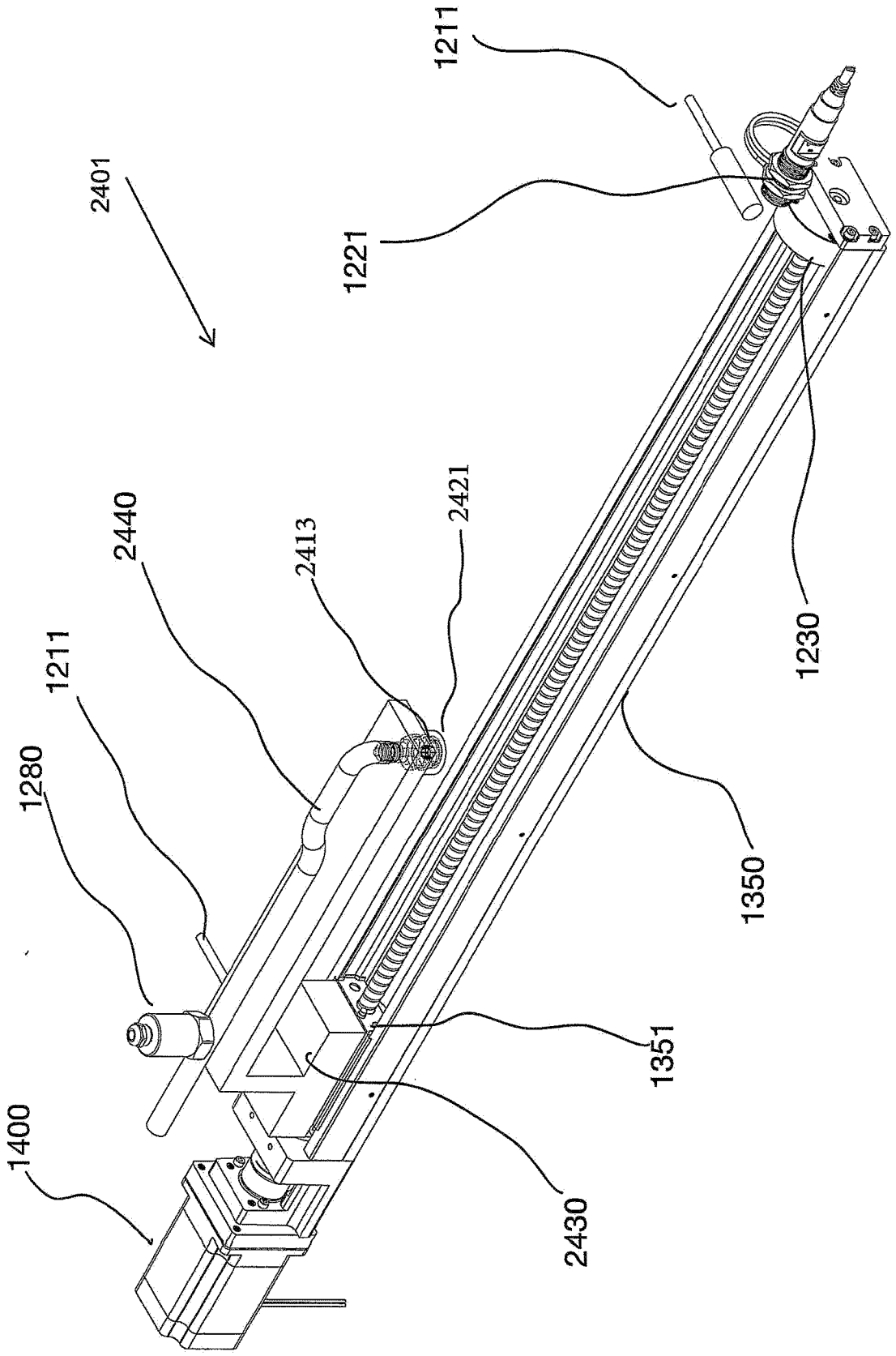

1211
2401
1221
2440
2413
2421
1211
1280
1230
1350
1351
1400
2430

FIG. 81

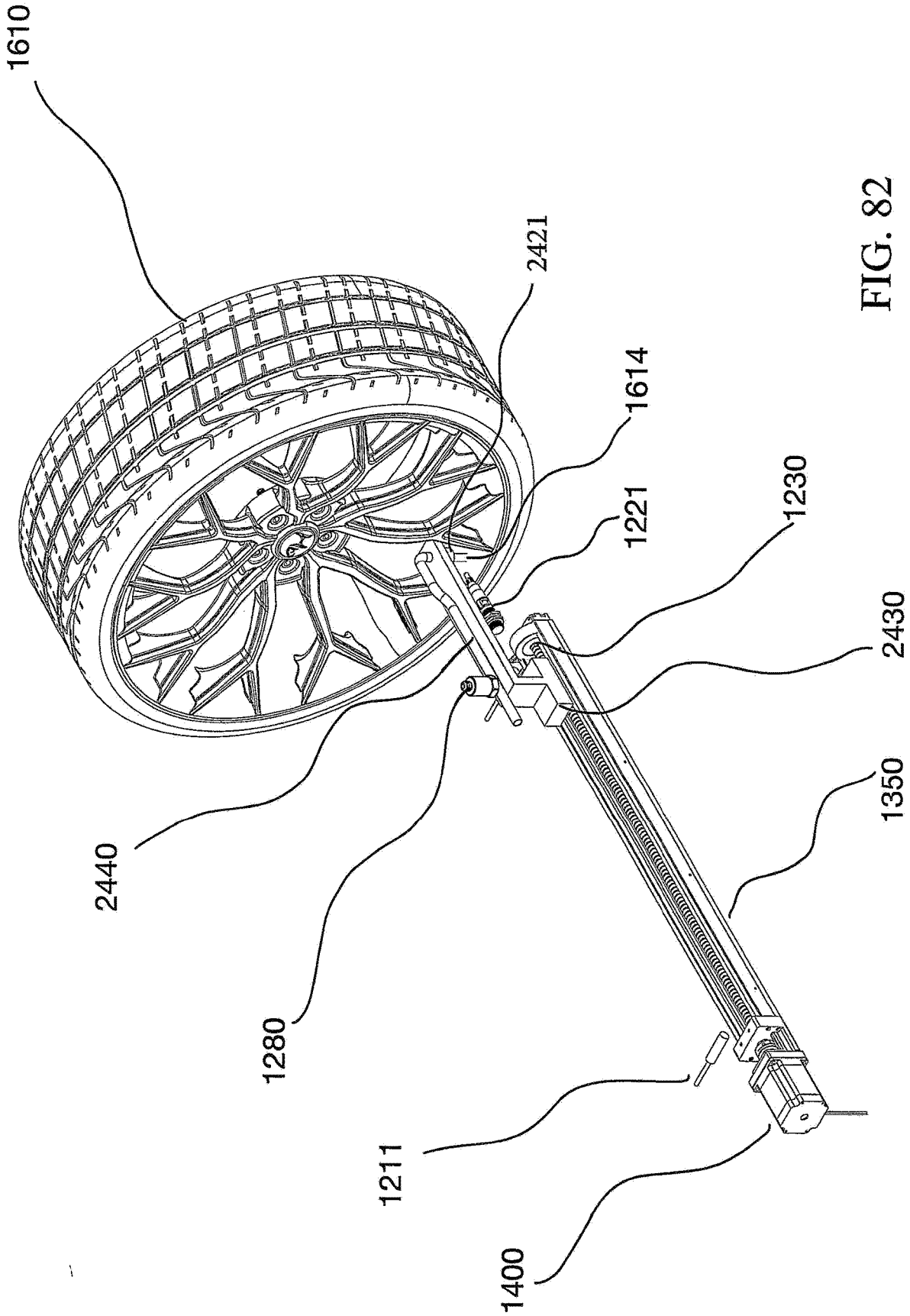


FIG. 82

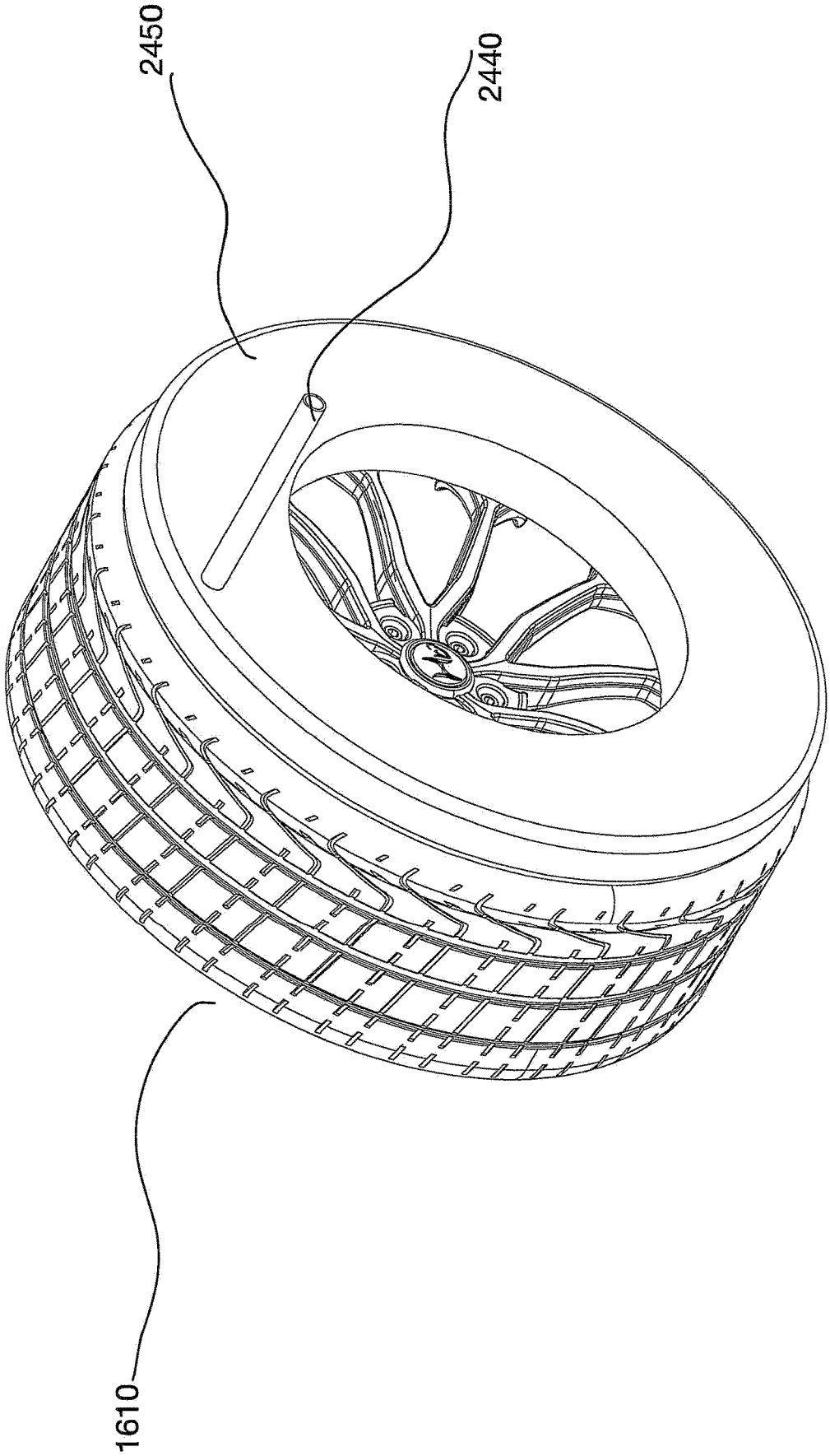


FIG. 83

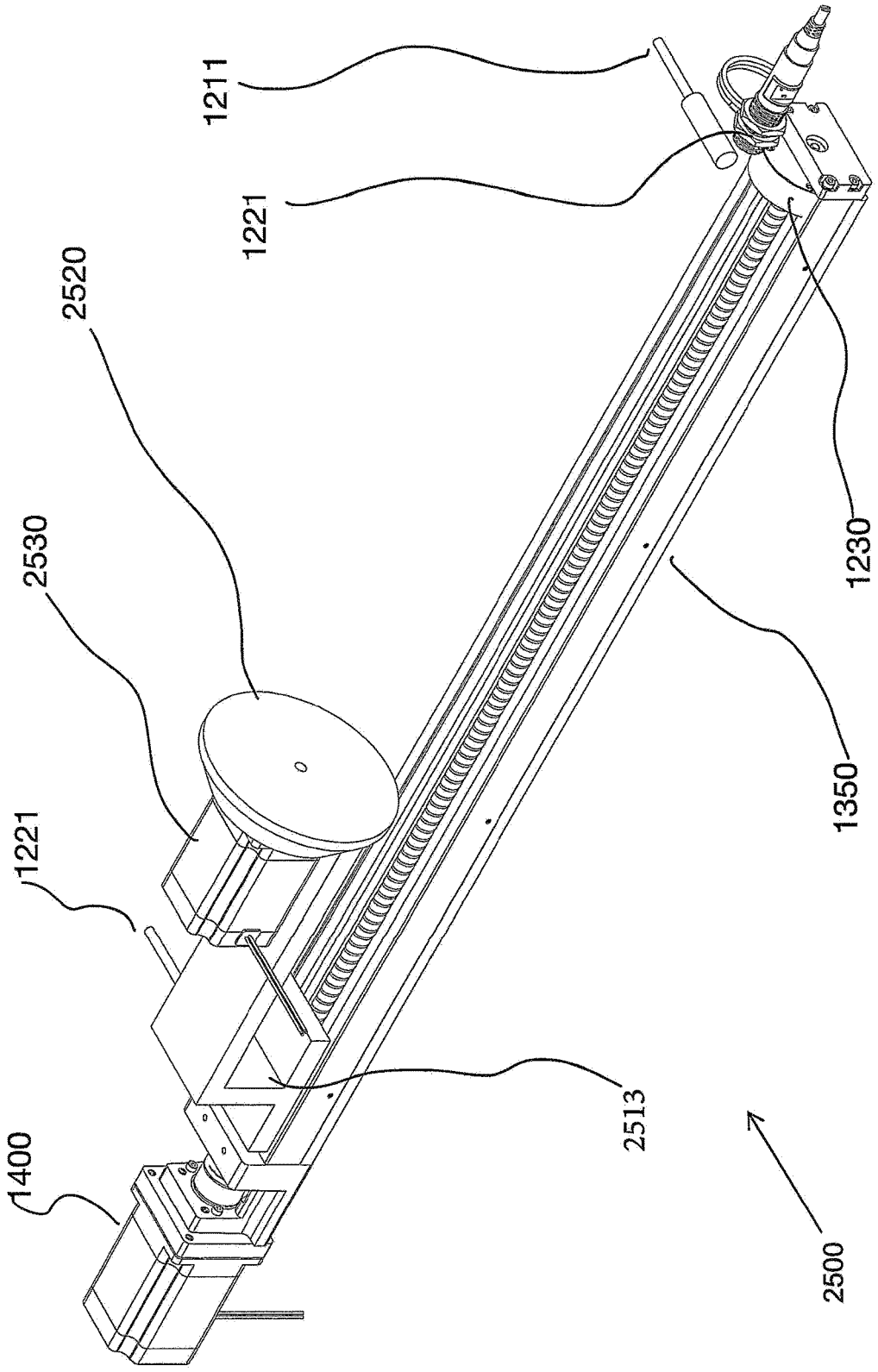


FIG. 84

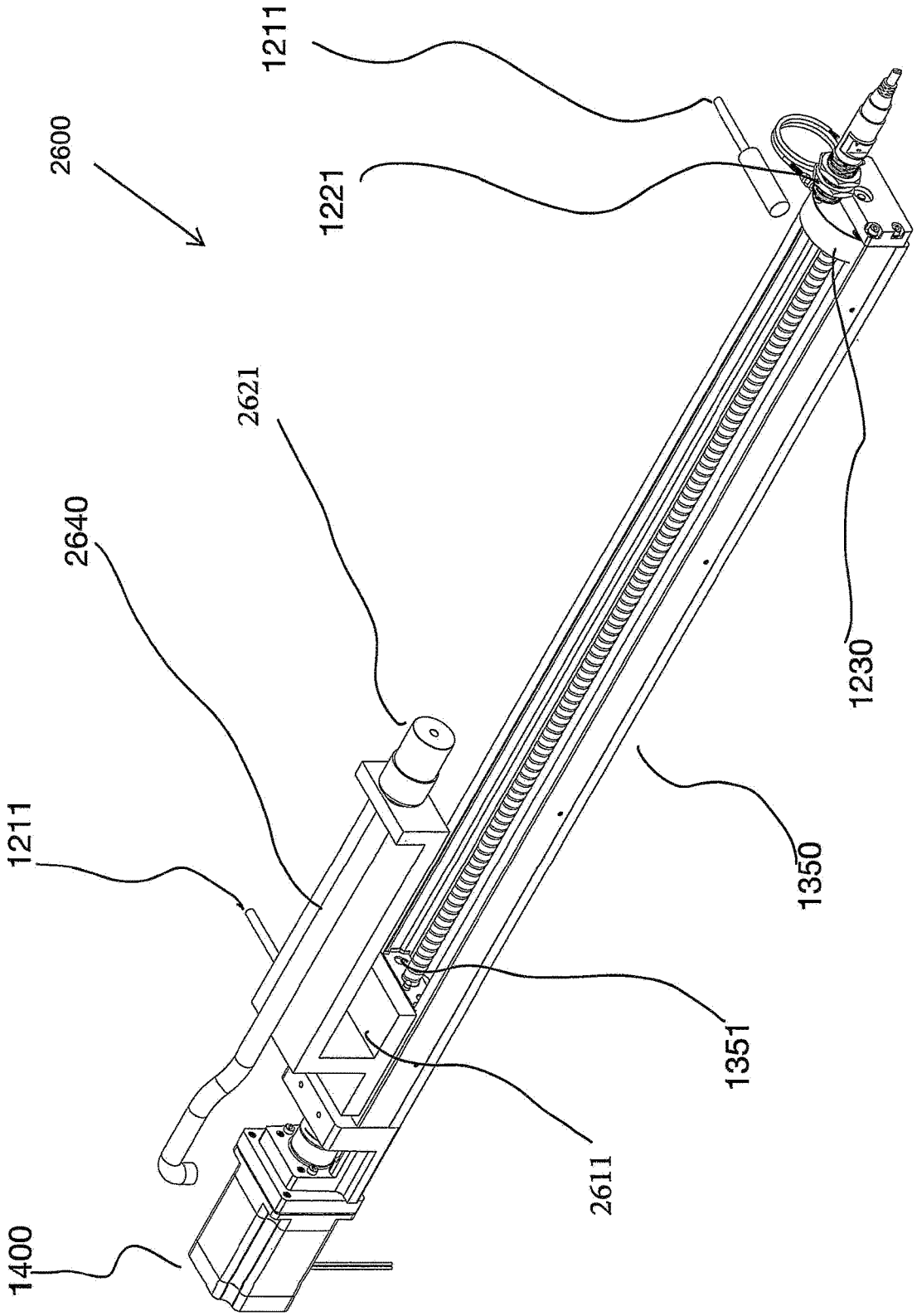


FIG. 85

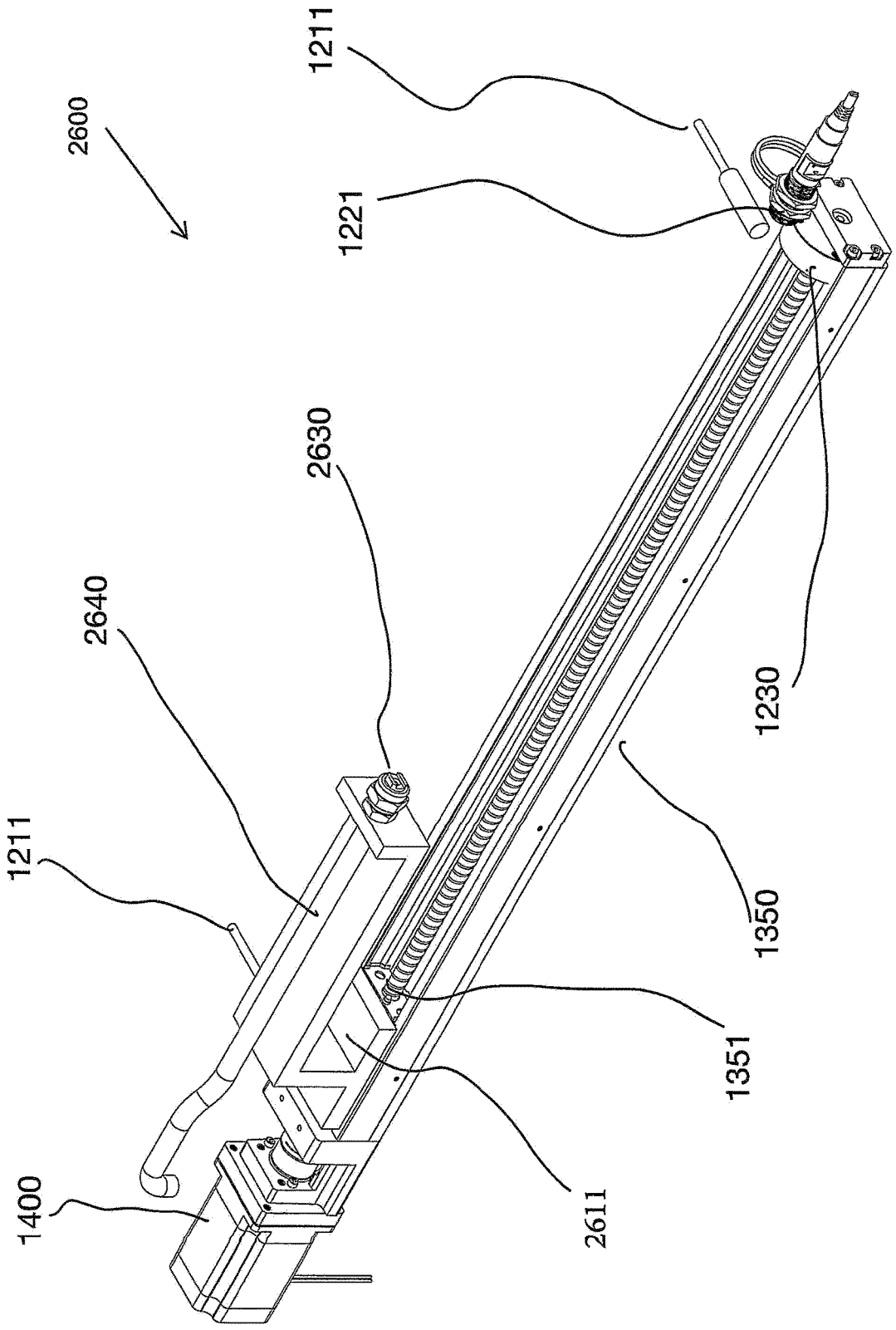


FIG. 86

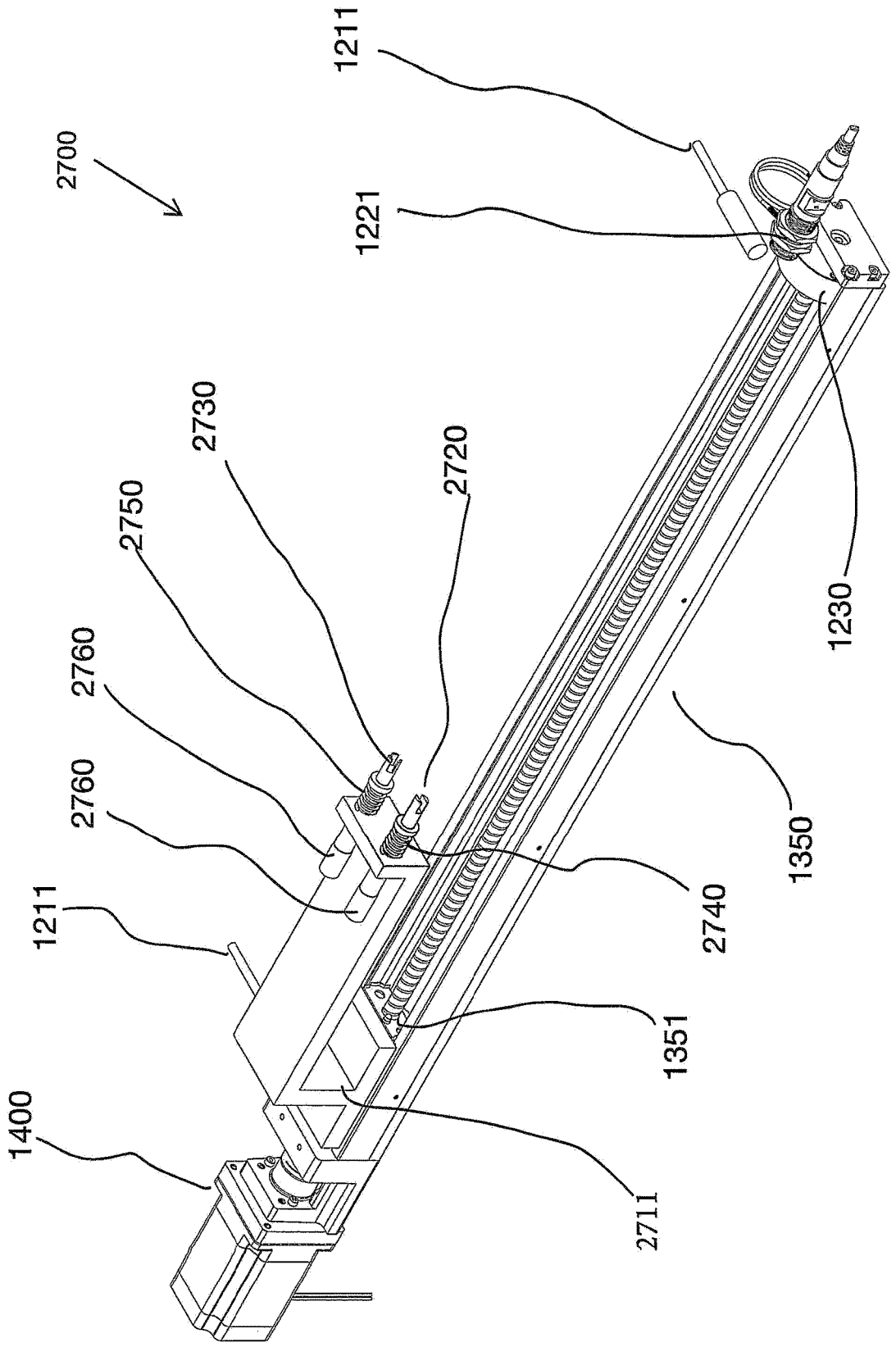

2700
1211
1221
2730
2720
2750
2760
2760
1211
1400
1230
1350
2740
1351
2711

FIG. 87

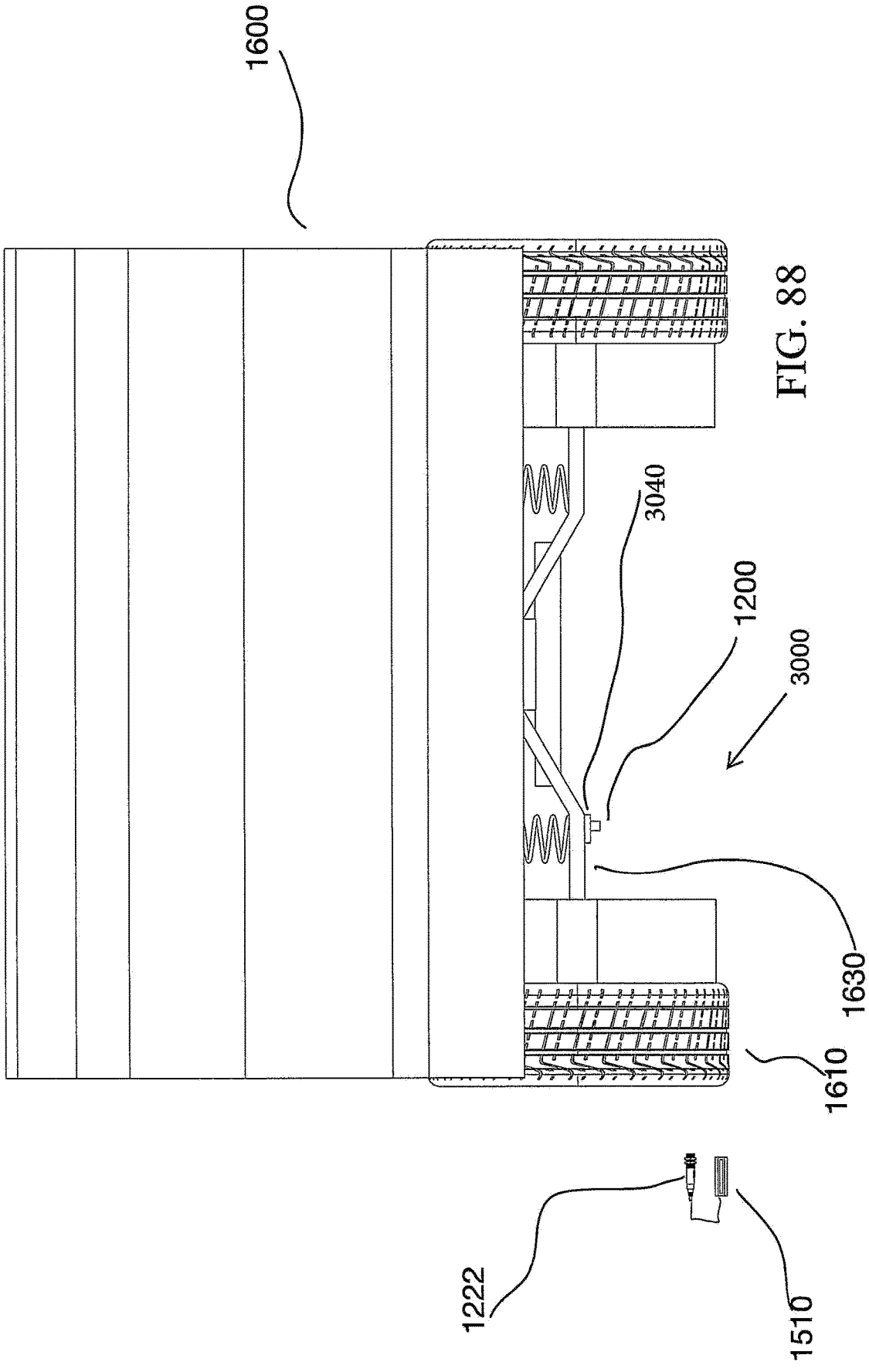


FIG. 88

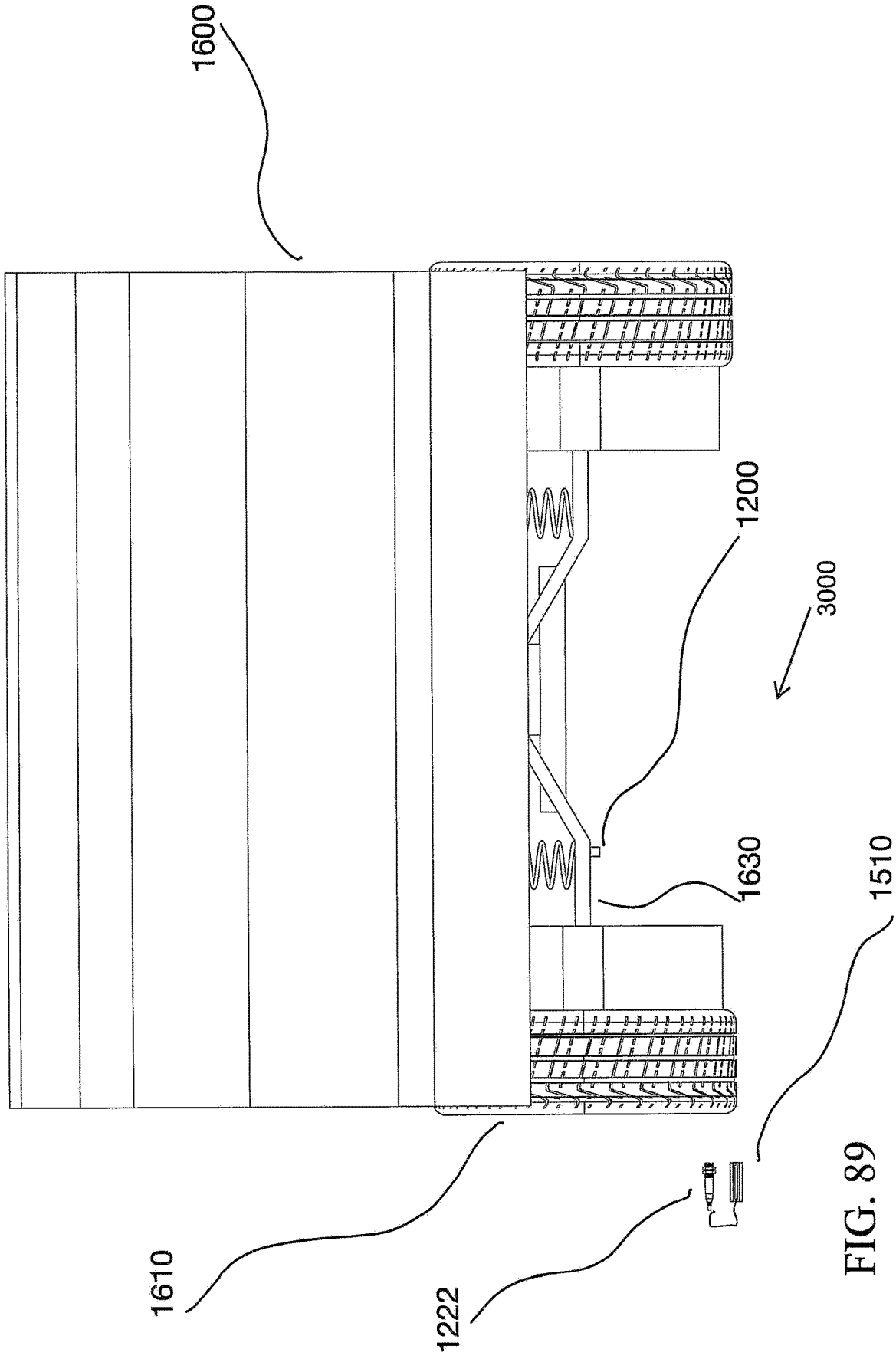


FIG. 89

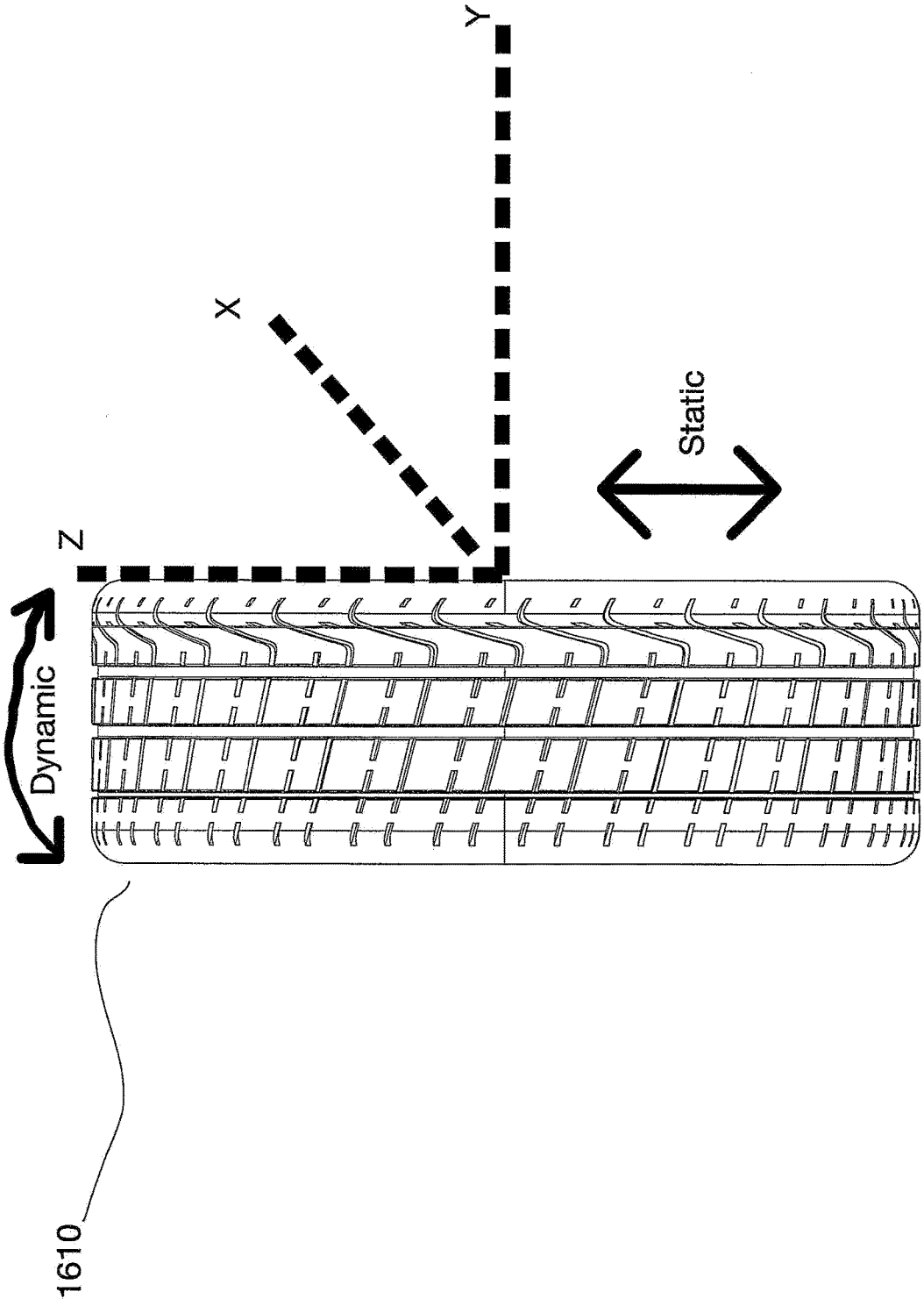


FIG. 90

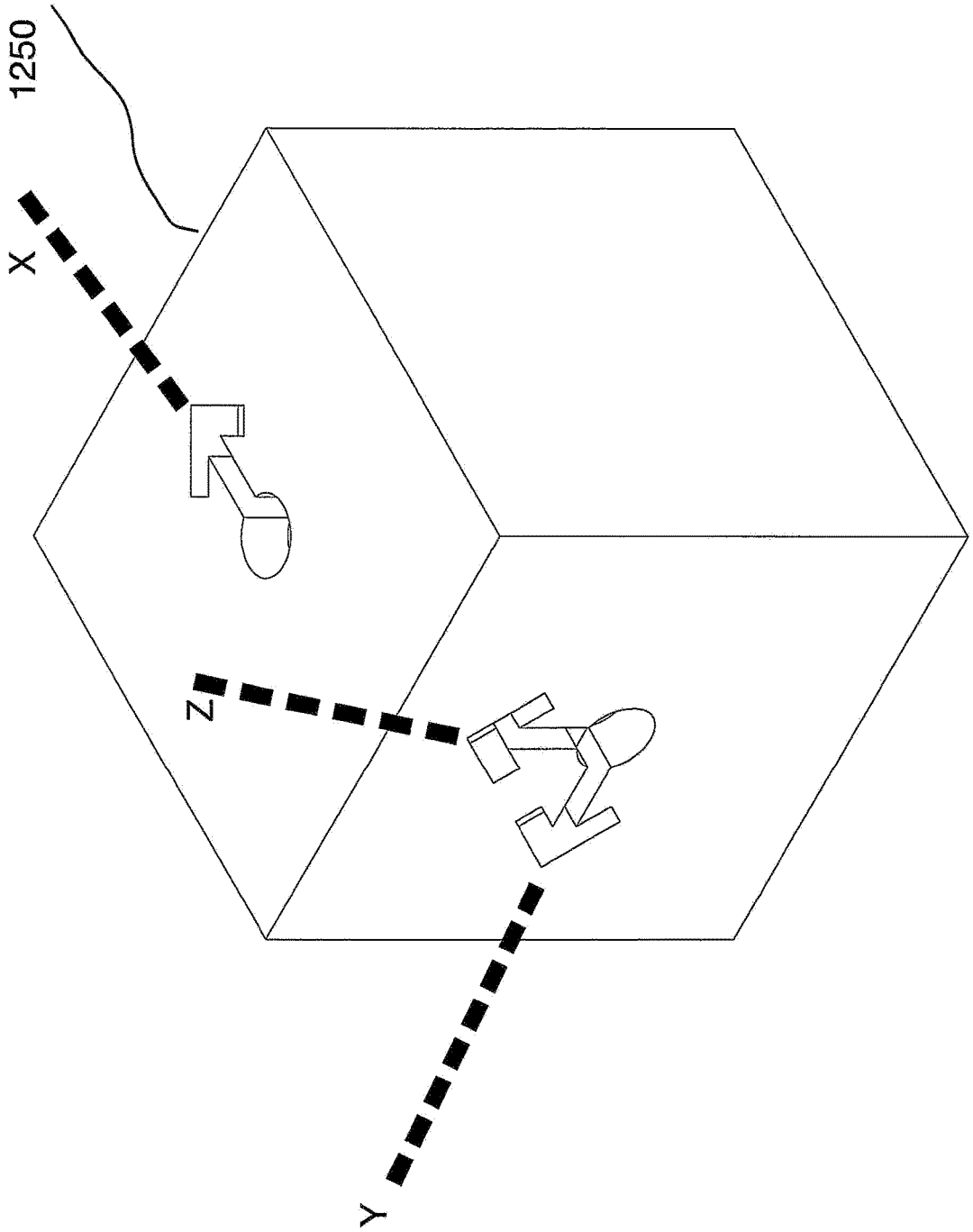


FIG. 91

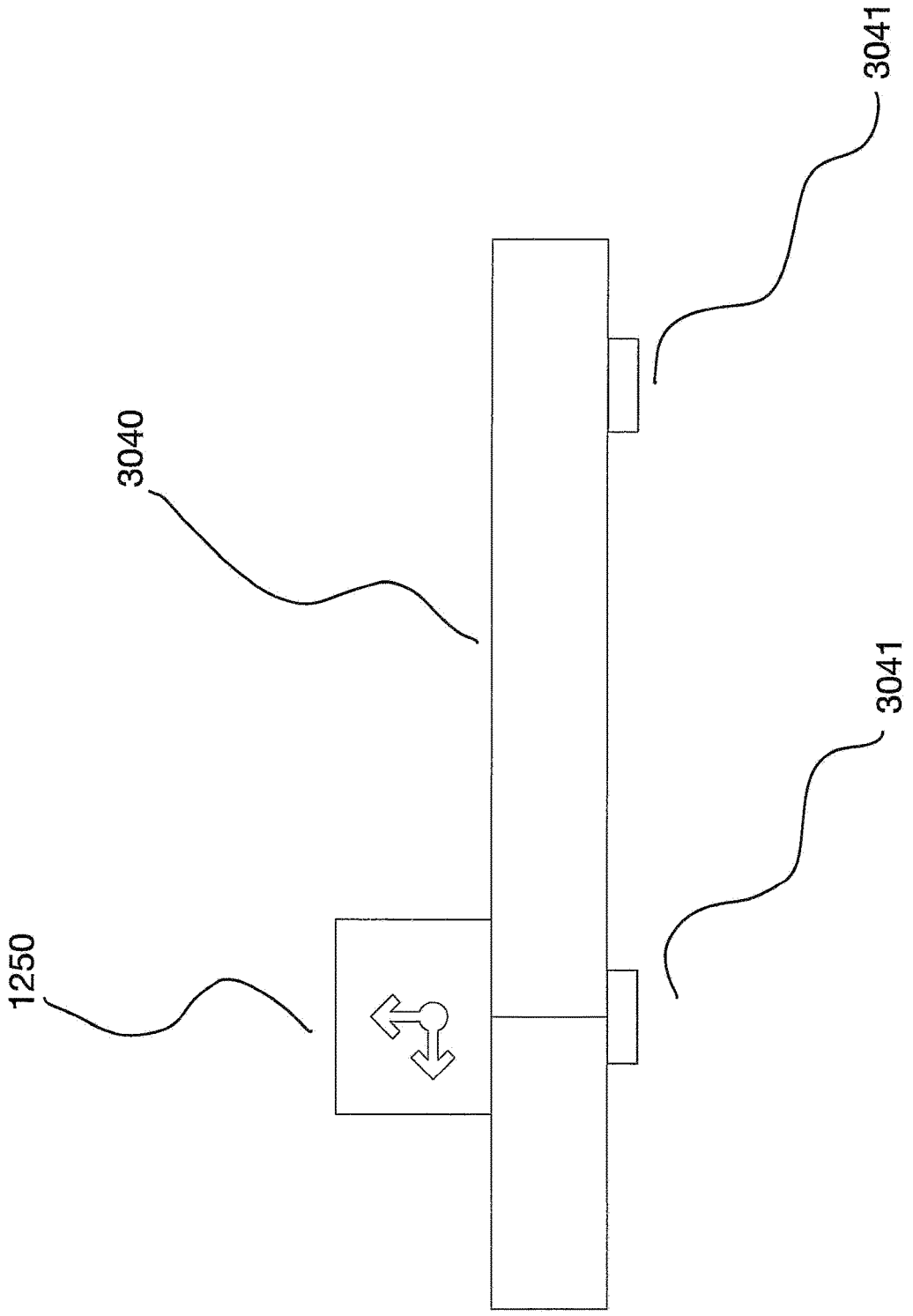


FIG. 92

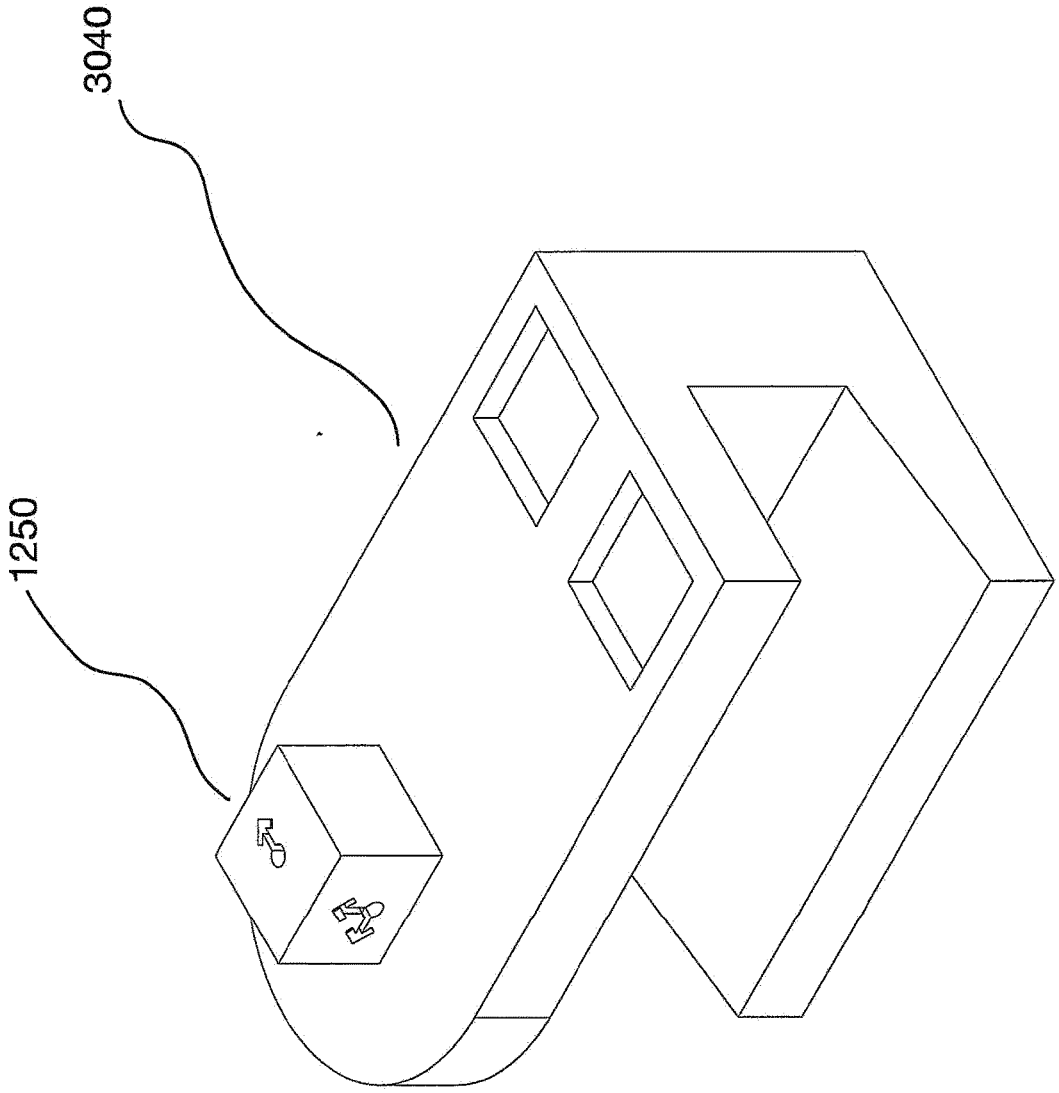


FIG. 93

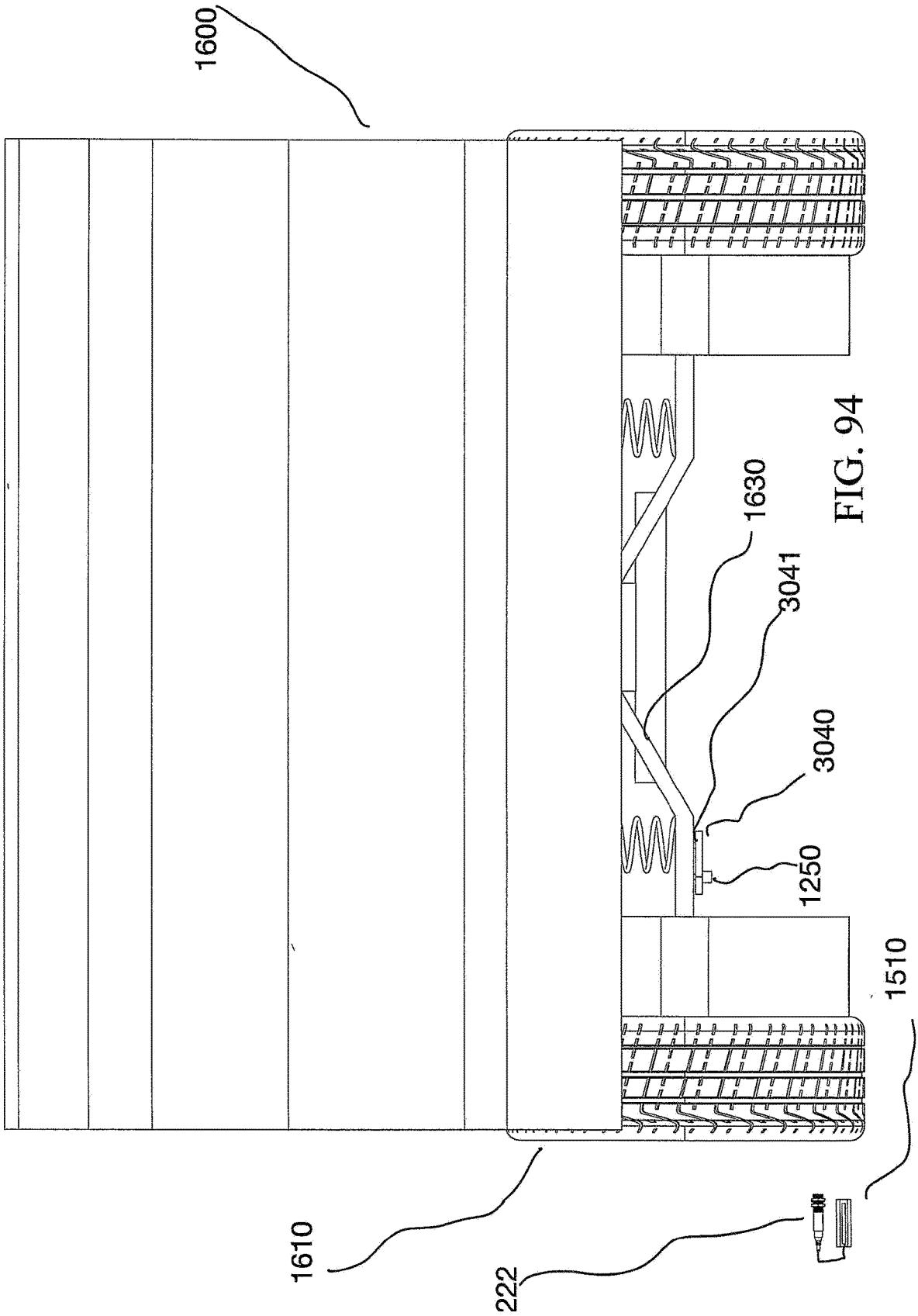


FIG. 94

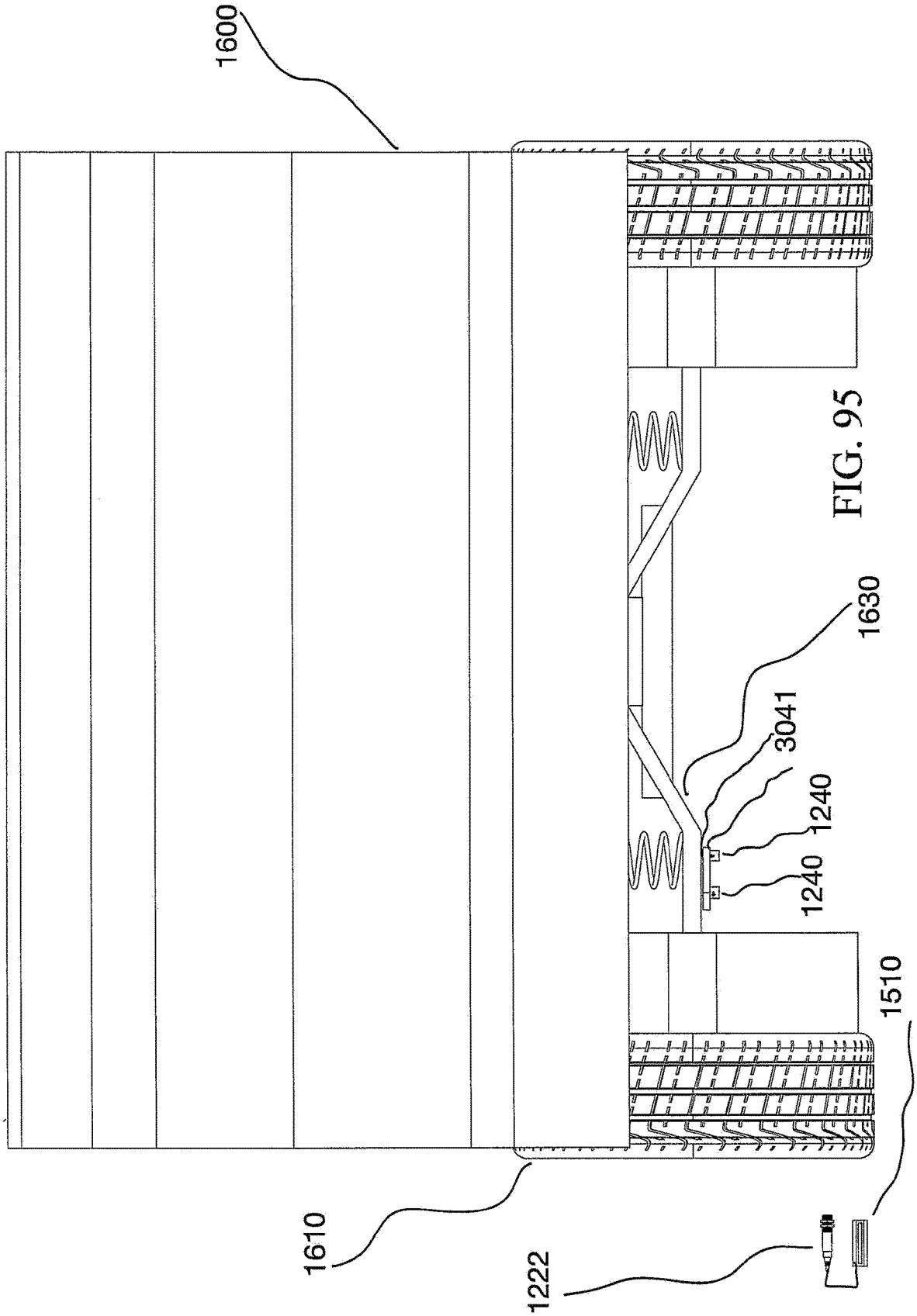


FIG. 95

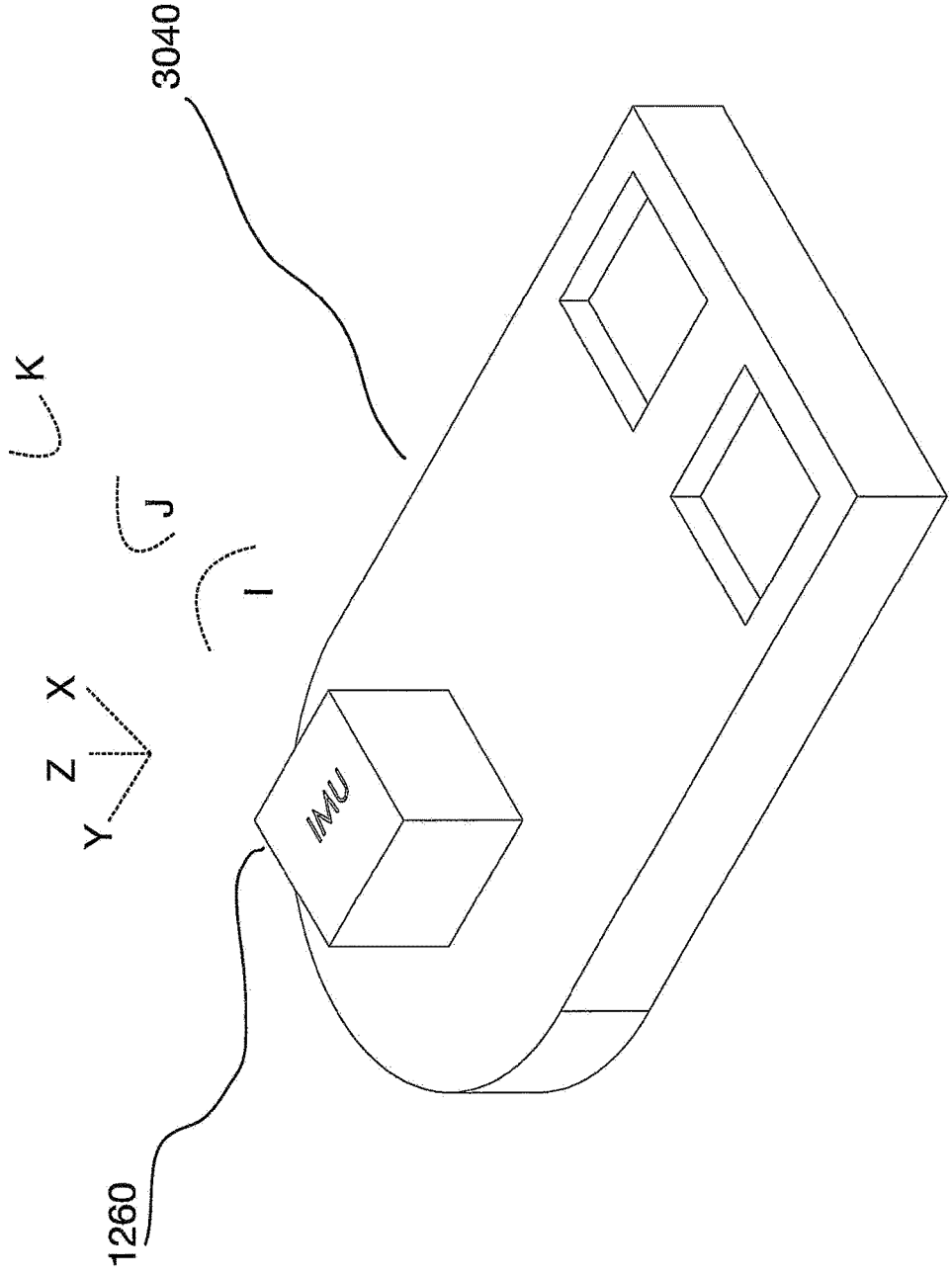


FIG. 96

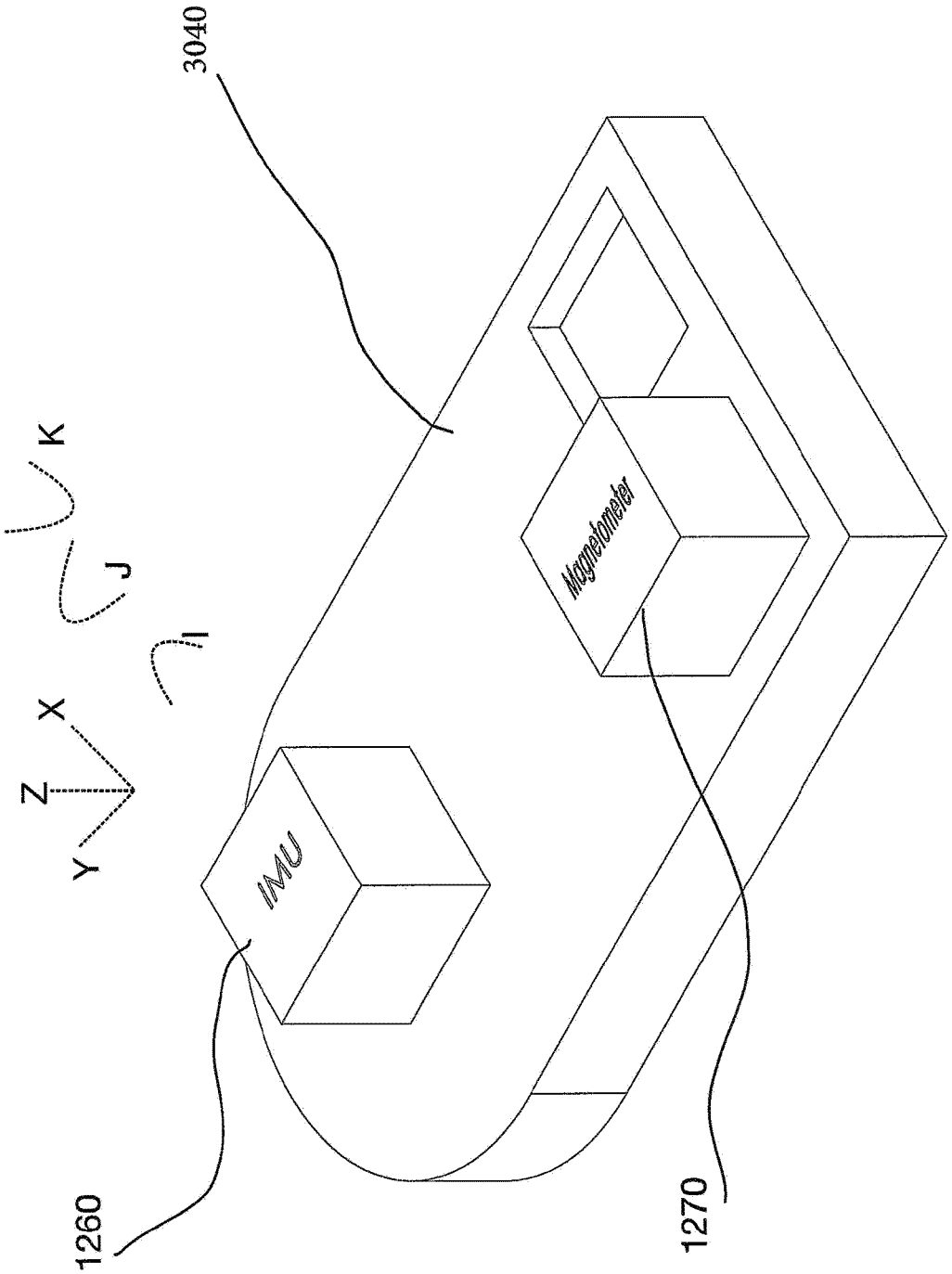


FIG. 97

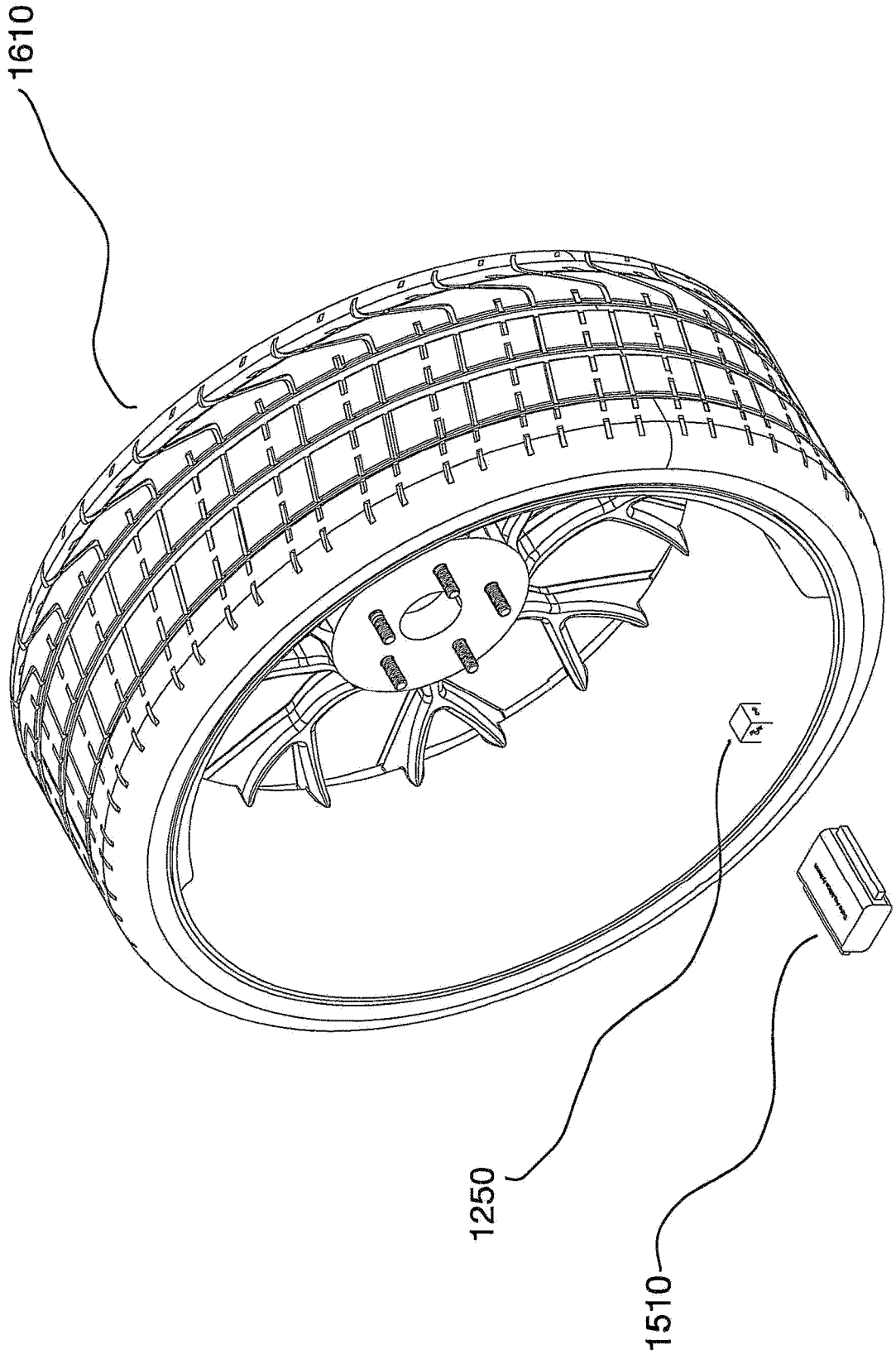


FIG. 98

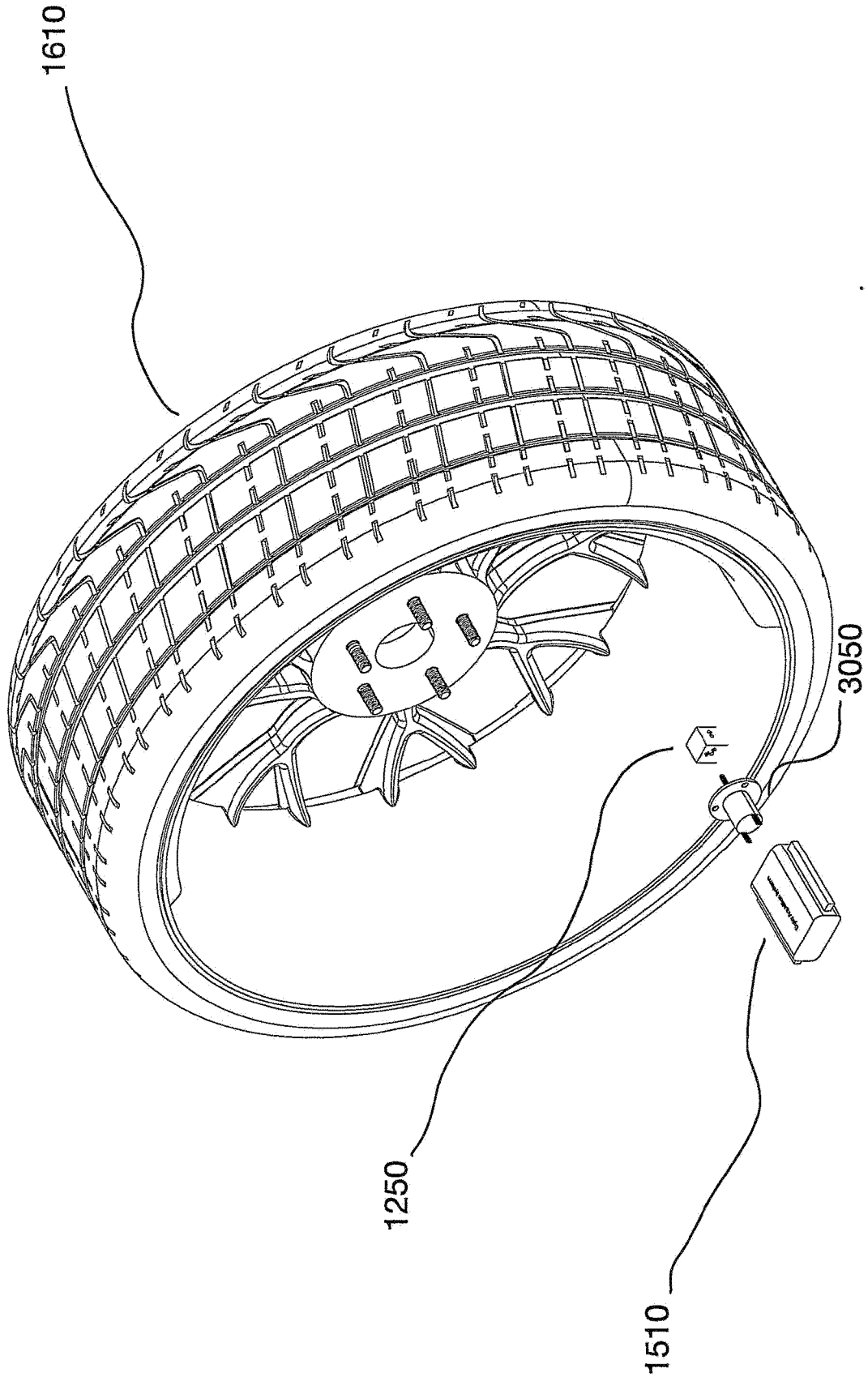


FIG. 99

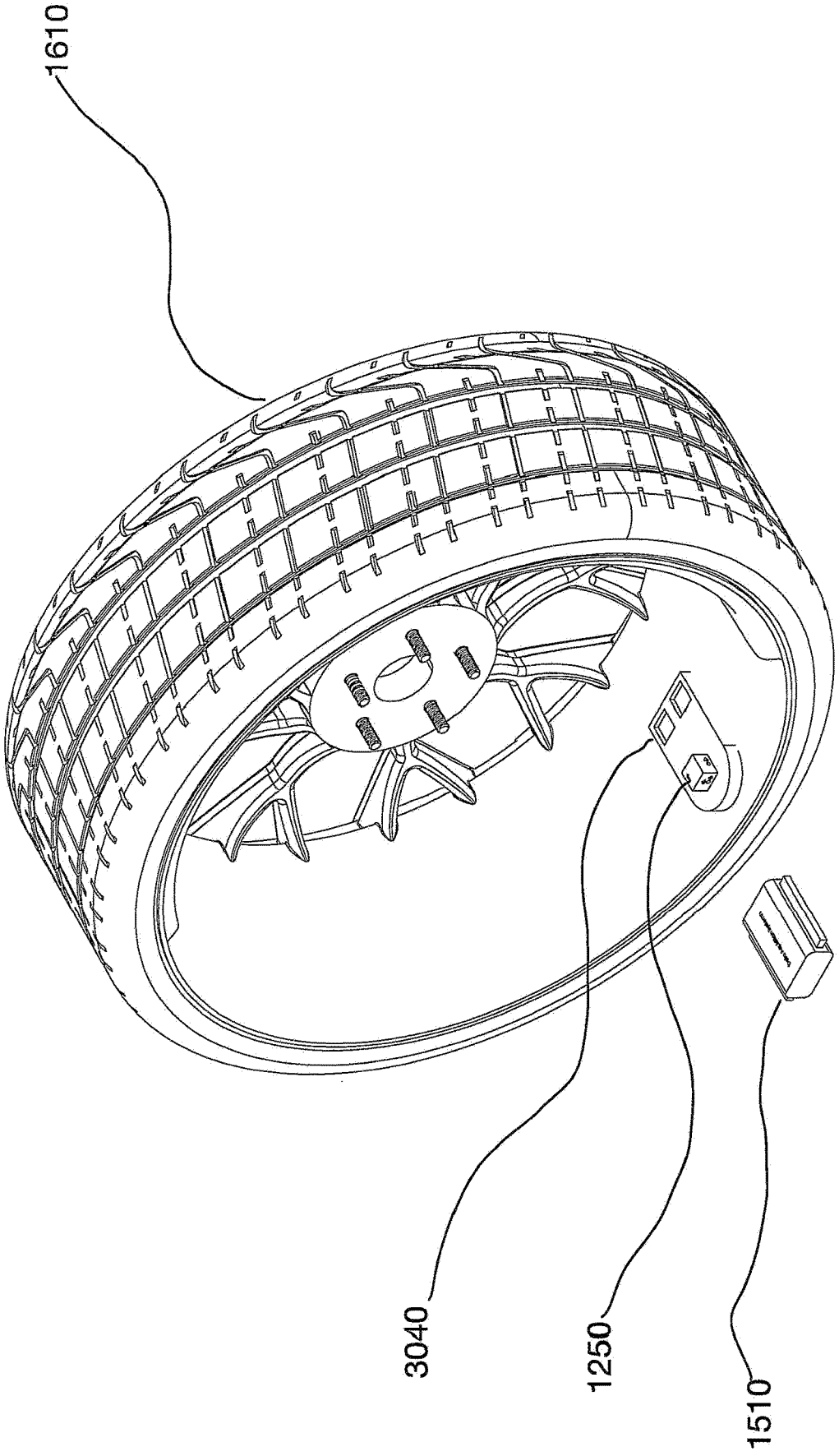


FIG. 100

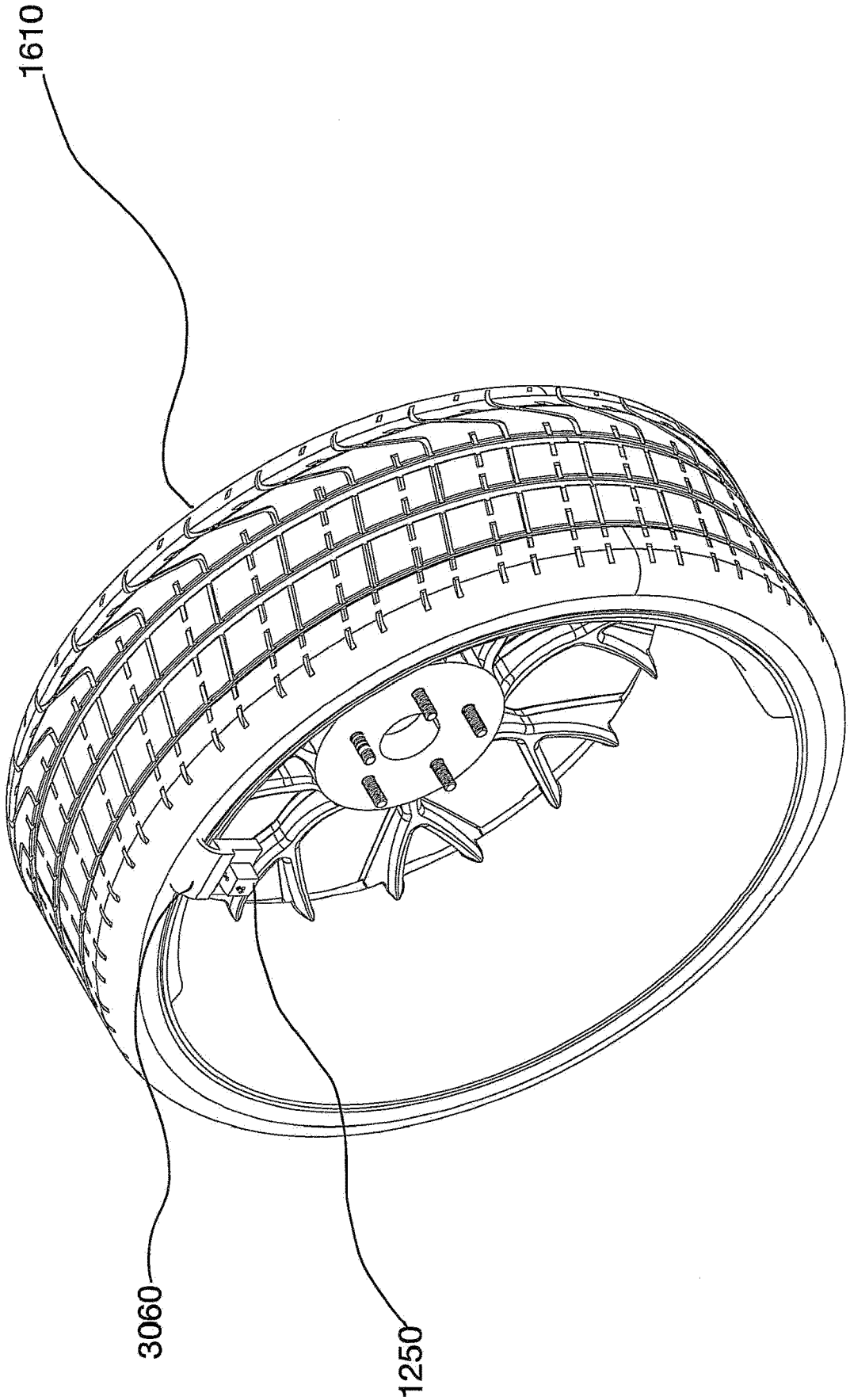


FIG. 101

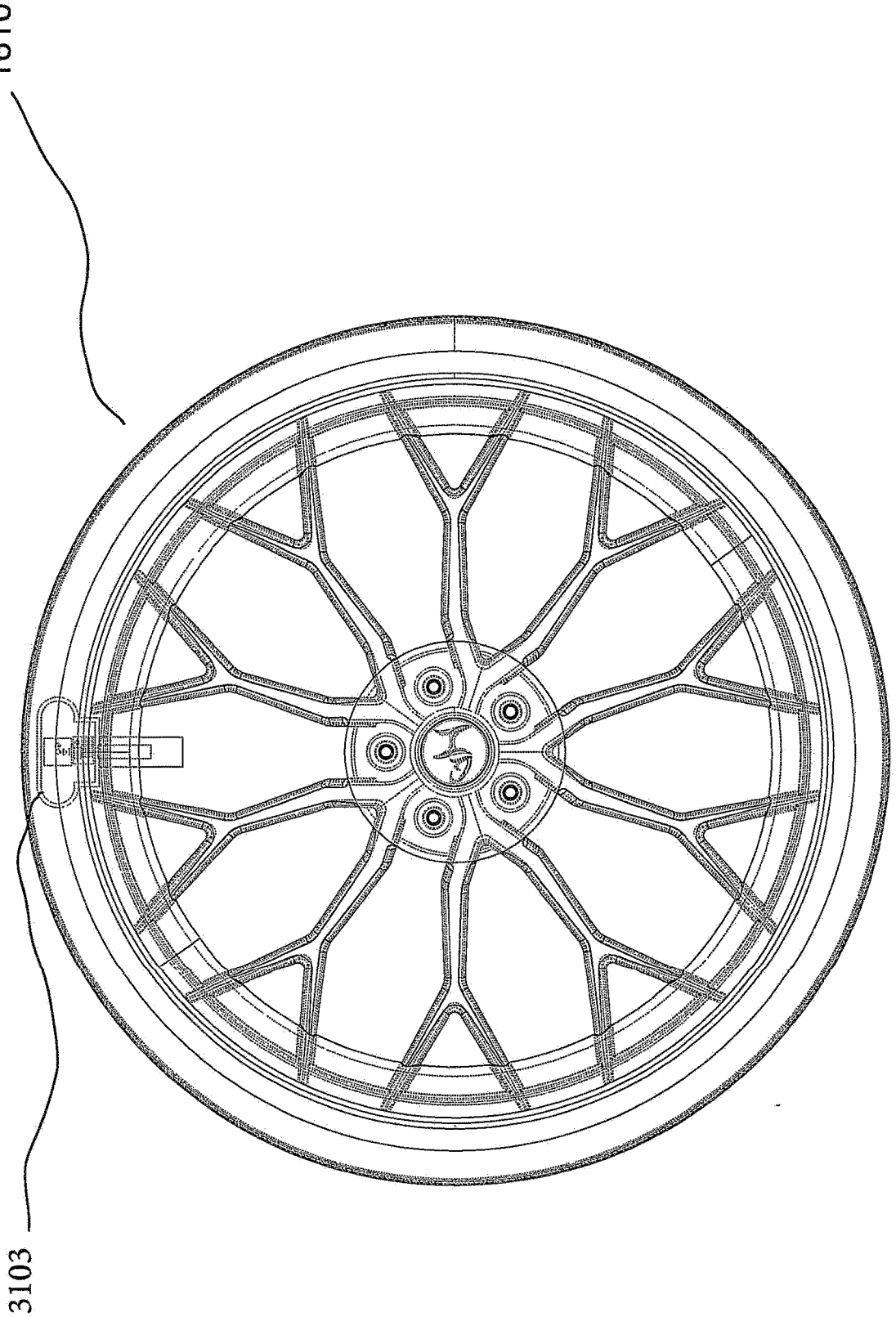


FIG. 102

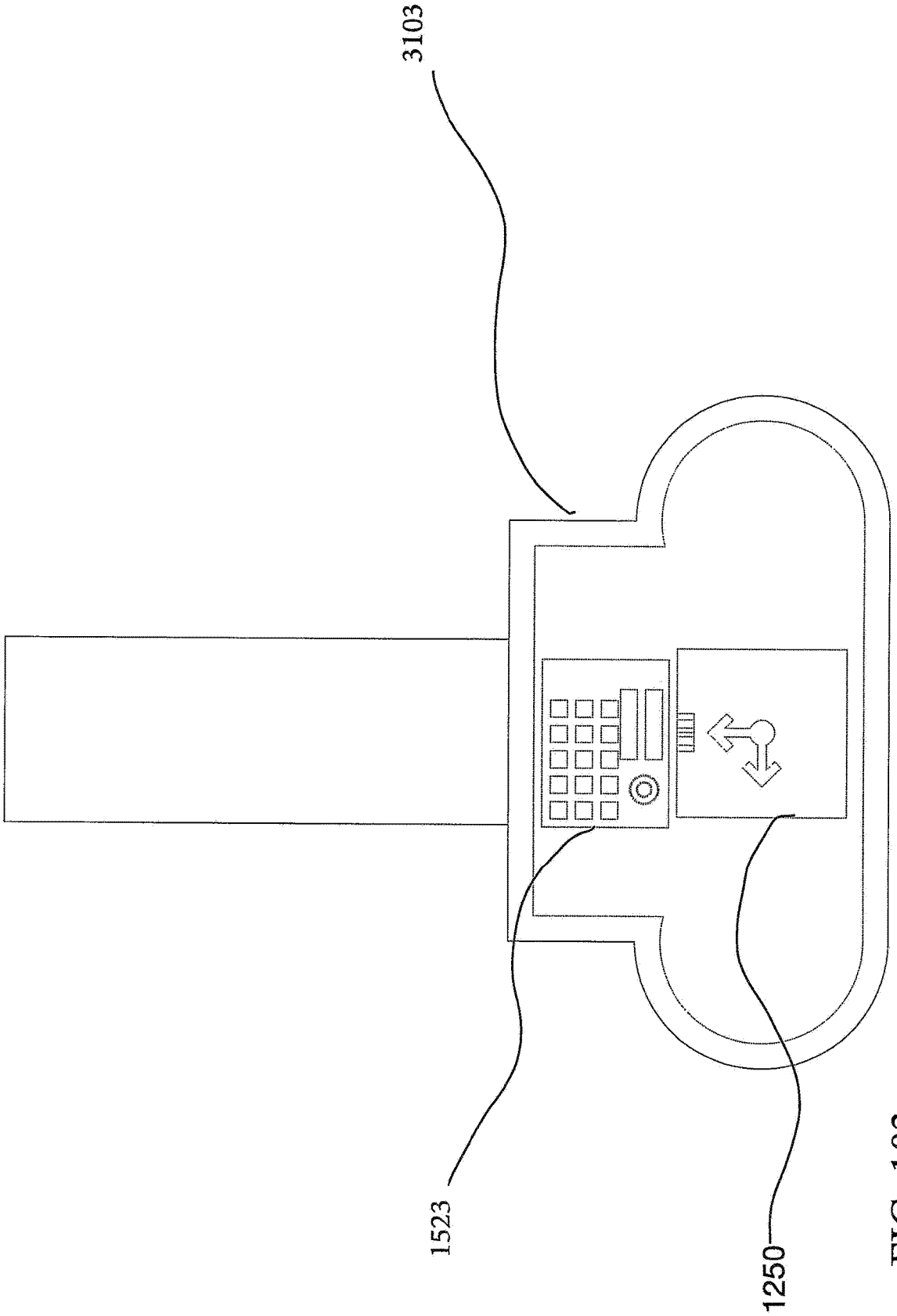


FIG. 103

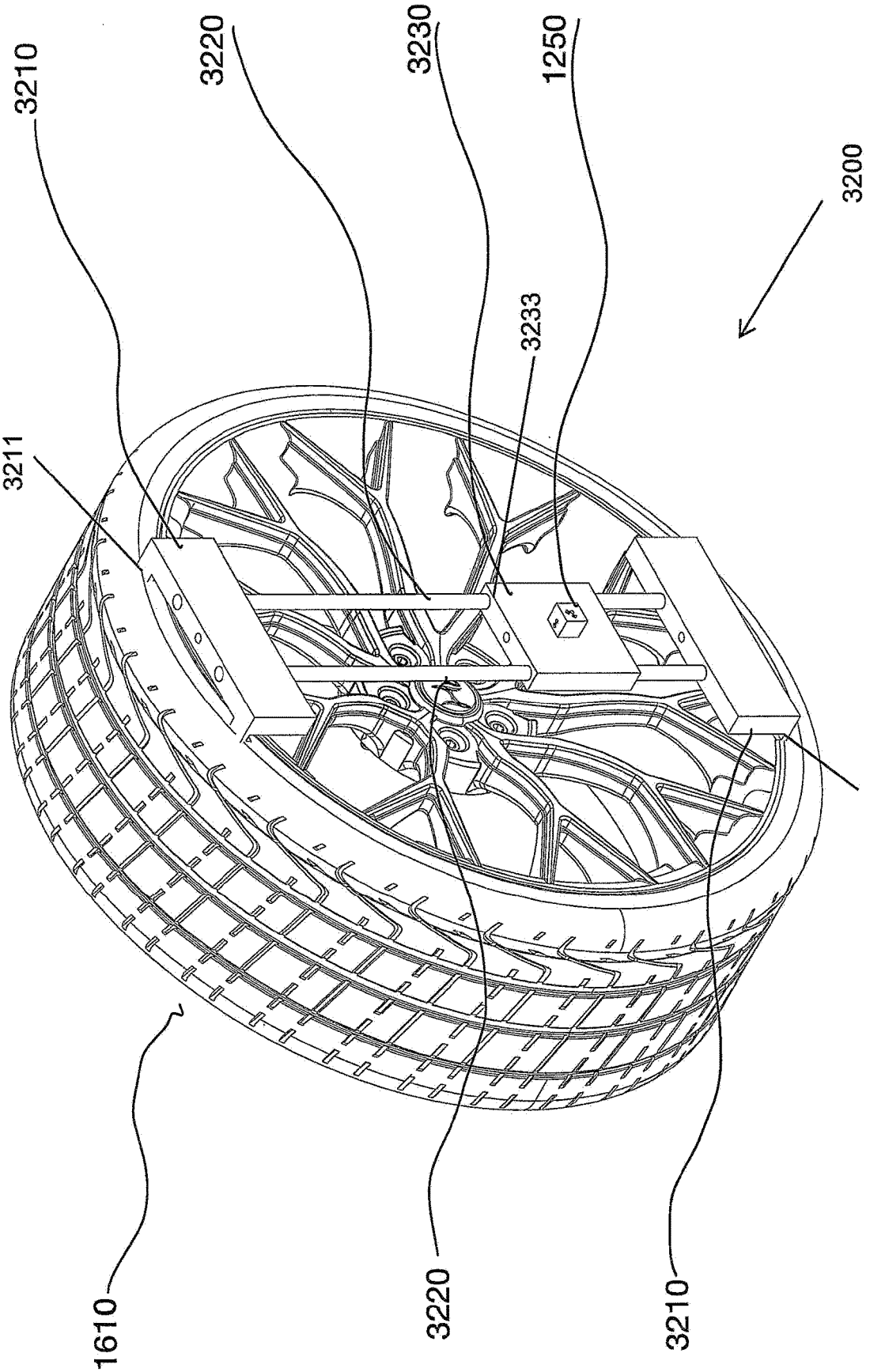


FIG. 104

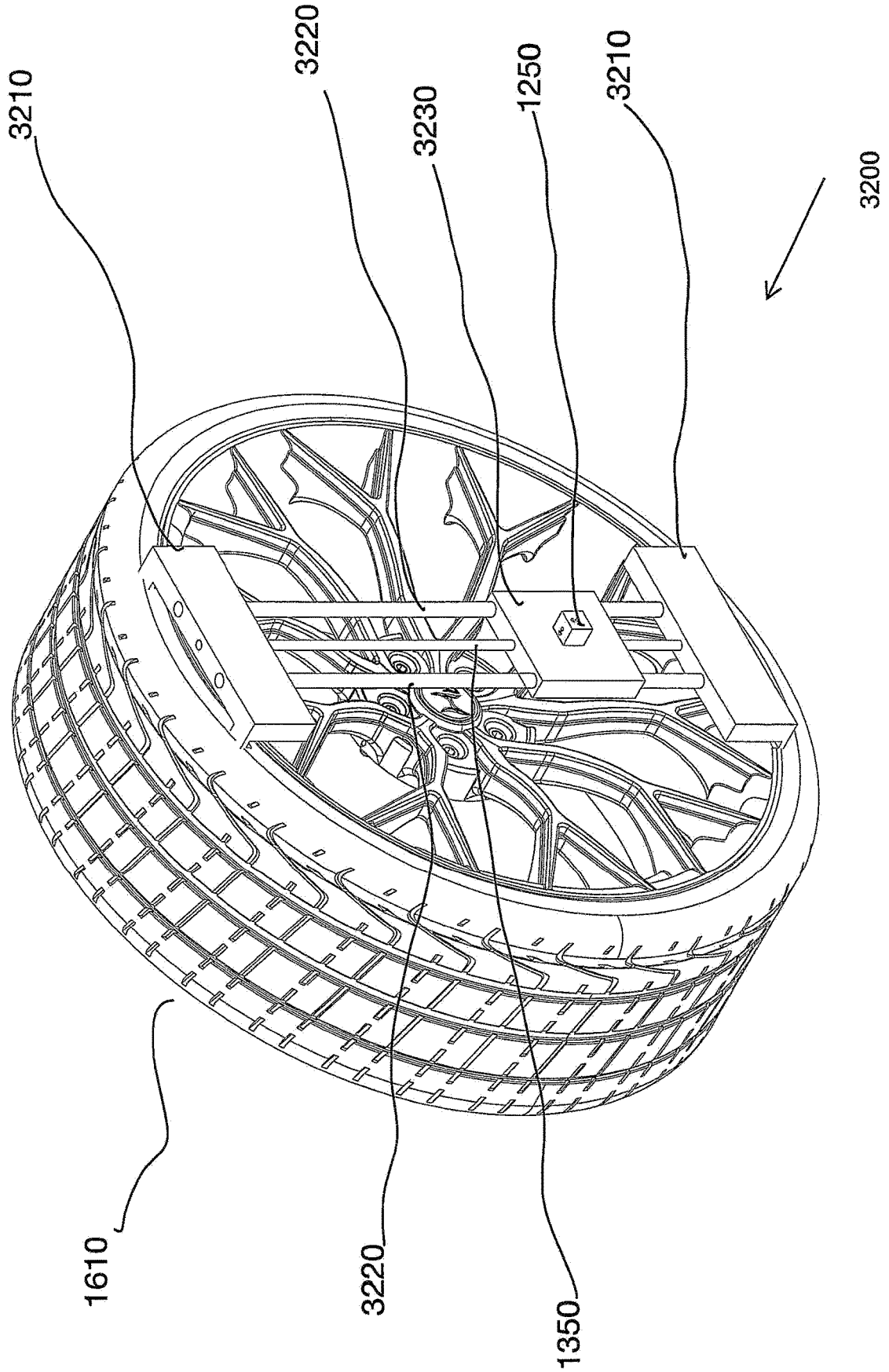


FIG. 105

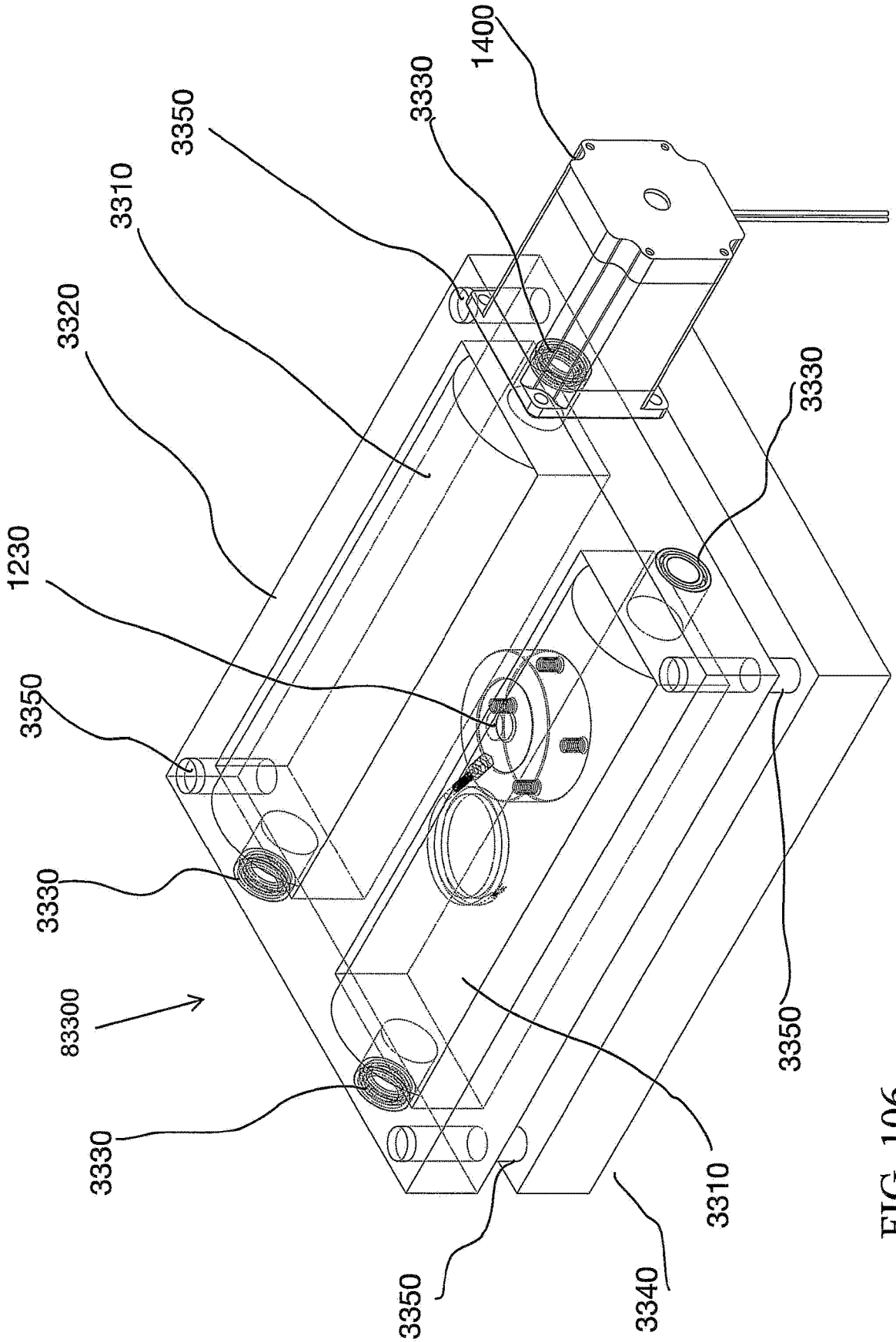

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3330
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3350
3310
3350
3340

FIG. 106

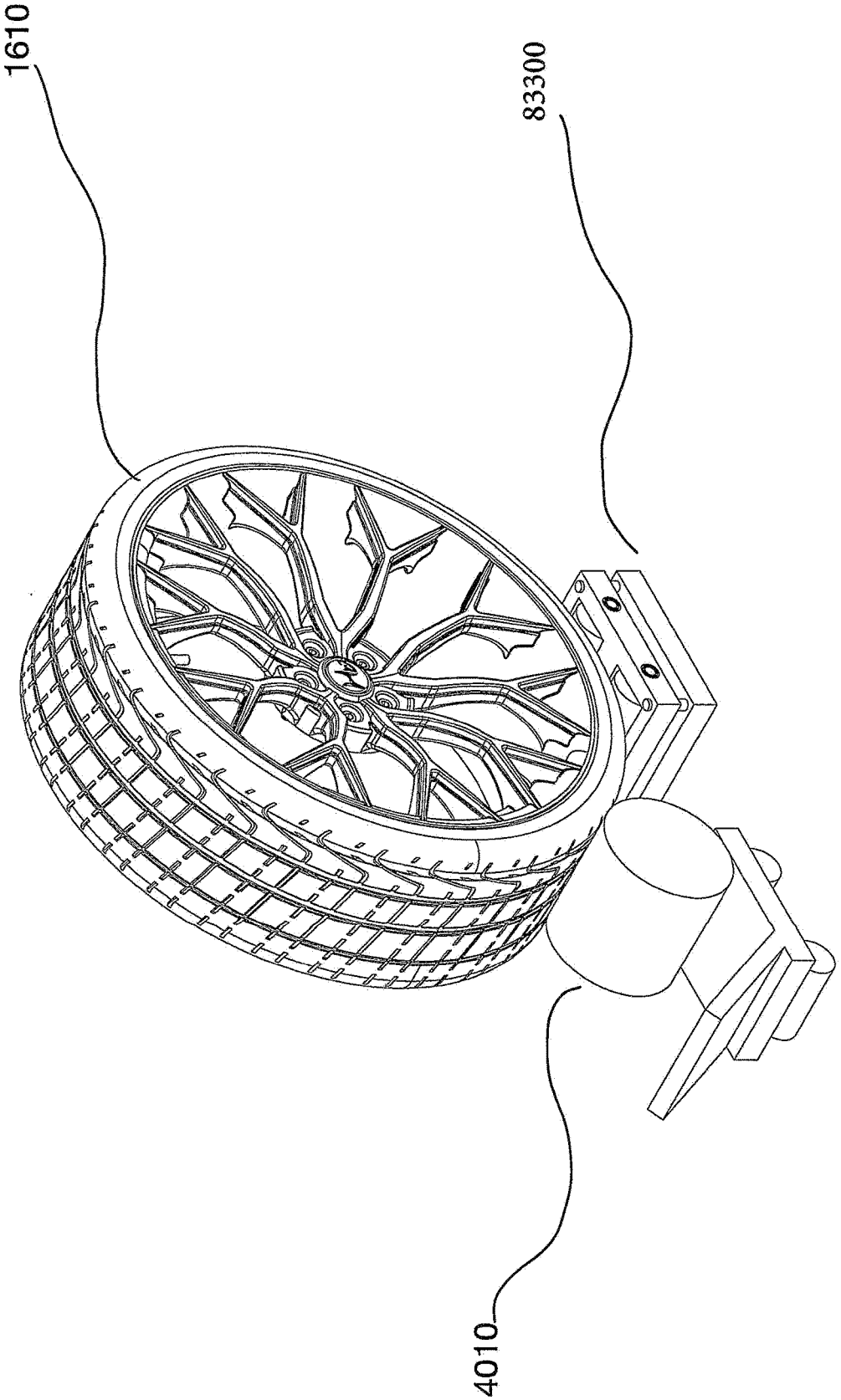


FIG. 107

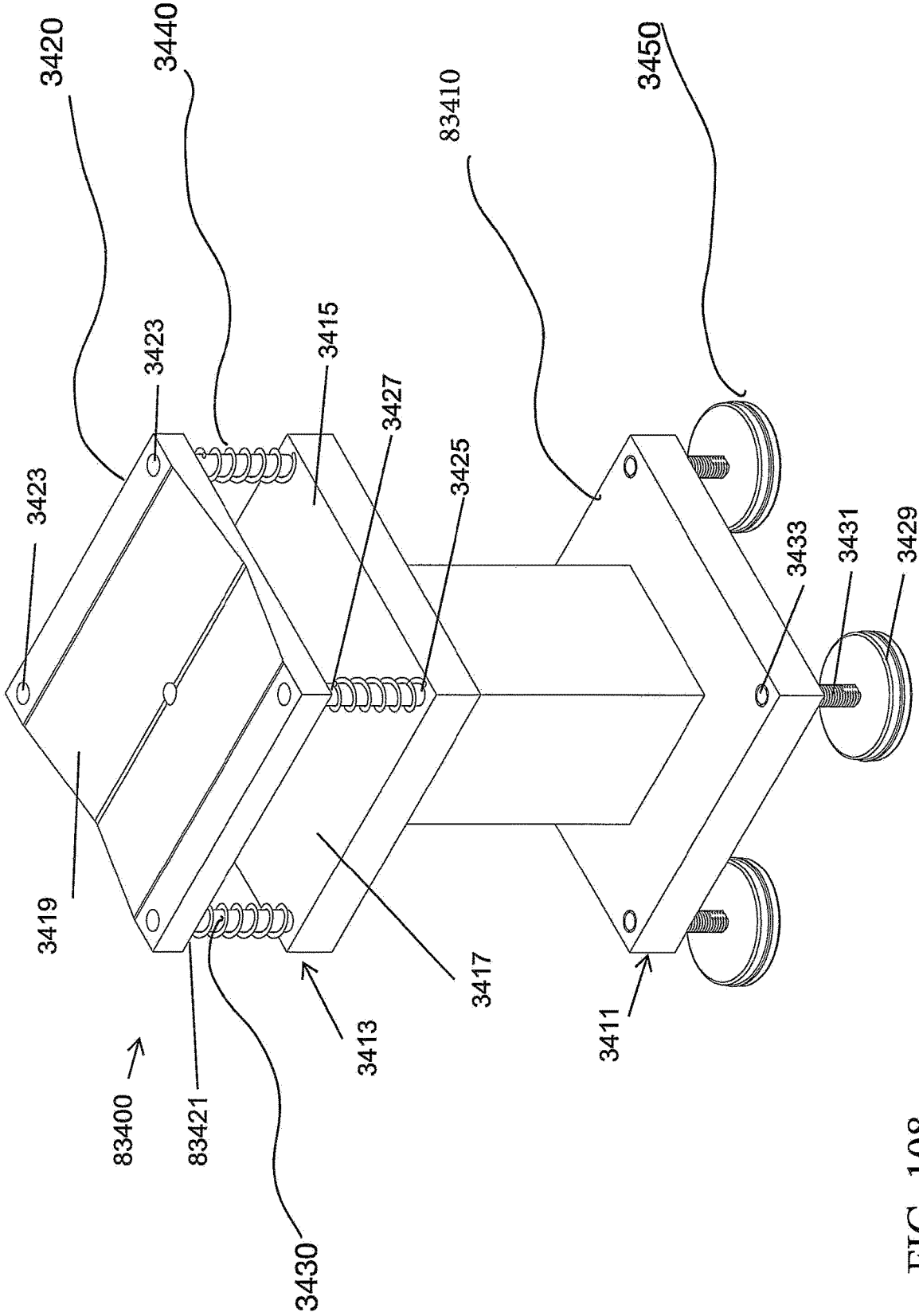

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83400
83421
3430

FIG. 108

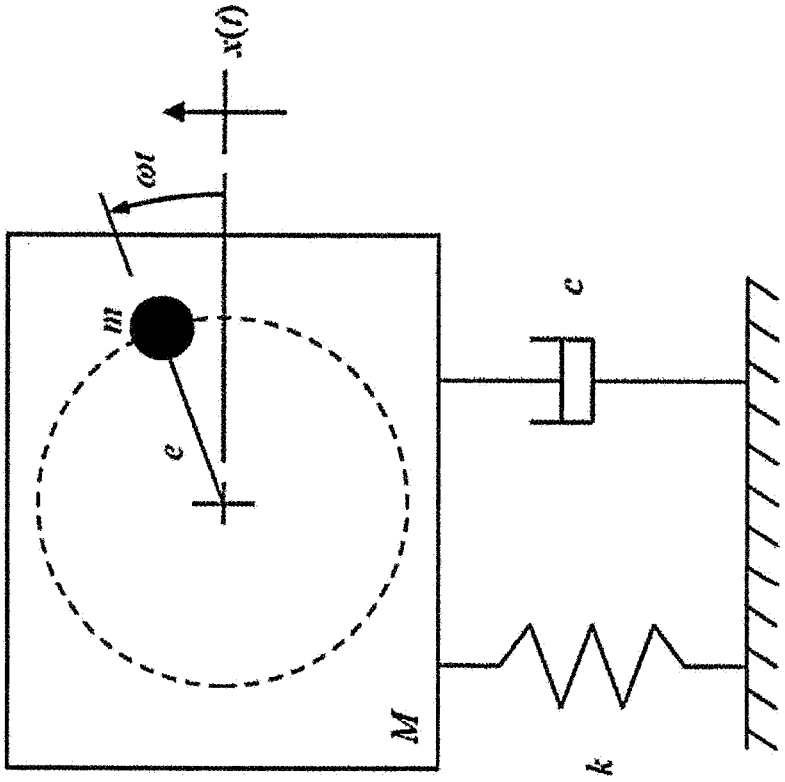


FIG. 109

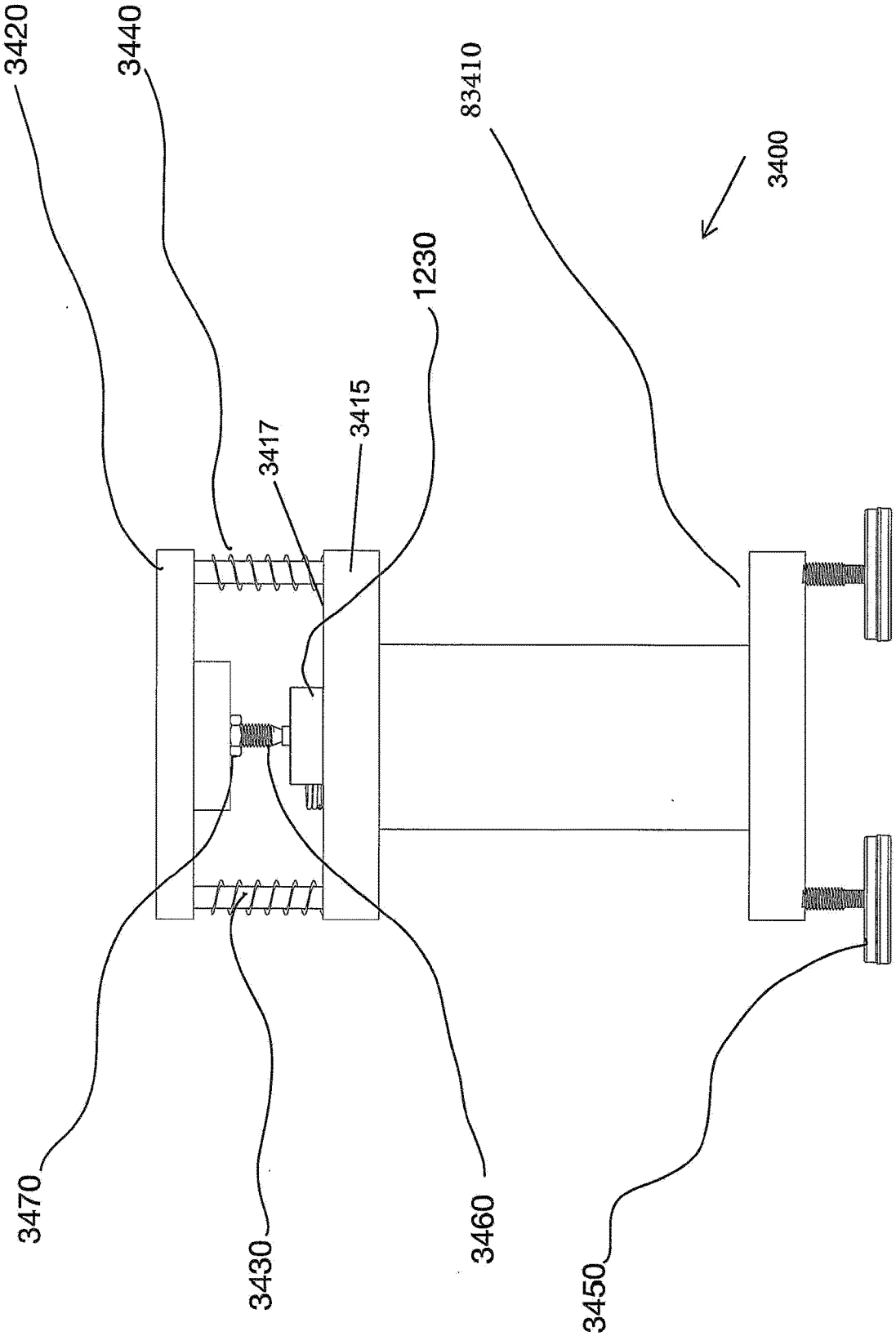


FIG. 110

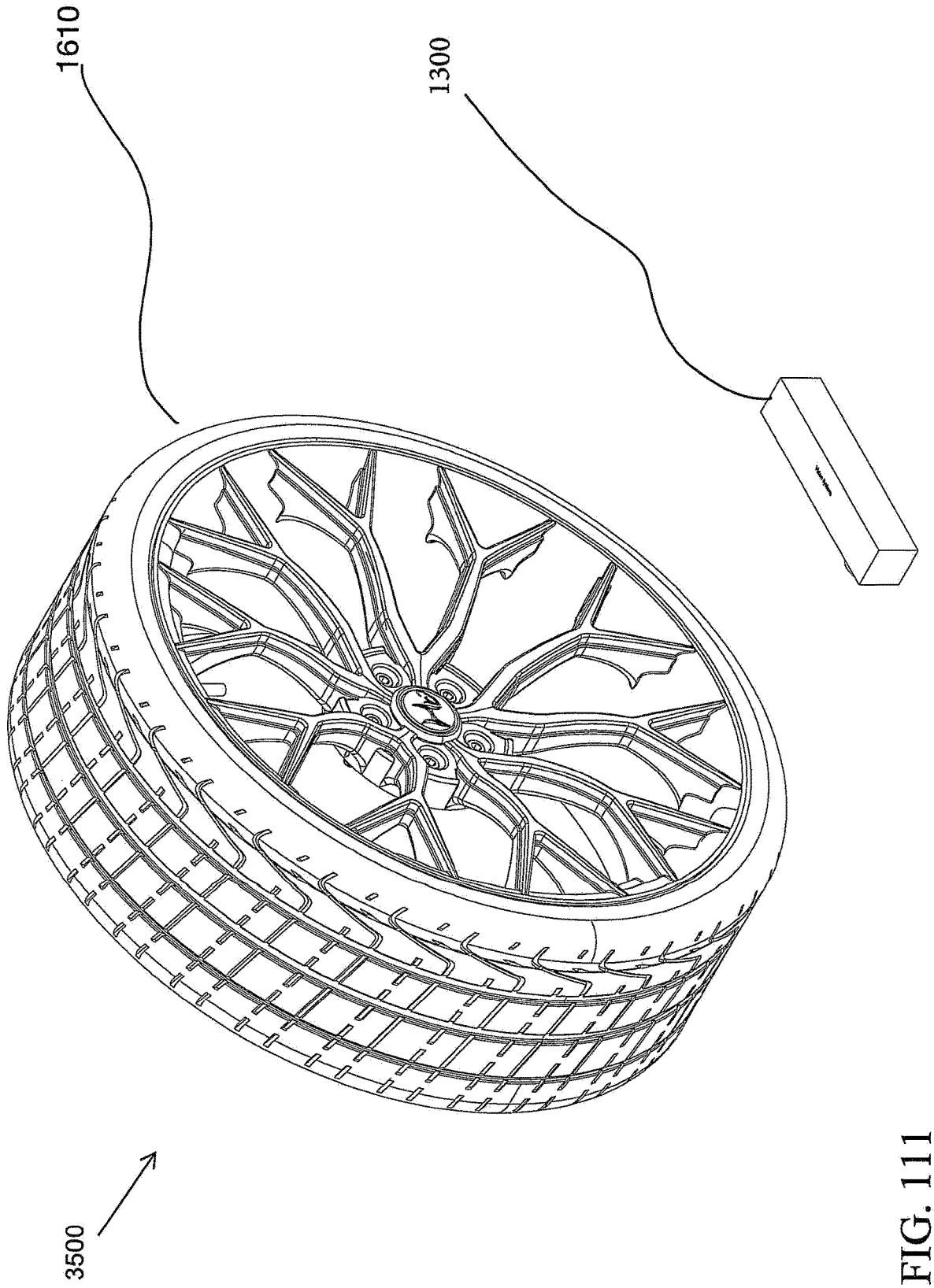


FIG. 111

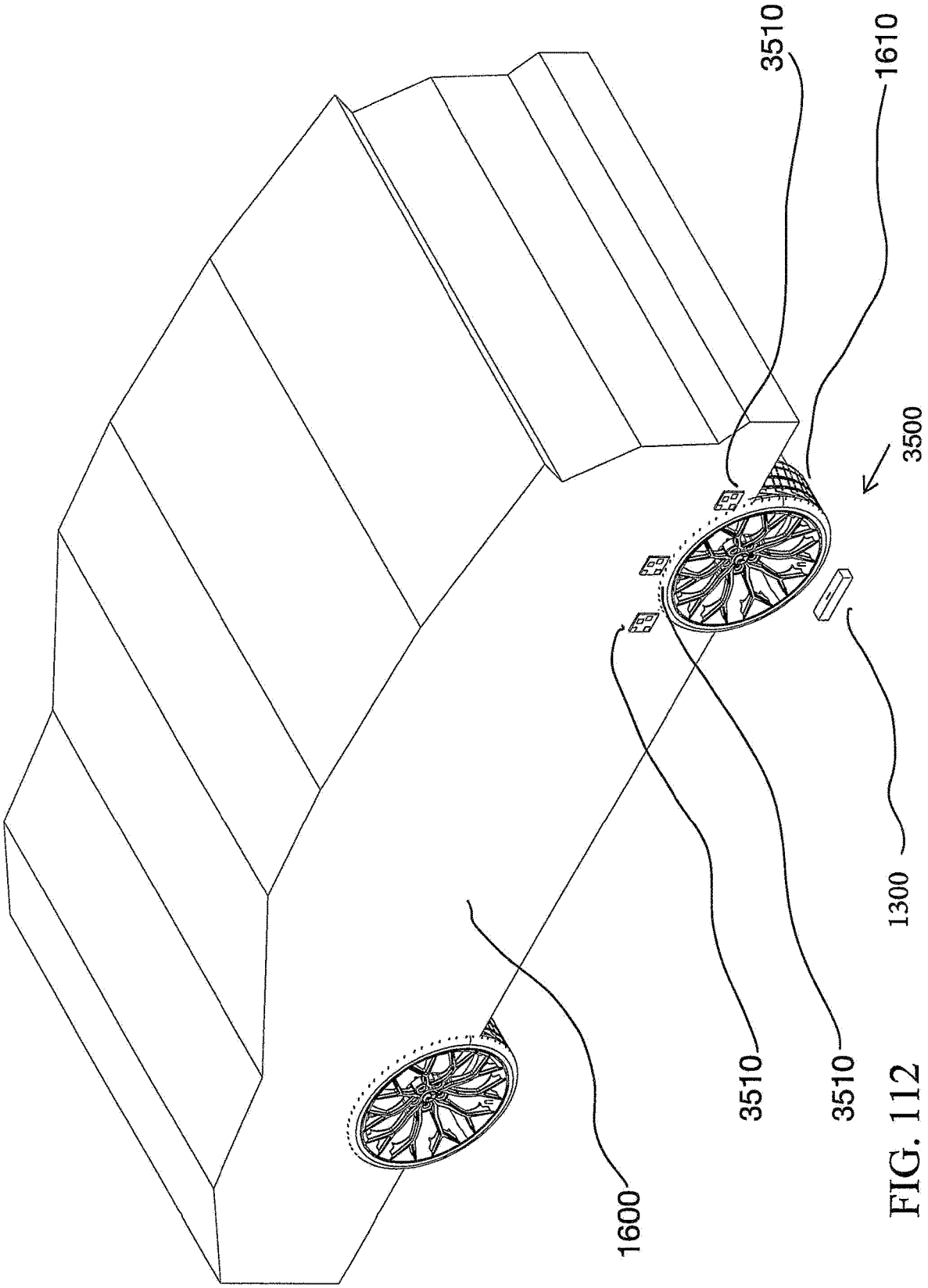


FIG. 112

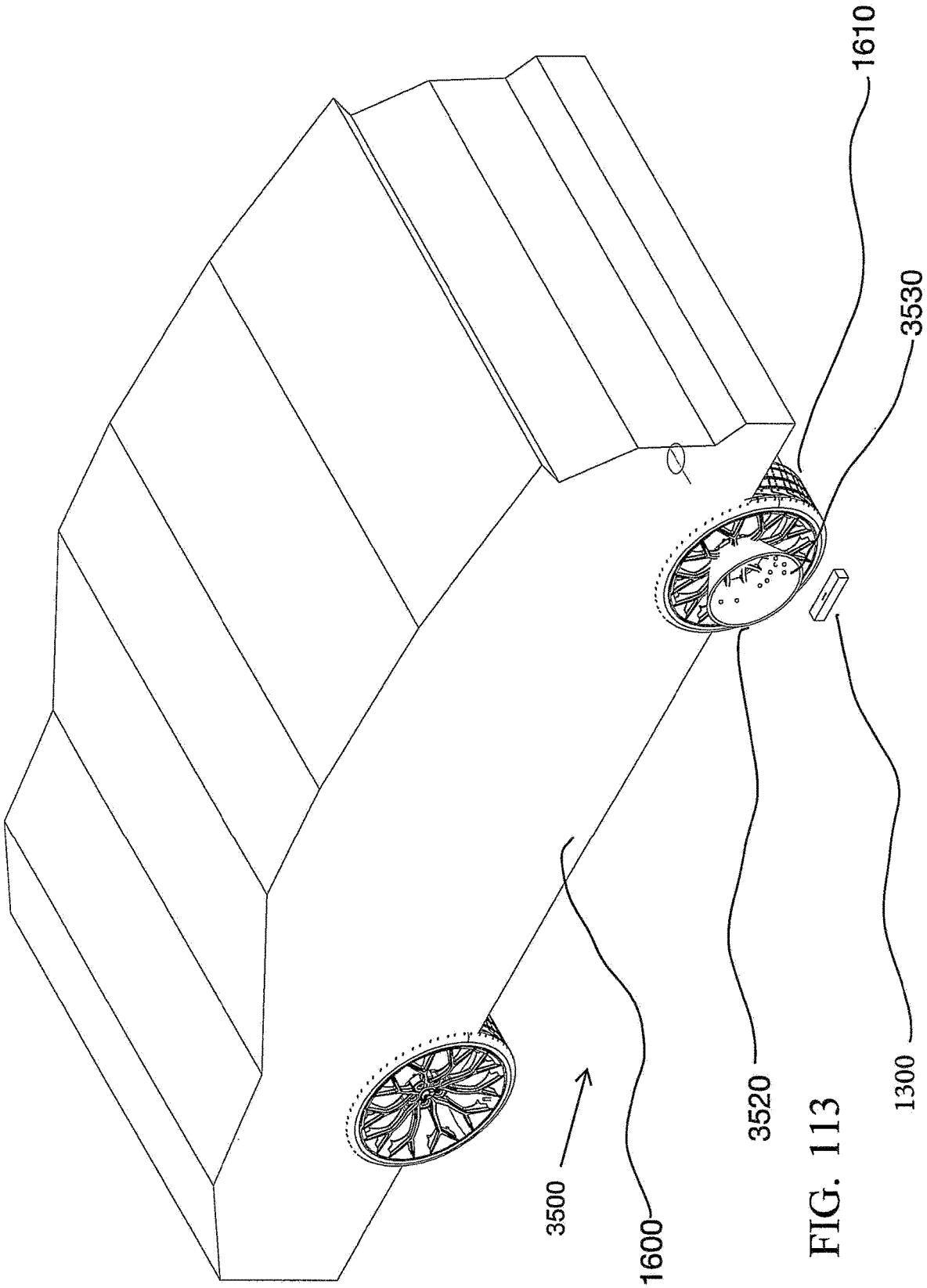


FIG. 113

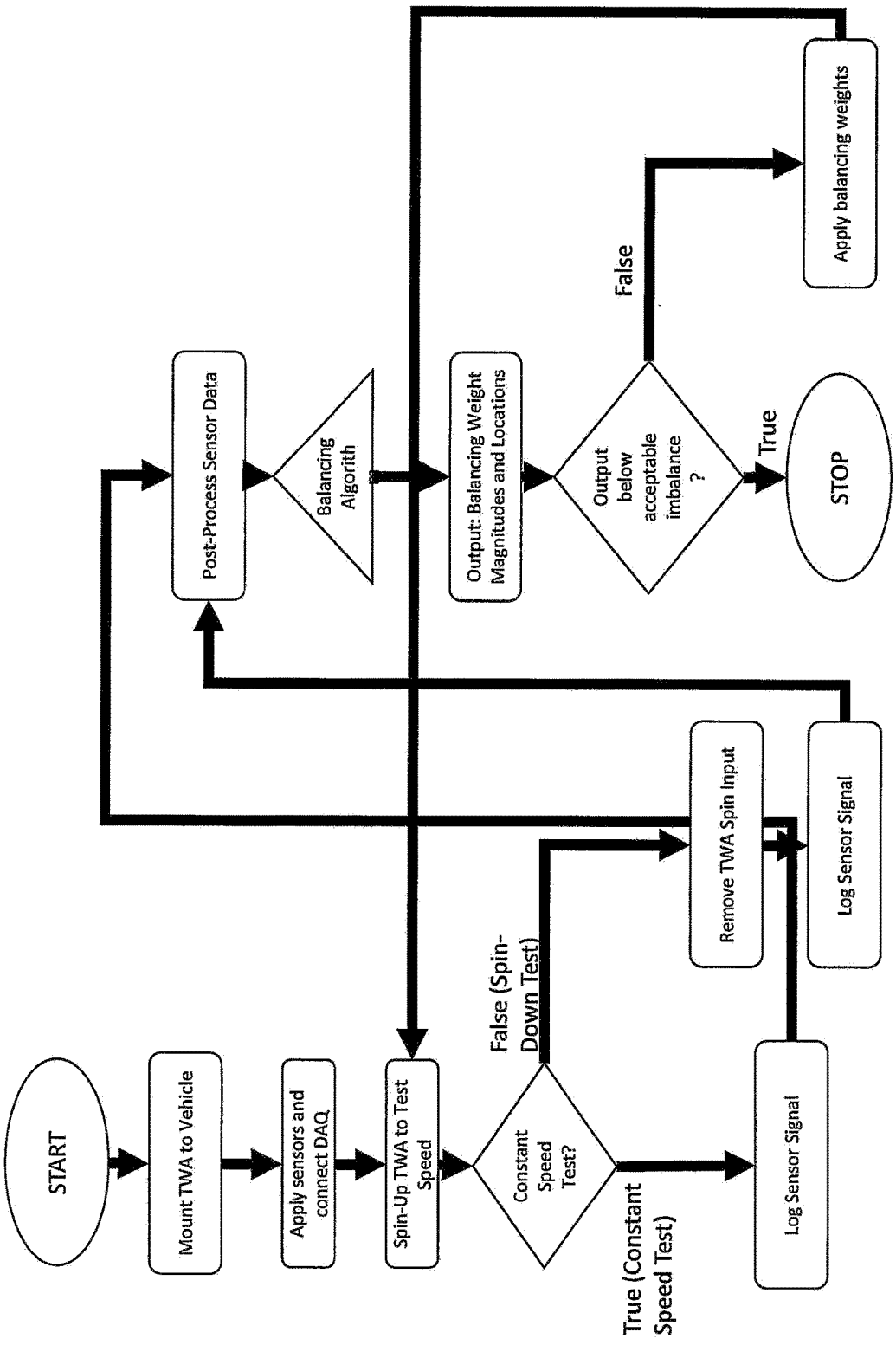

START
Mount TWA to Vehicle
Apply sensors and connect DAQ
Spin-Up TWA to Test Speed
Constant Speed Test?
False (Spin-Down Test)
True (Constant Speed Test)
Log Sensor Signal
Remove TWA Spin Input
Log Sensor Signal
Post-Process Sensor Data
Balancing Algorith m
Output: Balancing Weight Magnitudes and Locations
Output below acceptable imbalance ?
False
True
STOP
Apply balancing weights

FIG. 114

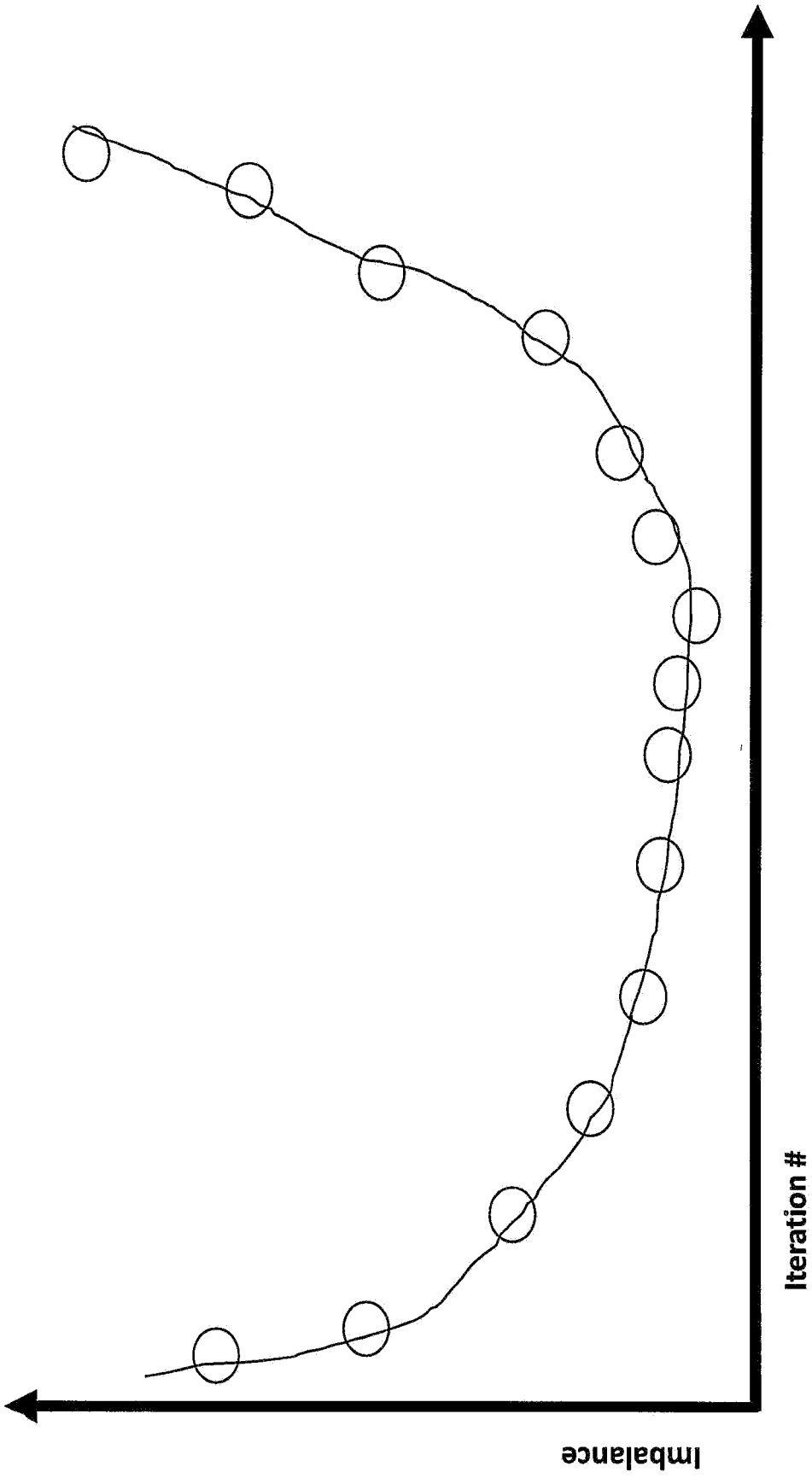


FIG. 115

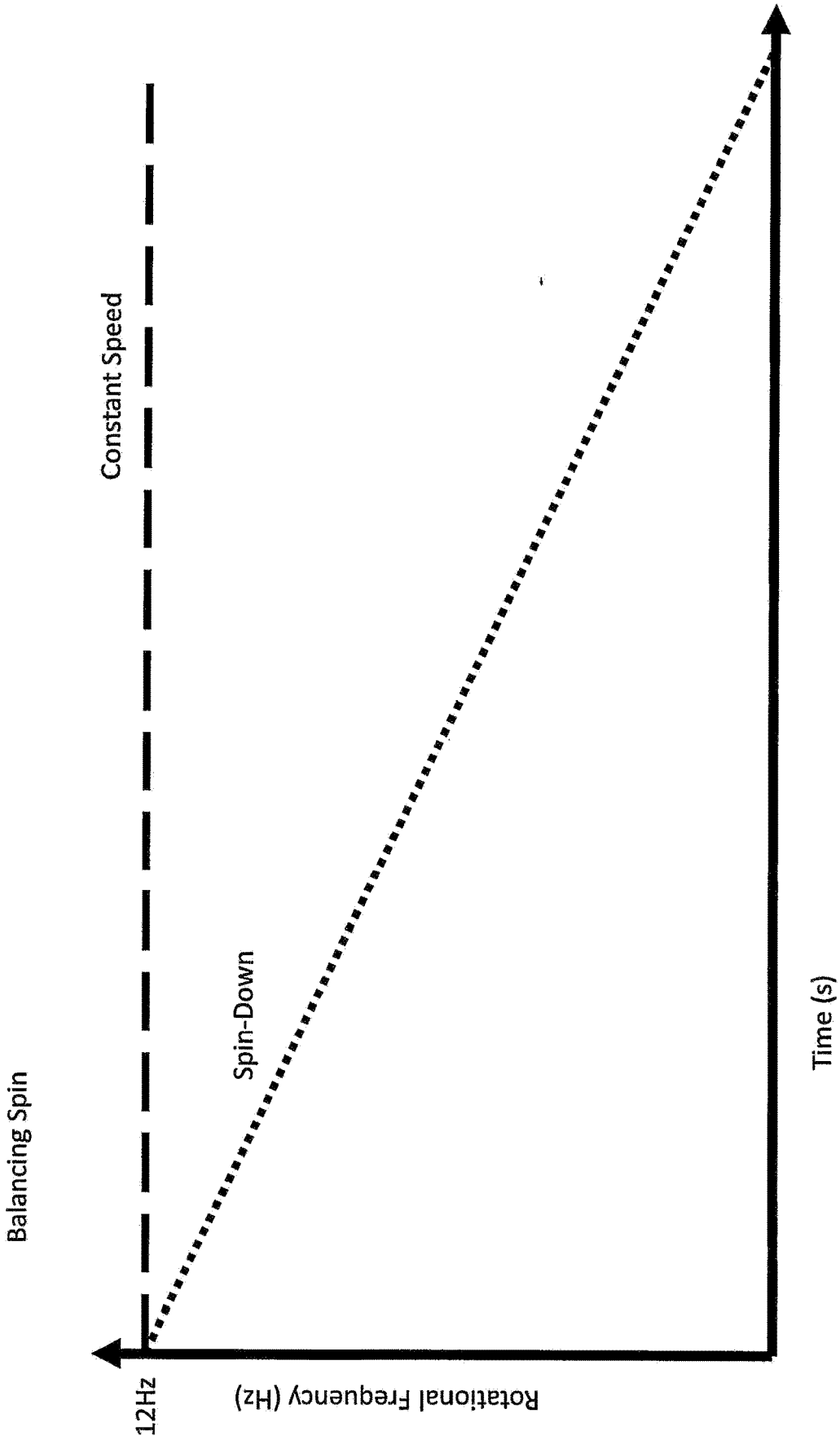

Balancing Spin
Constant Speed
Spin-Down
12Hz
Rotational Frequency (Hz)
Time (s)

FIG. 116

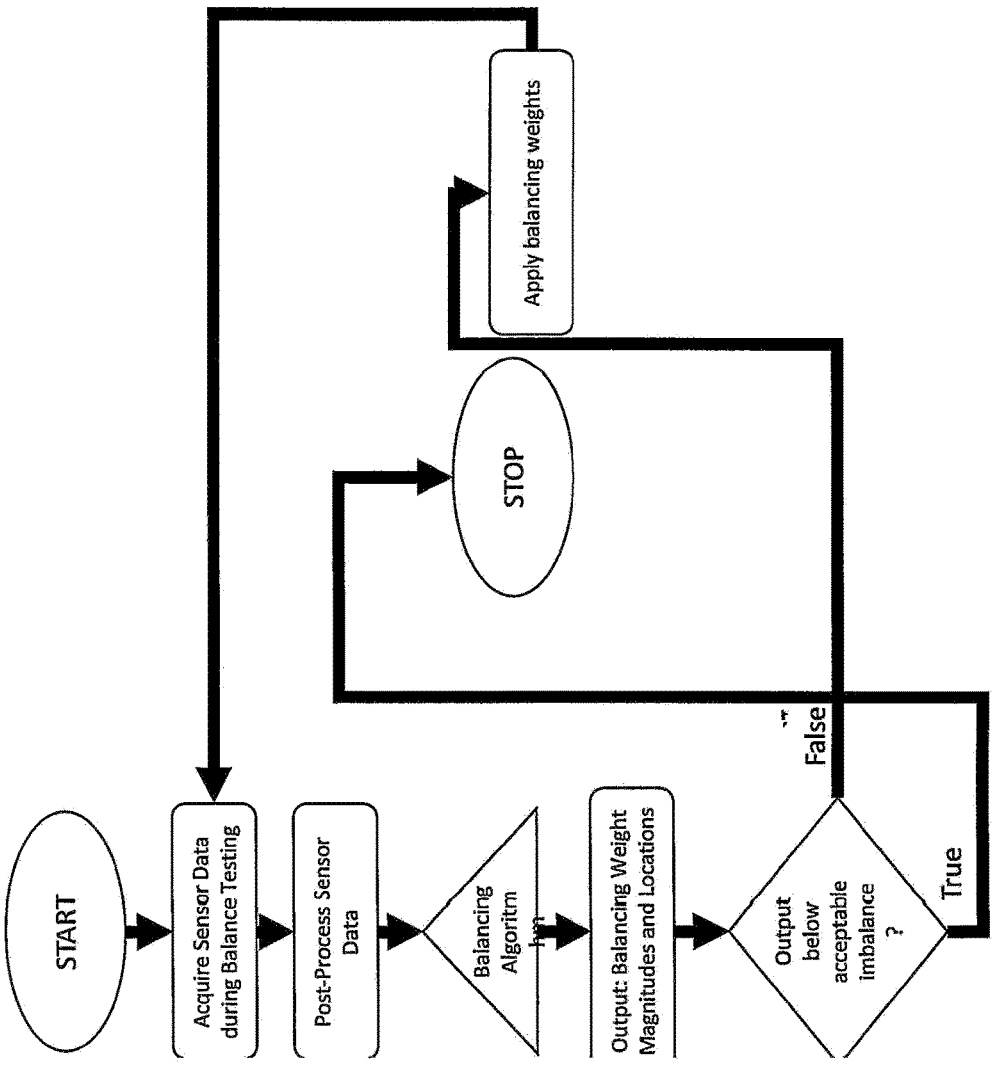

START
Acquire Sensor Data during Balance Testing
Post-Process Sensor Data
Balancing Algoritm
Output: Balancing Weight Magnitudes and Locations
Output below acceptable imbalance ?
False
True
STOP
Apply balancing weights

FIG. 117

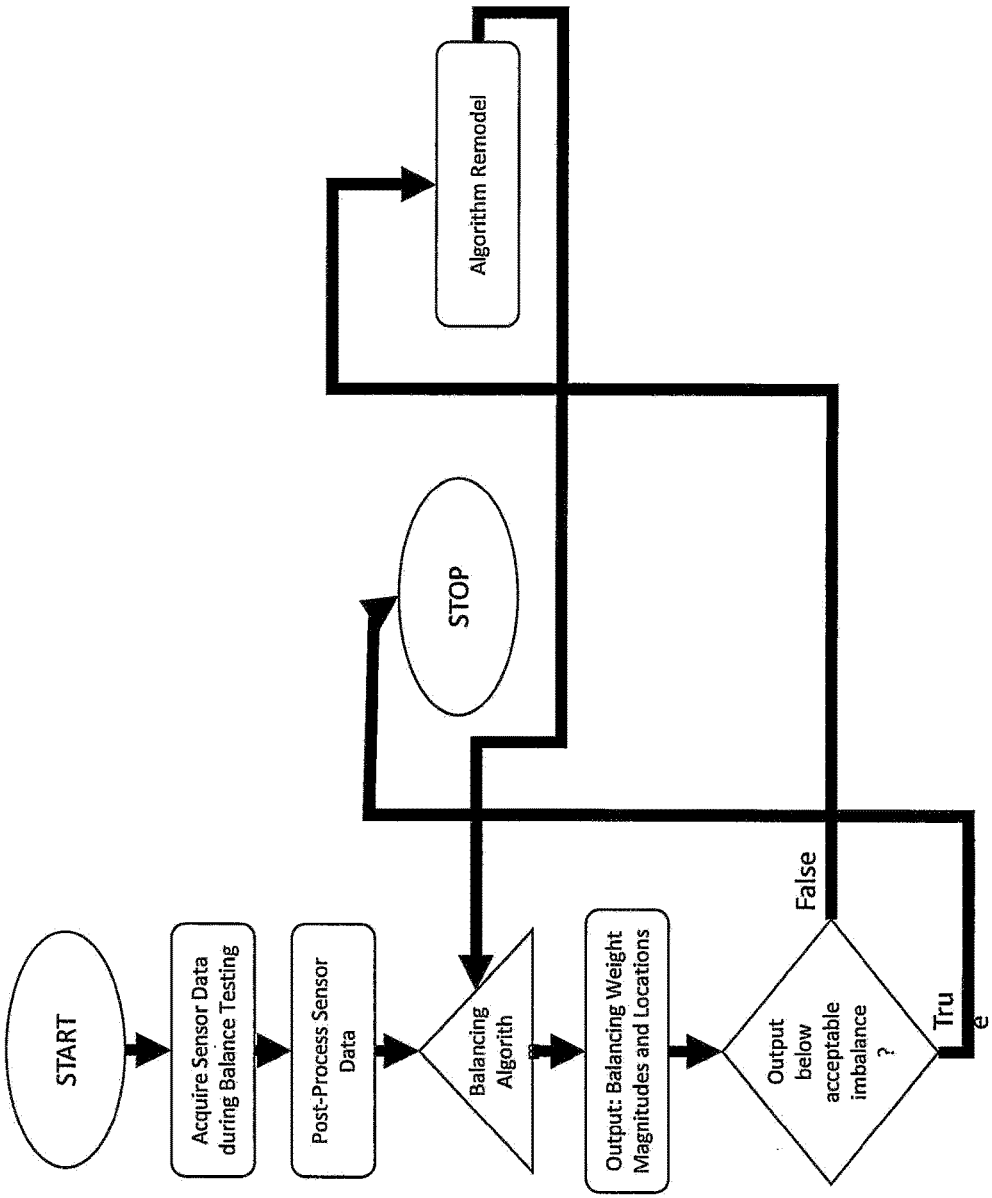

START
Acquire Sensor Data during Balance Testing
Post-Process Sensor Data
Balancing Algorith
Output: Balancing Weight Magnitudes and Locations
Output below acceptable imbalance ?
False
Tru
e
STOP
Algorithm Remodel

FIG. 118

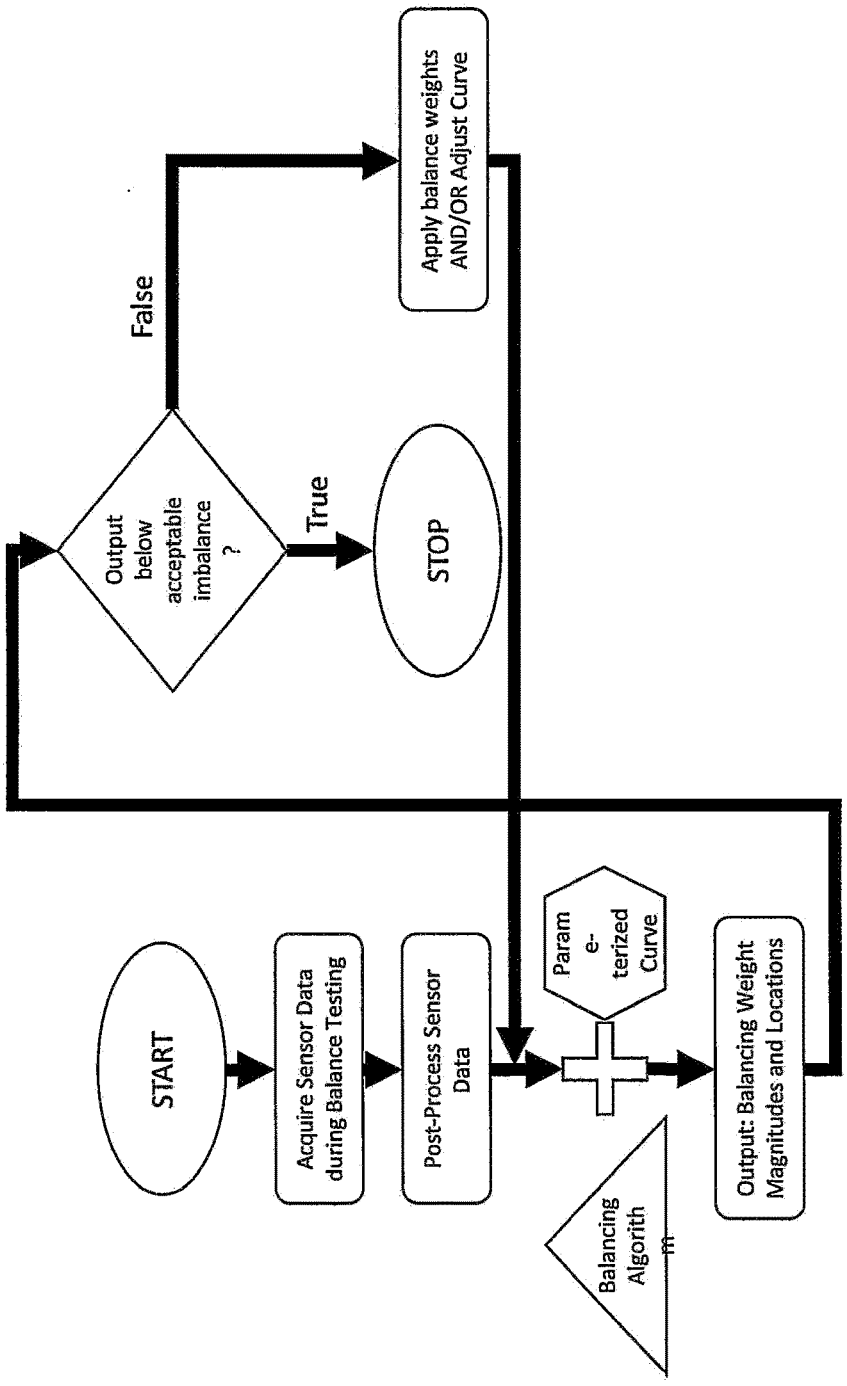

START
Acquire Sensor Data during Balance Testing
Post-Process Sensor Data
Param e- terized Curve
Balancing Algorith m
Output: Balancing Weight Magnitudes and Locations
Output below acceptable imbalance ?
False
True
STOP
Apply balance weights AND/OR Adjust Curve

FIG. 119

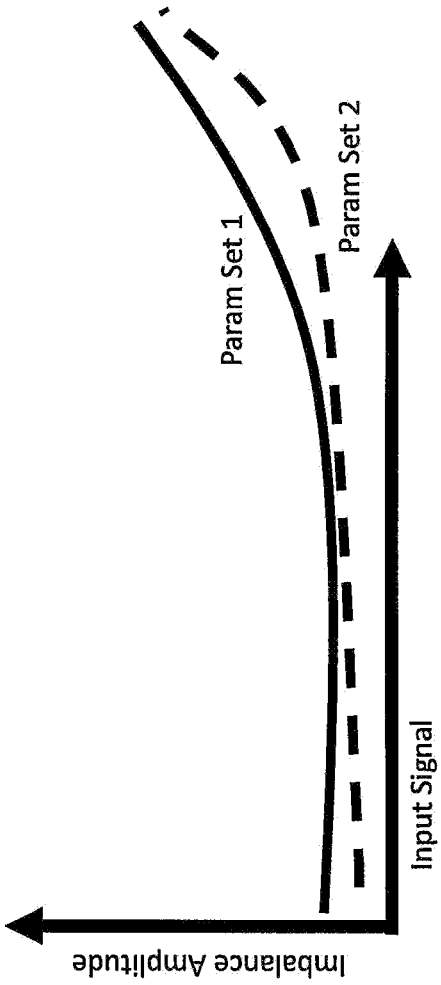


FIG. 120

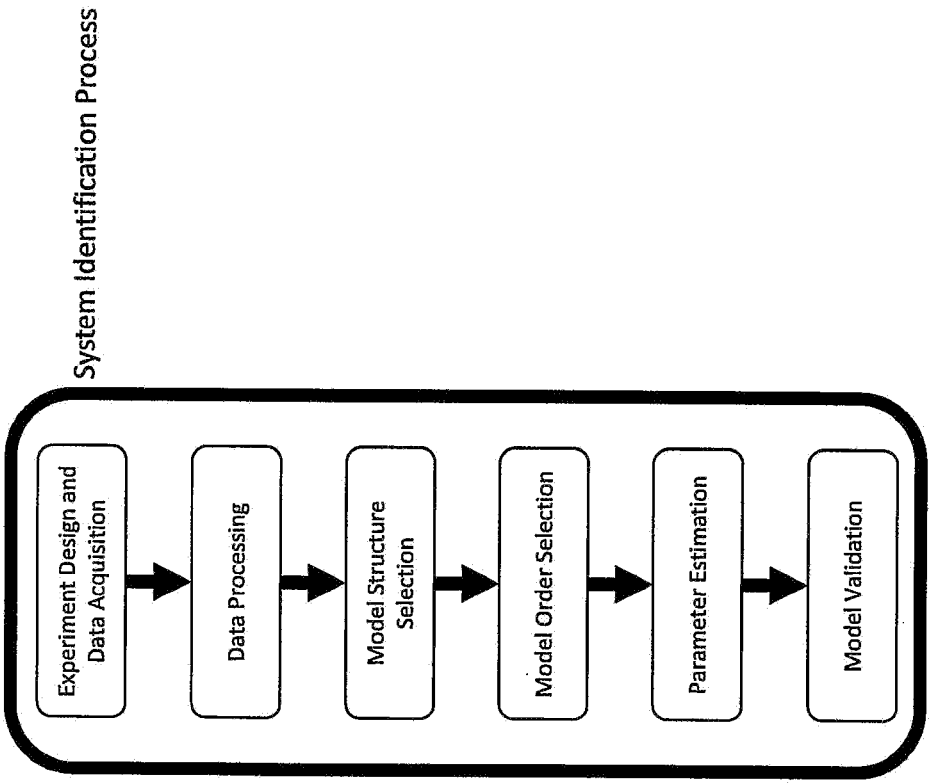

System Identification Process
Experiment Design and Data Acquisition
Data Processing
Model Structure Selection
Model Order Selection
Parameter Estimation
Model Validation

FIG. 121

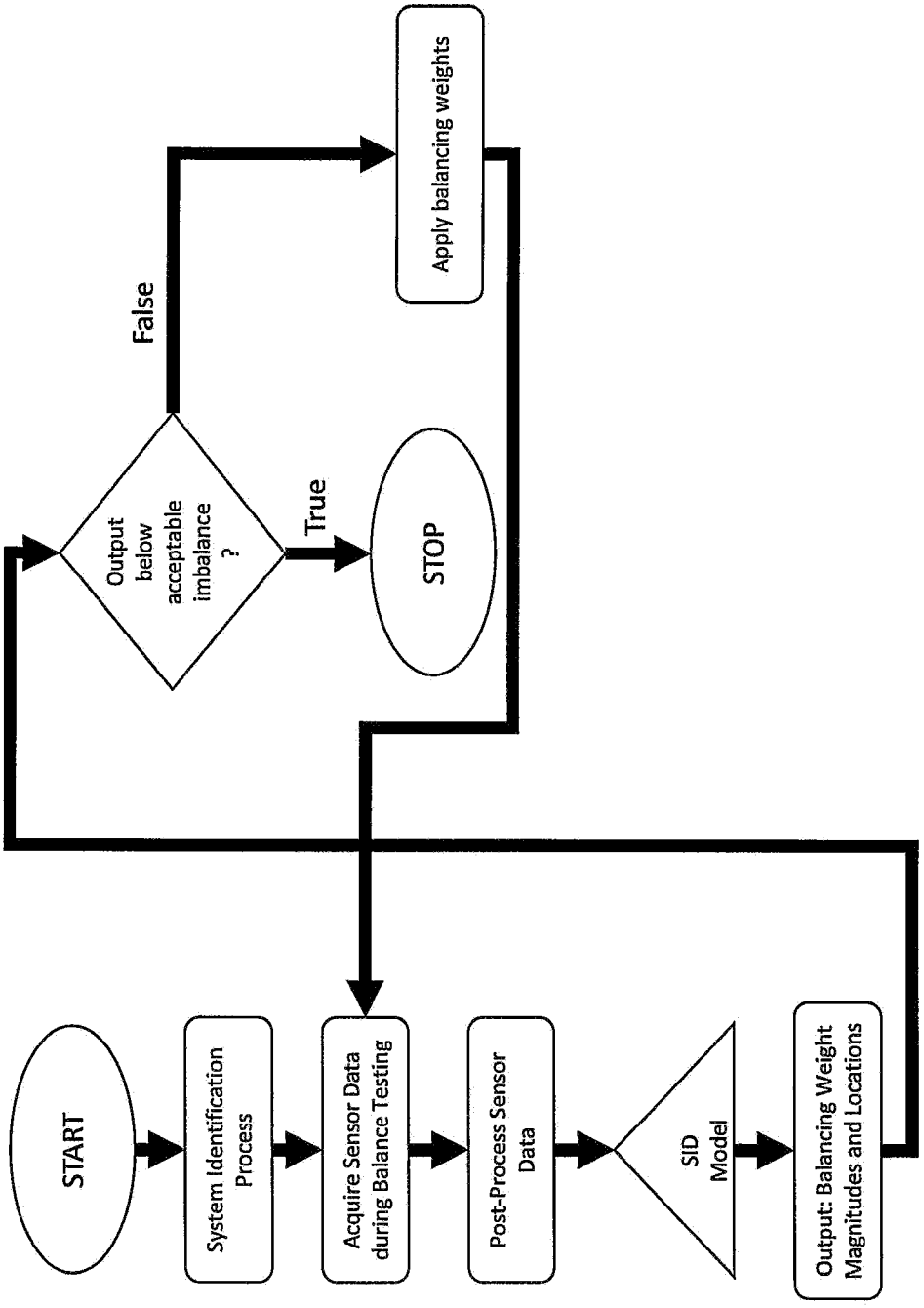

START
System Identification Process
Acquire Sensor Data during Balance Testing
Post-Process Sensor Data
SID Model
Output: Balancing Weight Magnitudes and Locations
Output below acceptable imbalance ?
False
True
Apply balancing weights
STOP

FIG. 122

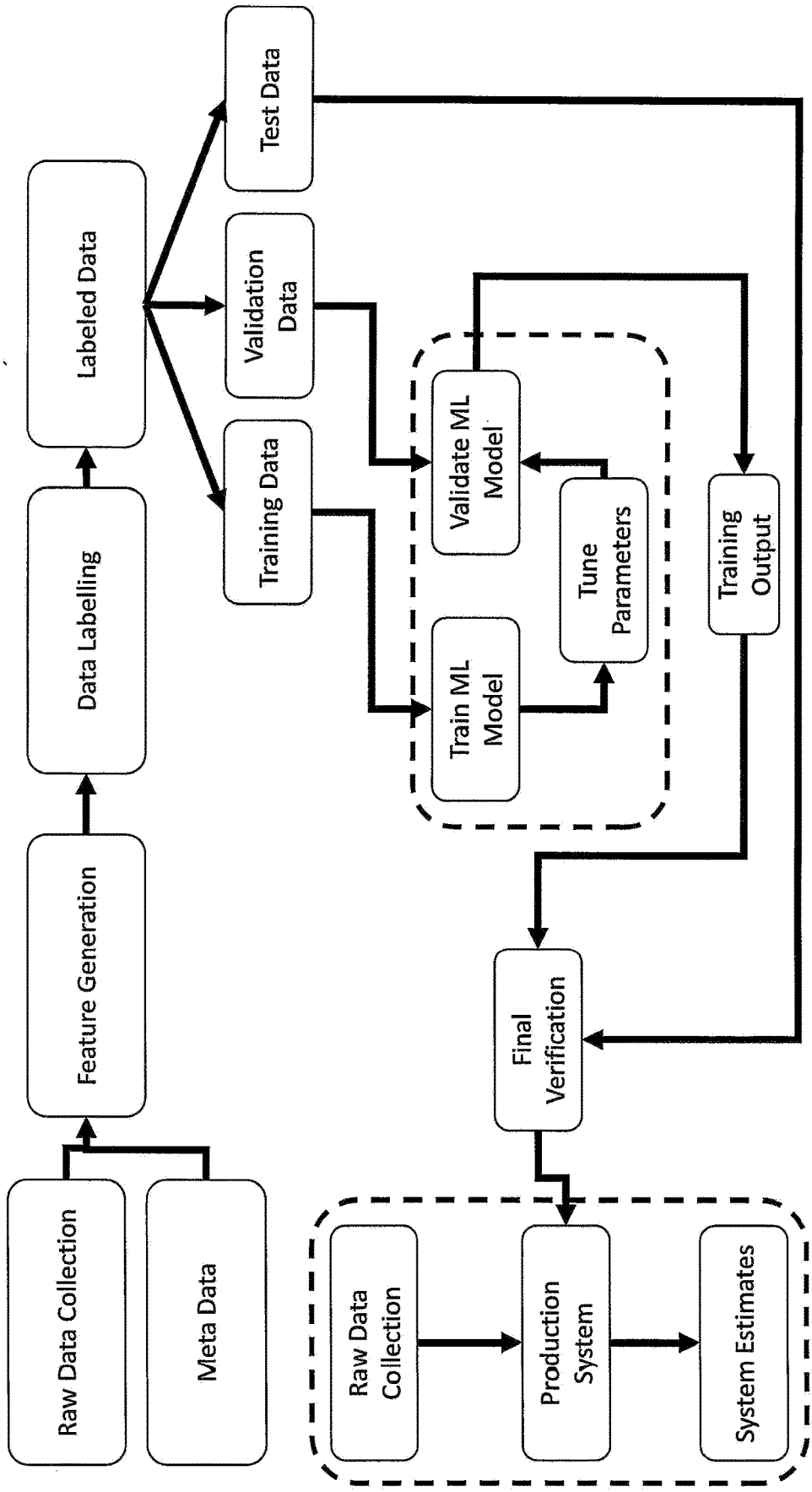

Raw Data Collection
Meta Data
Feature Generation
Data Labelling
Labeled Data
Test Data
Validation Data
Training Data
Validate ML Model
Tune Parameters
Train ML Model
Training Output
Final Verification
Raw Data Collection
Production System
System Estimates

FIG. 123

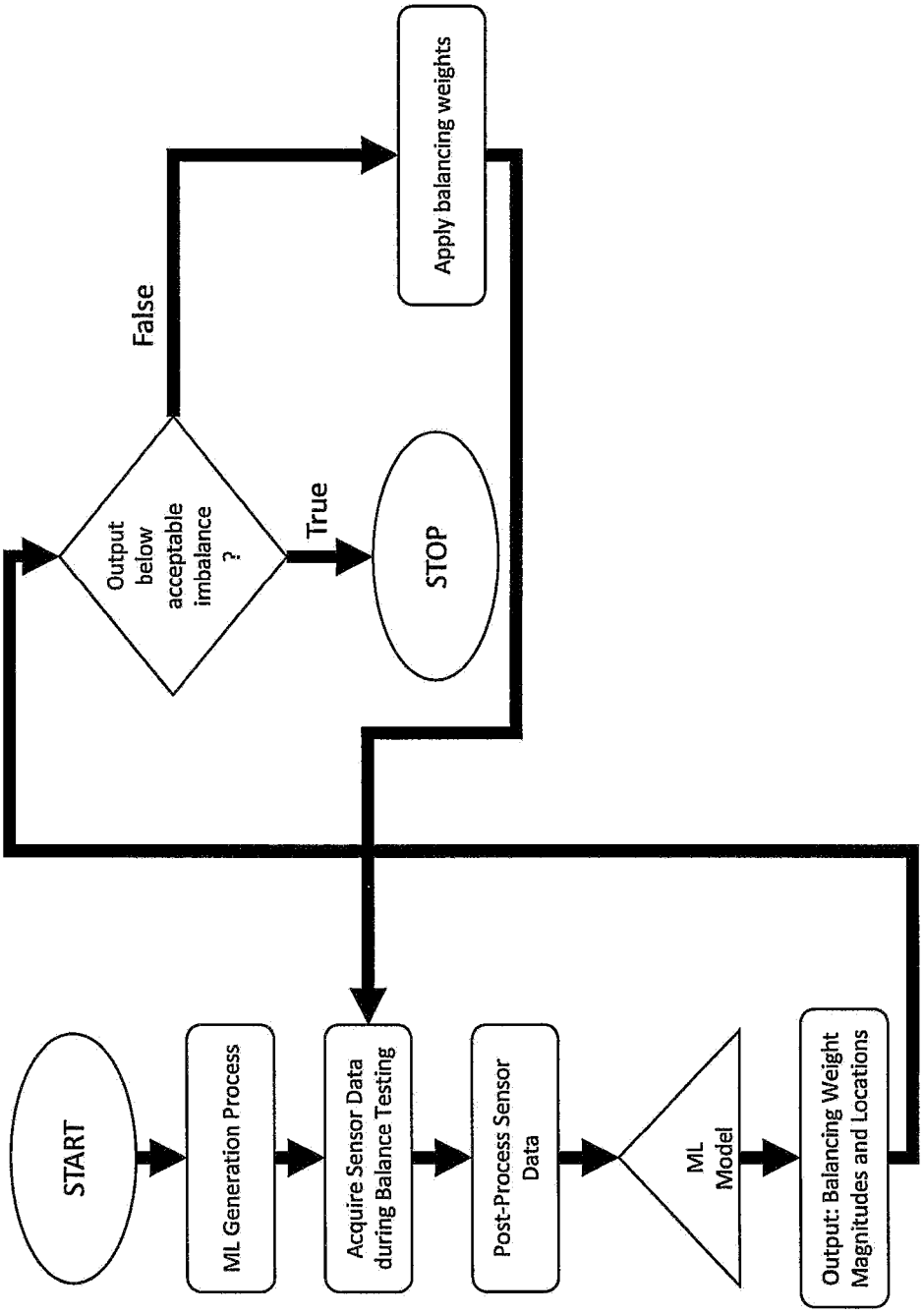

START
ML Generation Process
Acquire Sensor Data during Balance Testing
Post-Process Sensor Data
ML Model
Output: Balancing Weight Magnitudes and Locations
Output below acceptable imbalance ?
False
True
Apply balancing weights
STOP

FIG. 124

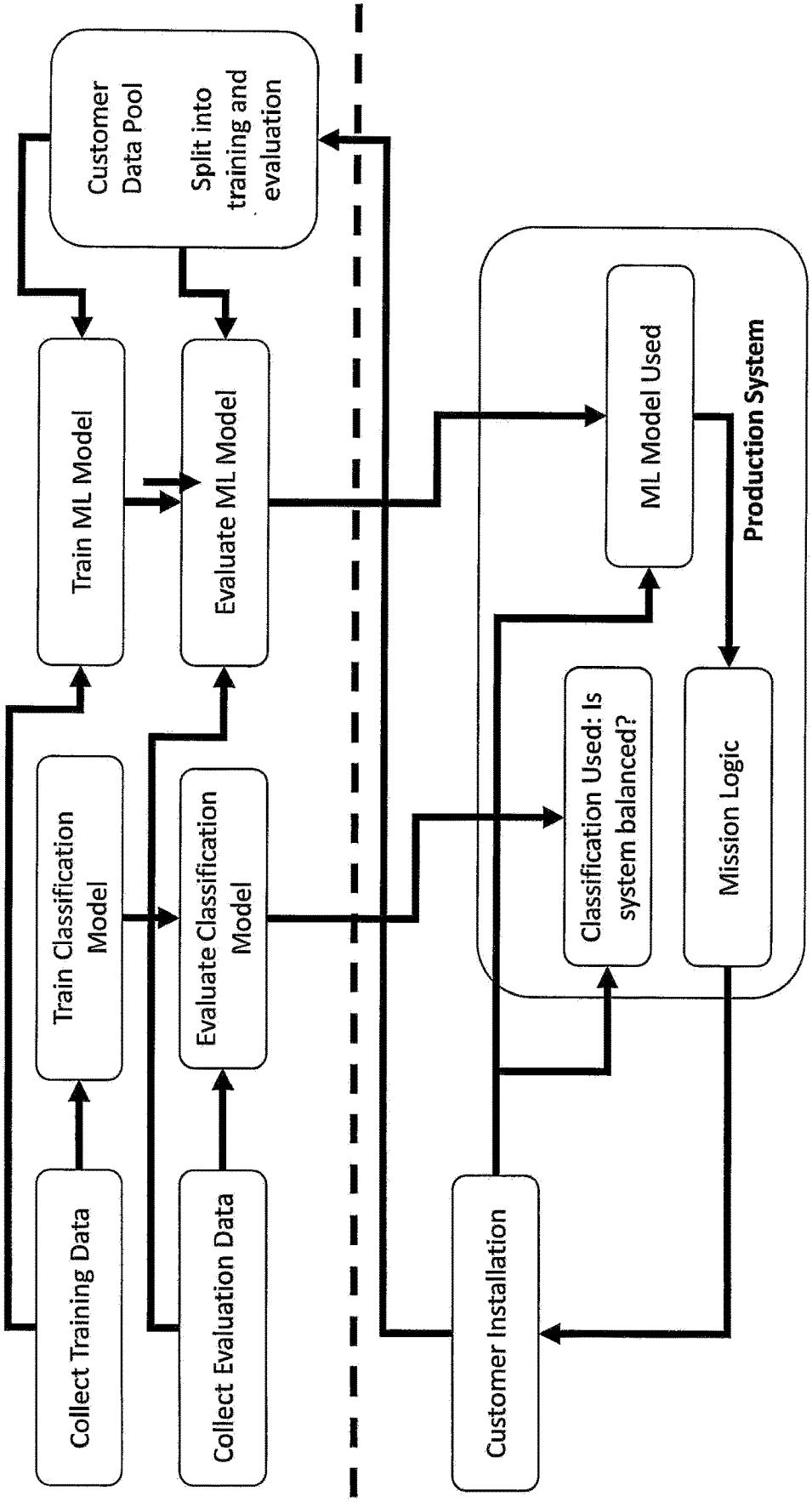

Customer Data Pool
Split into training and evaluation
Train ML Model
Evaluate ML Model
ML Model Used
Production System
Train Classification Model
Evaluate Classification Model
Classification Used: Is system balanced?
Mission Logic
Collect Training Data
Collect Evaluation Data
Customer Installation

FIG. 125

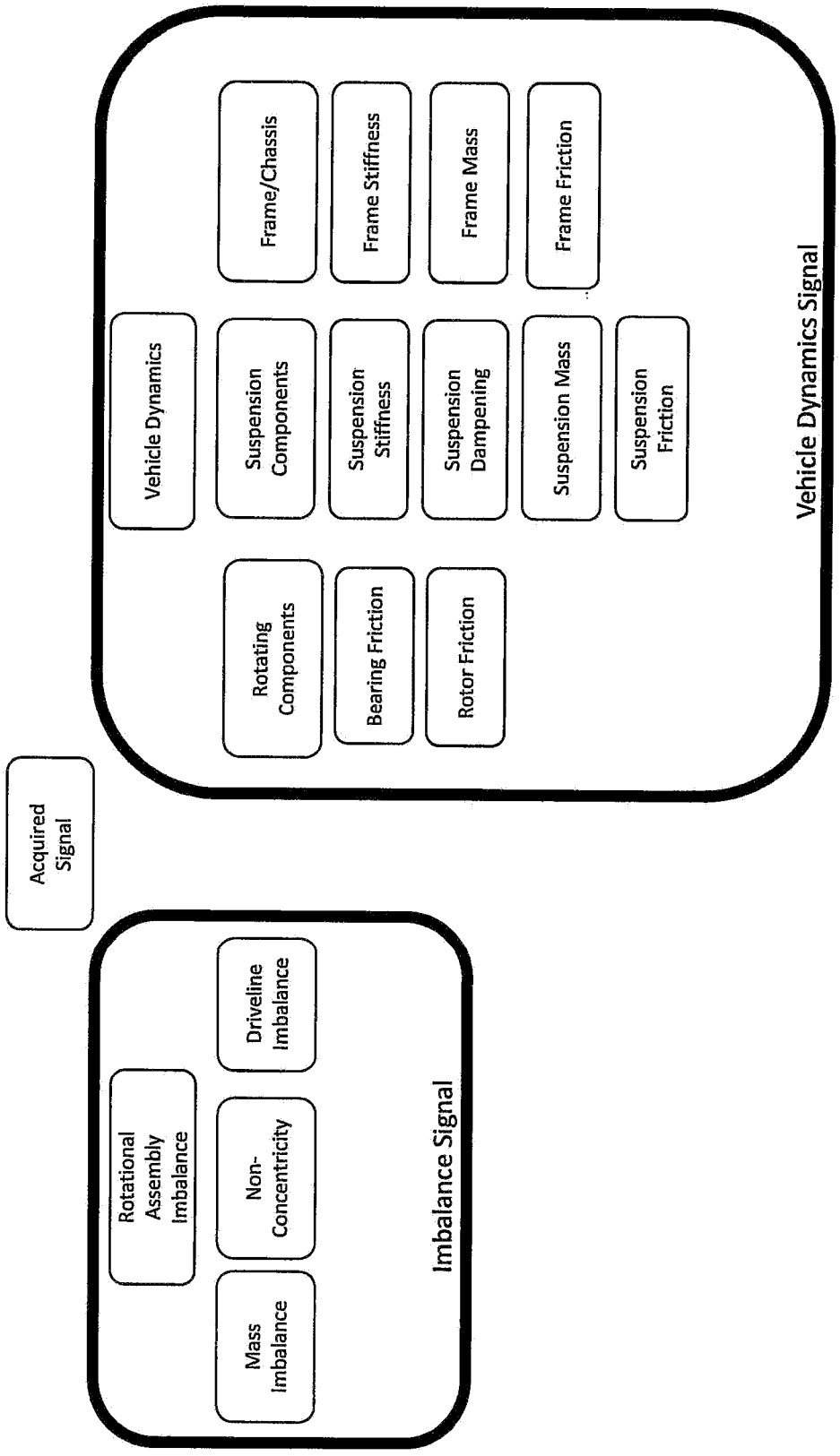

Acquired Signal
Imbalance Signal
Mass Imbalance
Non-Concentricity
Rotational Assembly Imbalance
Driveline Imbalance
Vehicle Dynamics Signal
Vehicle Dynamics
Suspension Components
Suspension Stiffness
Suspension Dampening
Suspension Mass
Suspension Friction
Frame/Chassis
Frame Stiffness
Frame Mass
Frame Friction
Rotating Components
Bearing Friction
Rotor Friction

FIG. 126

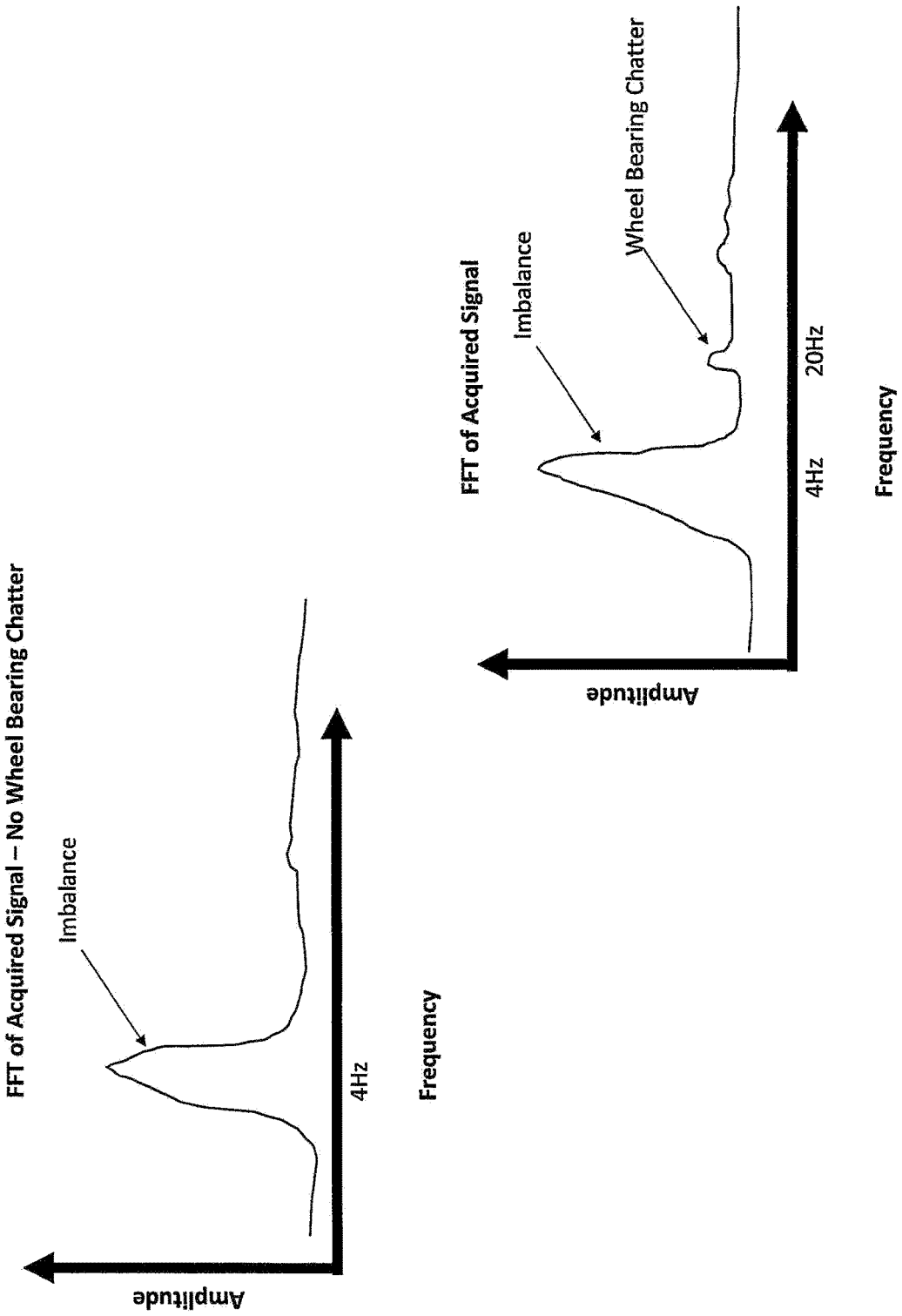

FFT of Acquired Signal – No Wheel Bearing Chatter
Imbalance
4Hz
Frequency
Amplitude
FFT of Acquired Signal
Imbalance
Wheel Bearing Chatter
4Hz
20Hz
Frequency
Amplitude

FIG. 127

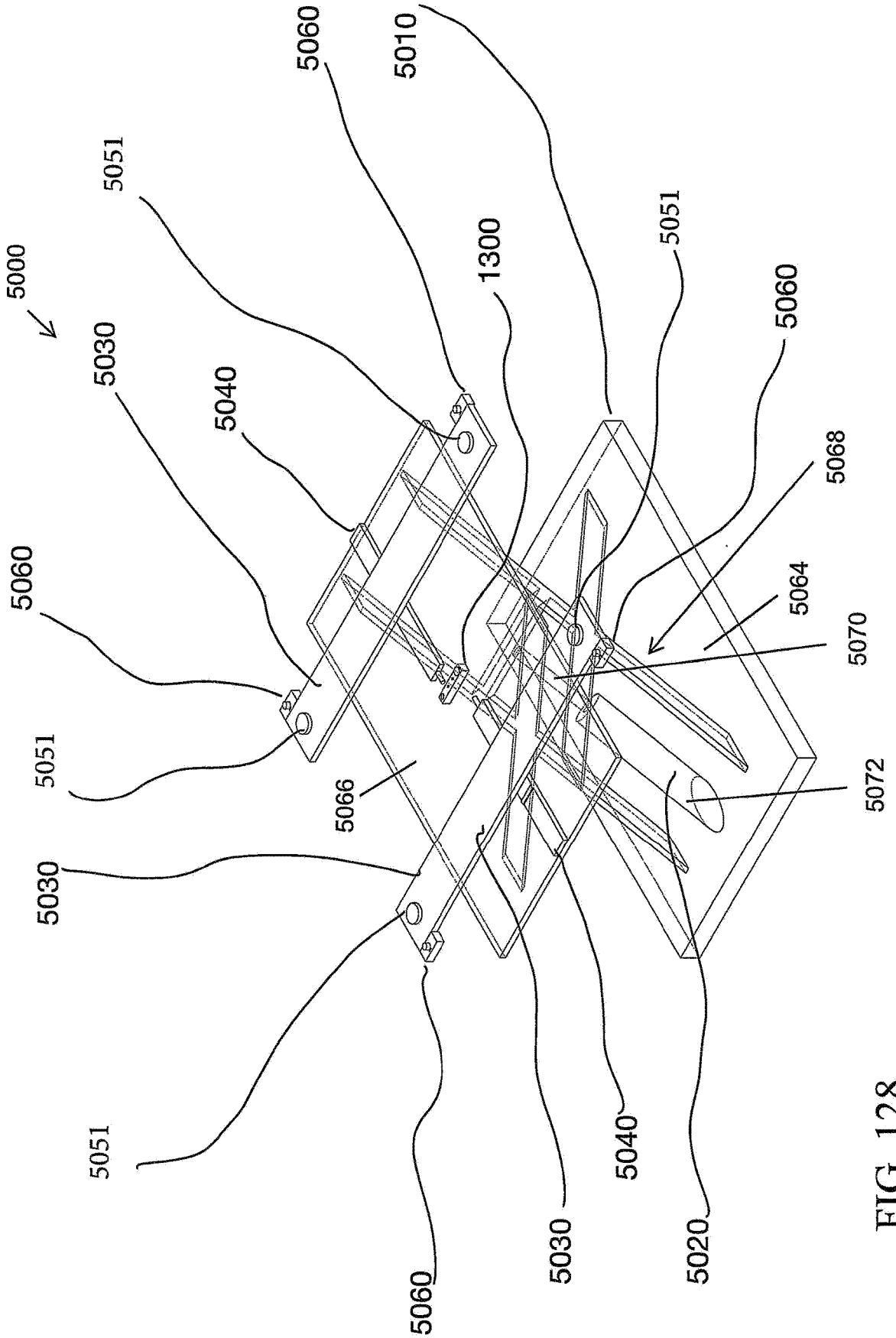

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5066
5030
5051

FIG. 128

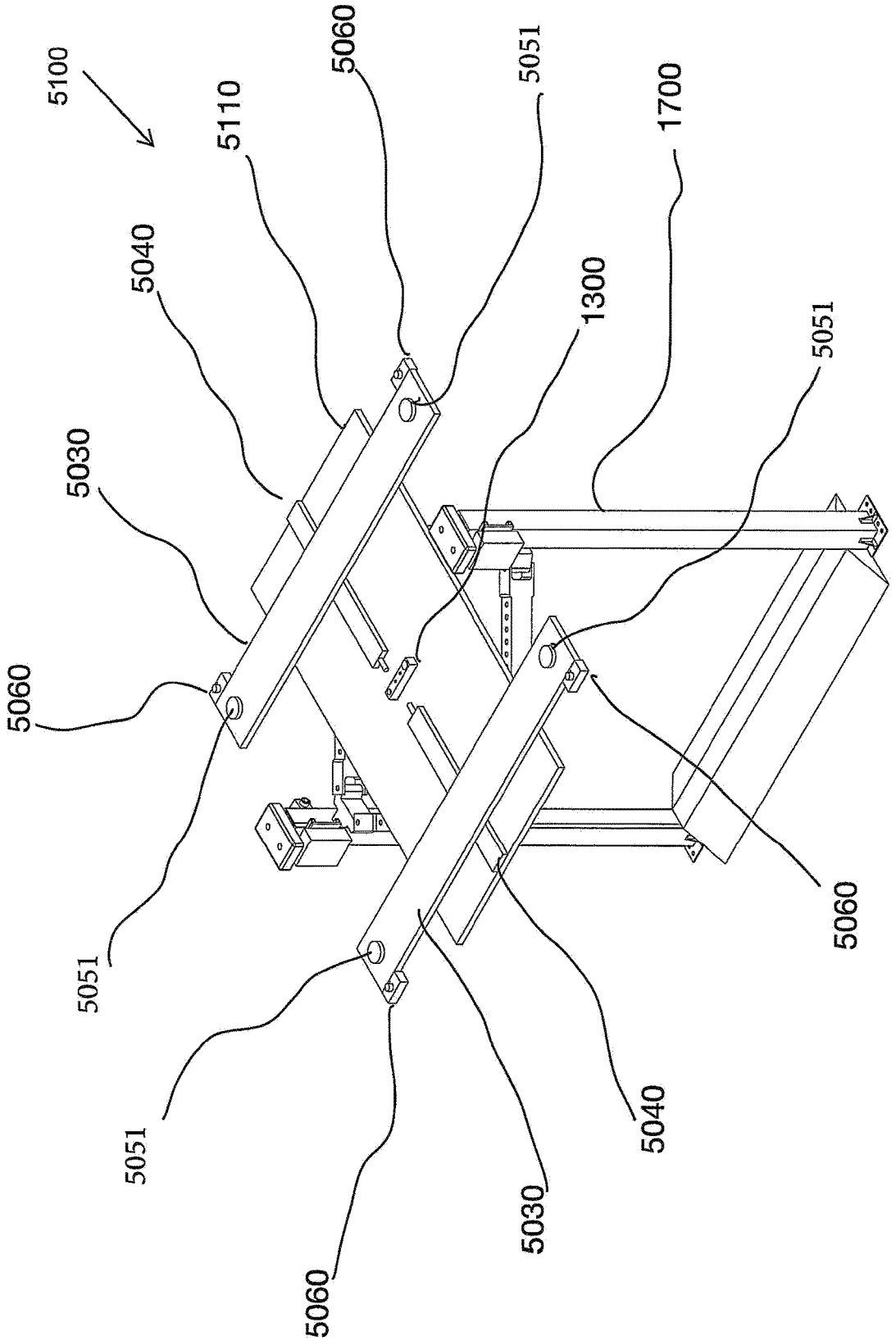

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5051
5060
5051
5040
5030
5060

FIG. 129

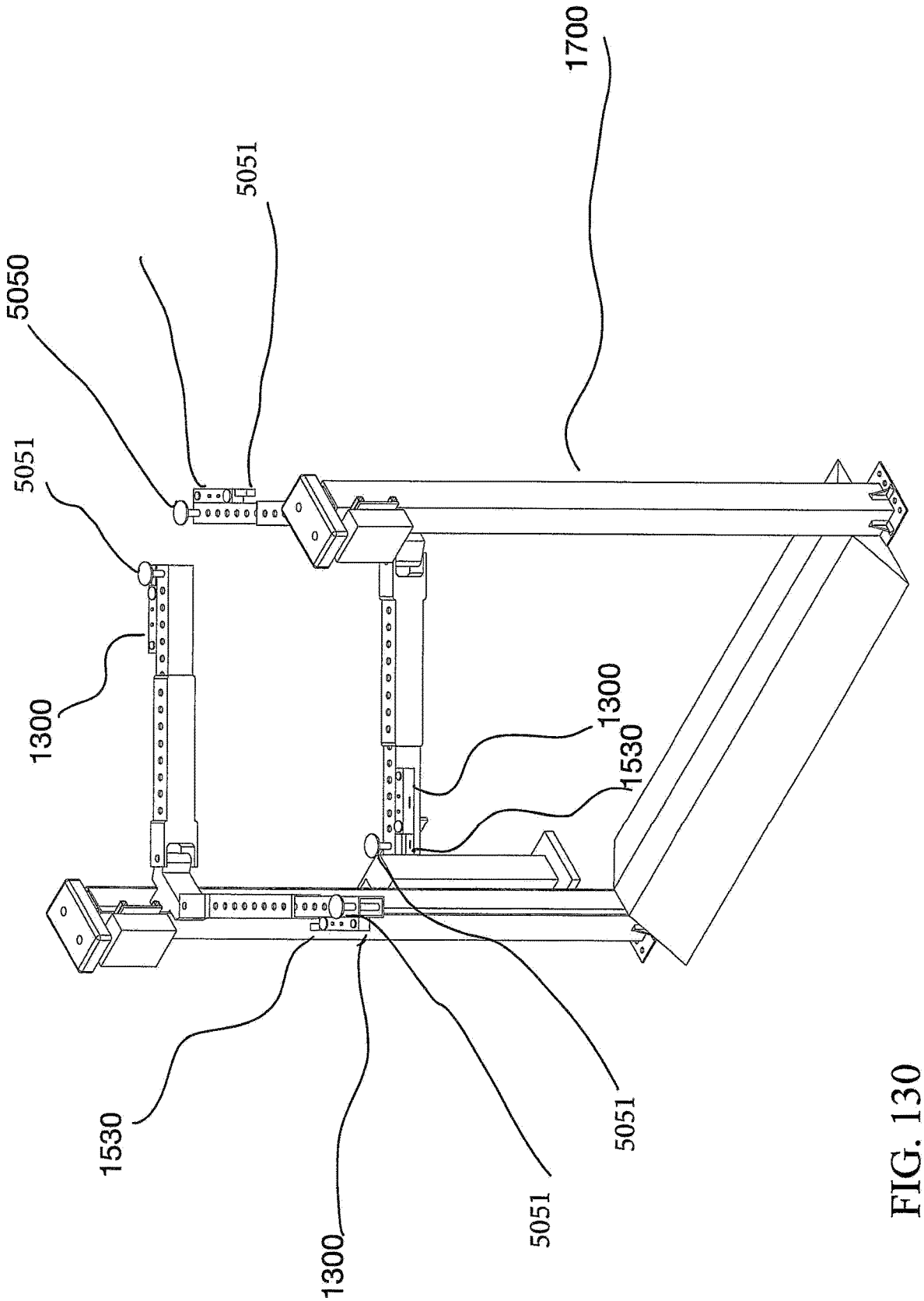


FIG. 130

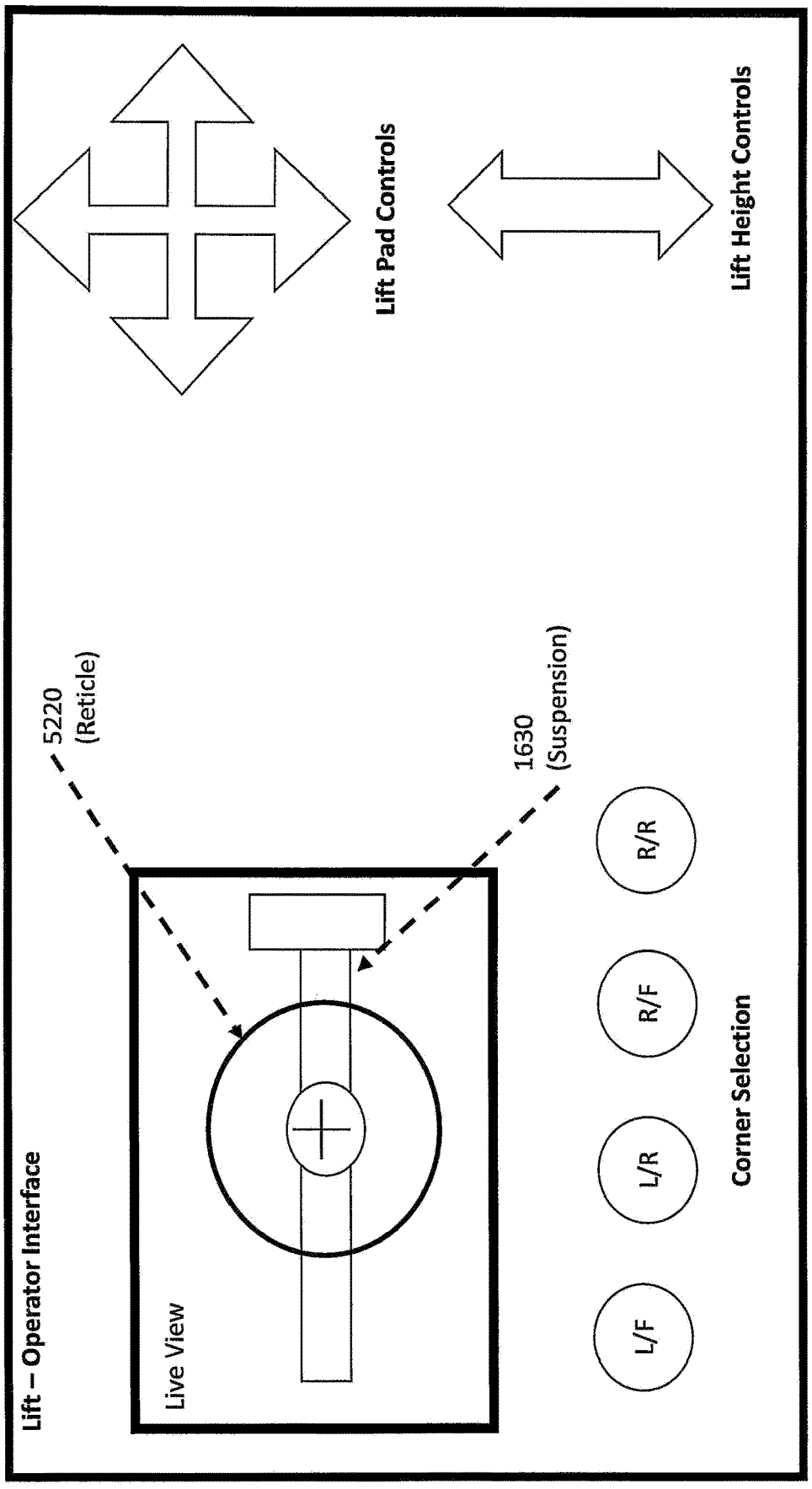

Lift – Operator Interface
Lift Pad Controls
Lift Height Controls
5220
(Reticle)
1630
(Suspension)
Live View
L/F
L/R
R/F
R/R
Corner Selection

FIG. 131

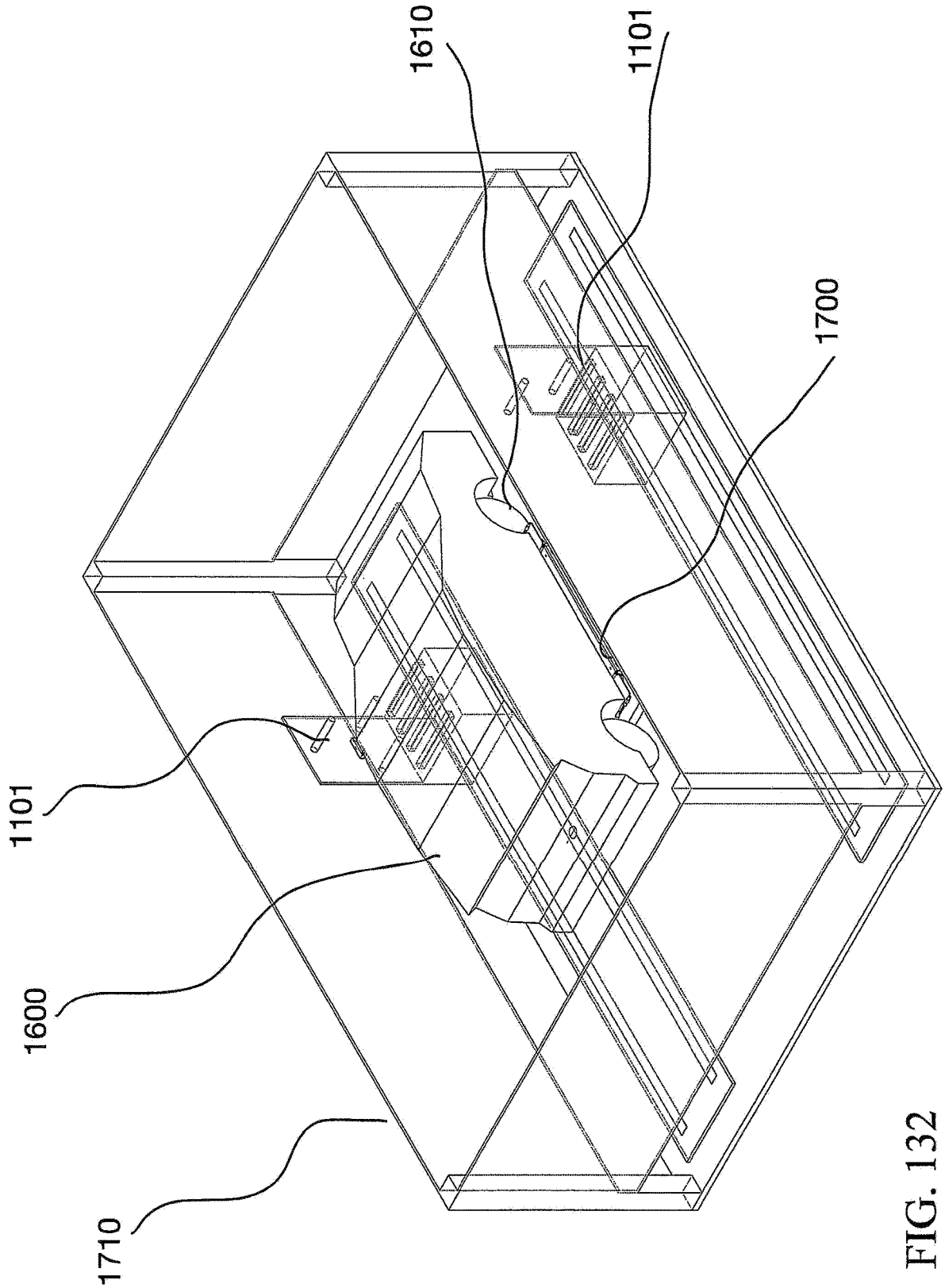


FIG. 132

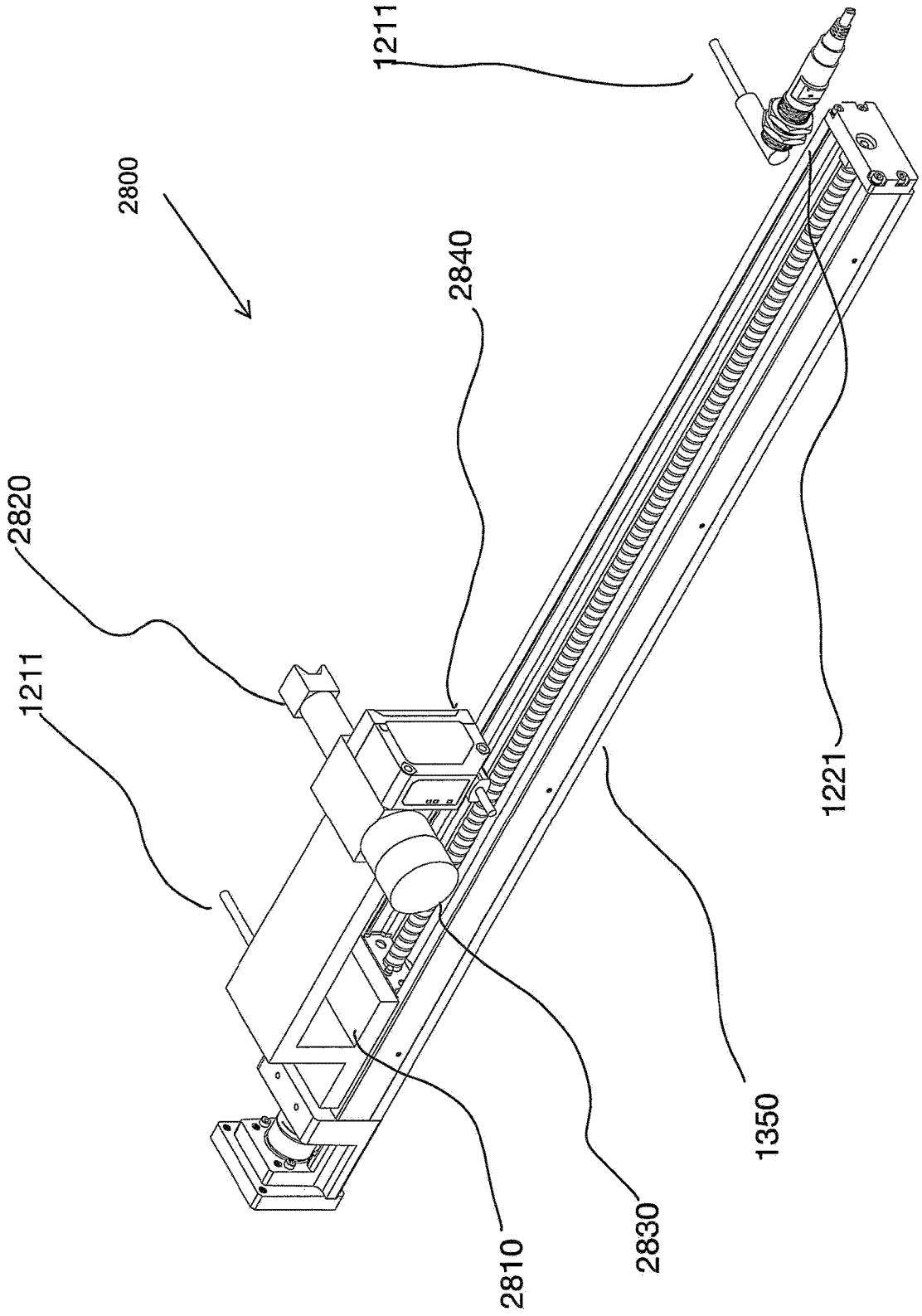


FIG. 133

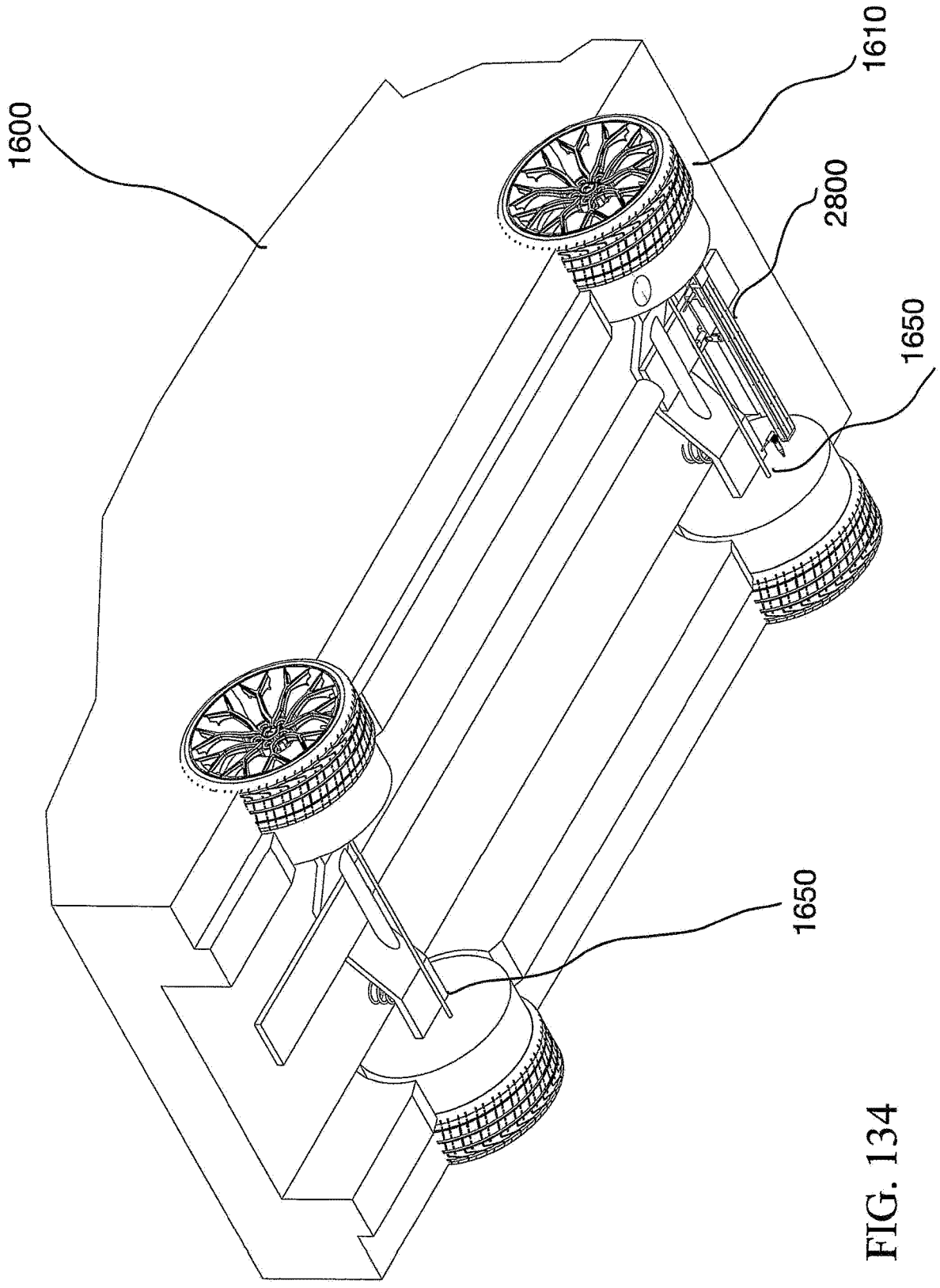


FIG. 134

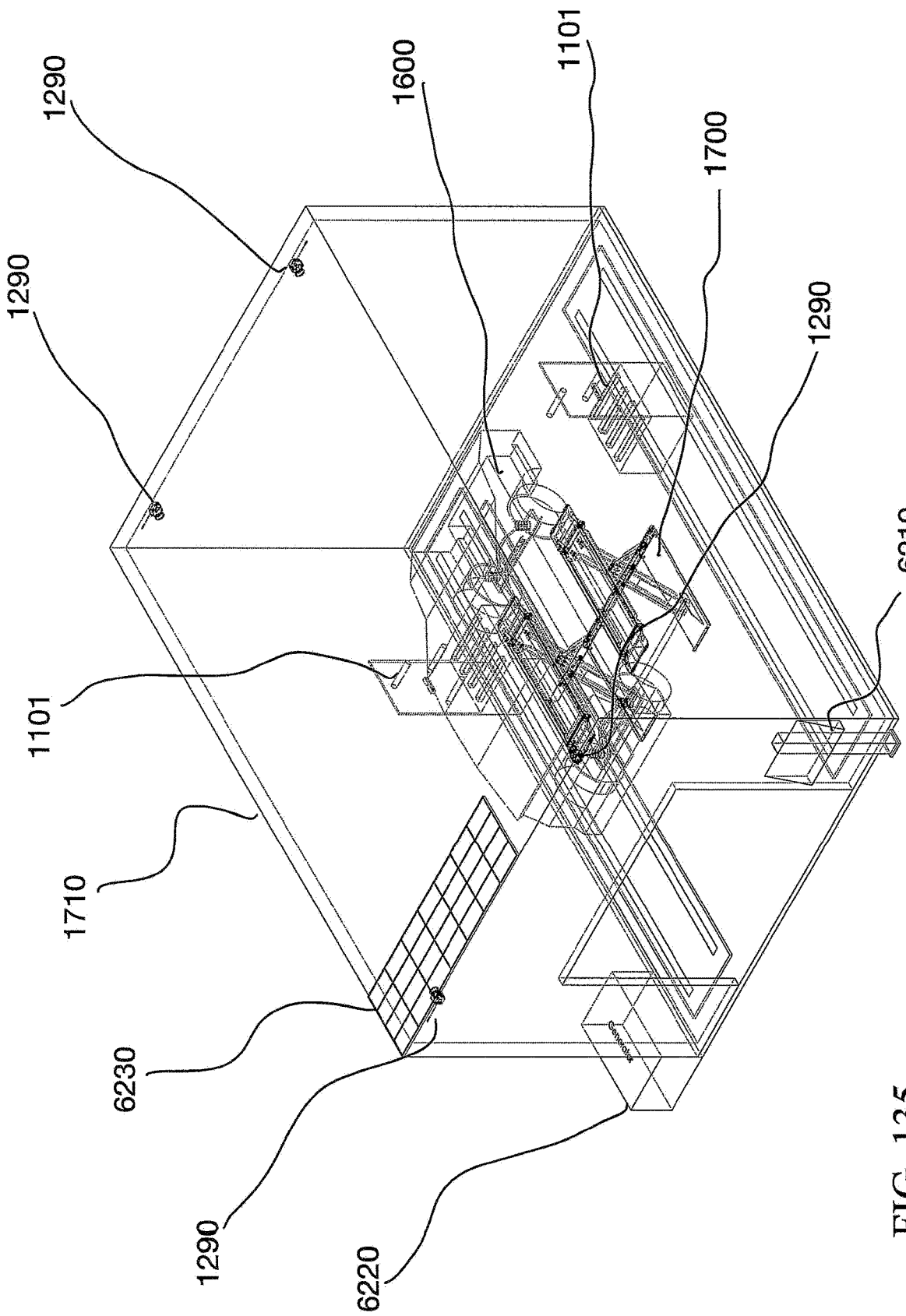


FIG. 135

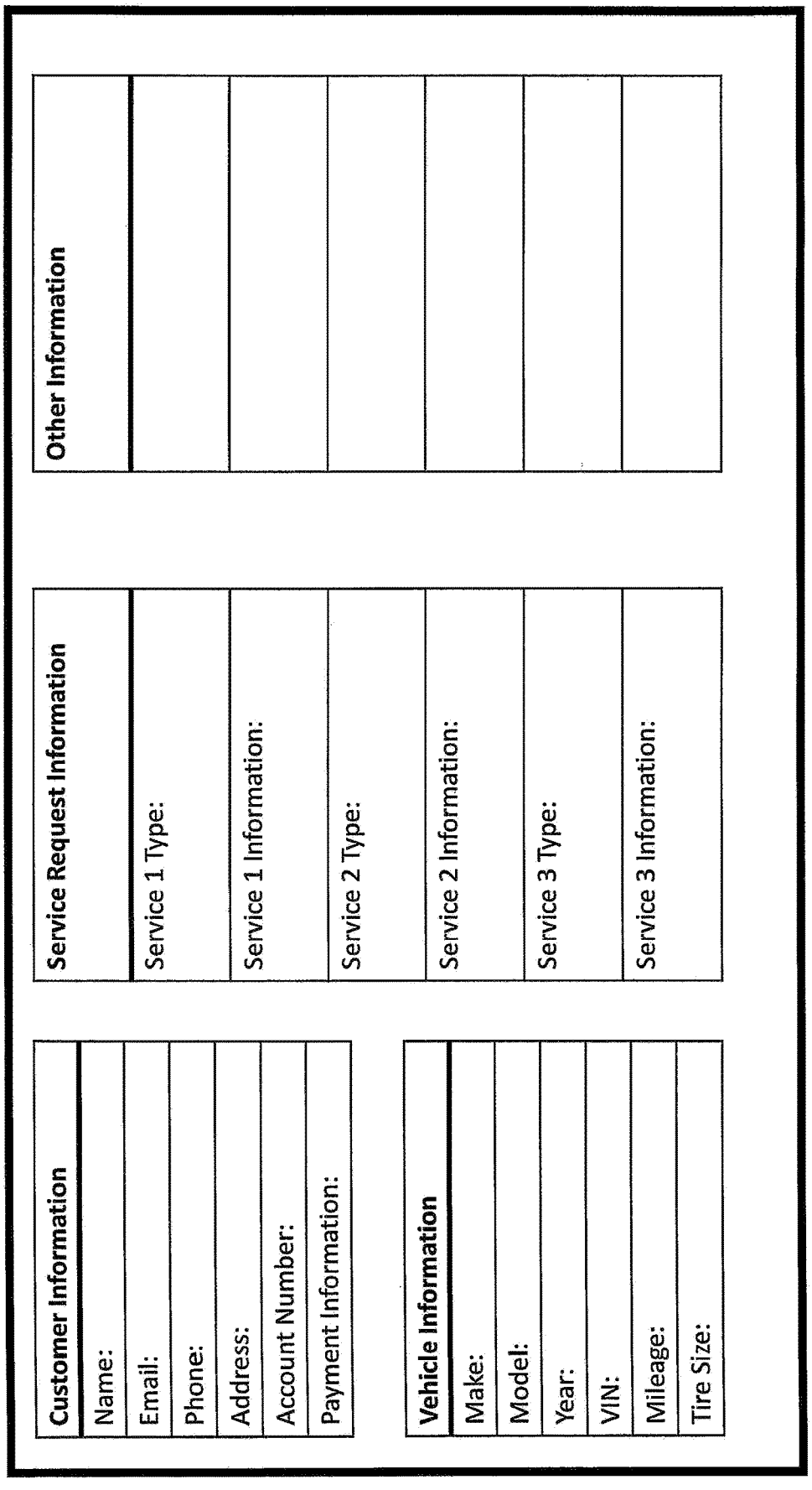

Customer Information
Name:
Email:
Phone:
Address:
Account Number:
Payment Information:
Vehicle Information
Make:
Model:
Year:
VIN:
Mileage:
Tire Size:
Service Request Information
Service 1 Type:
Service 1 Information:
Service 2 Type:
Service 2 Information:
Service 3 Type:
Service 3 Information:
Other Information

FIG. 136

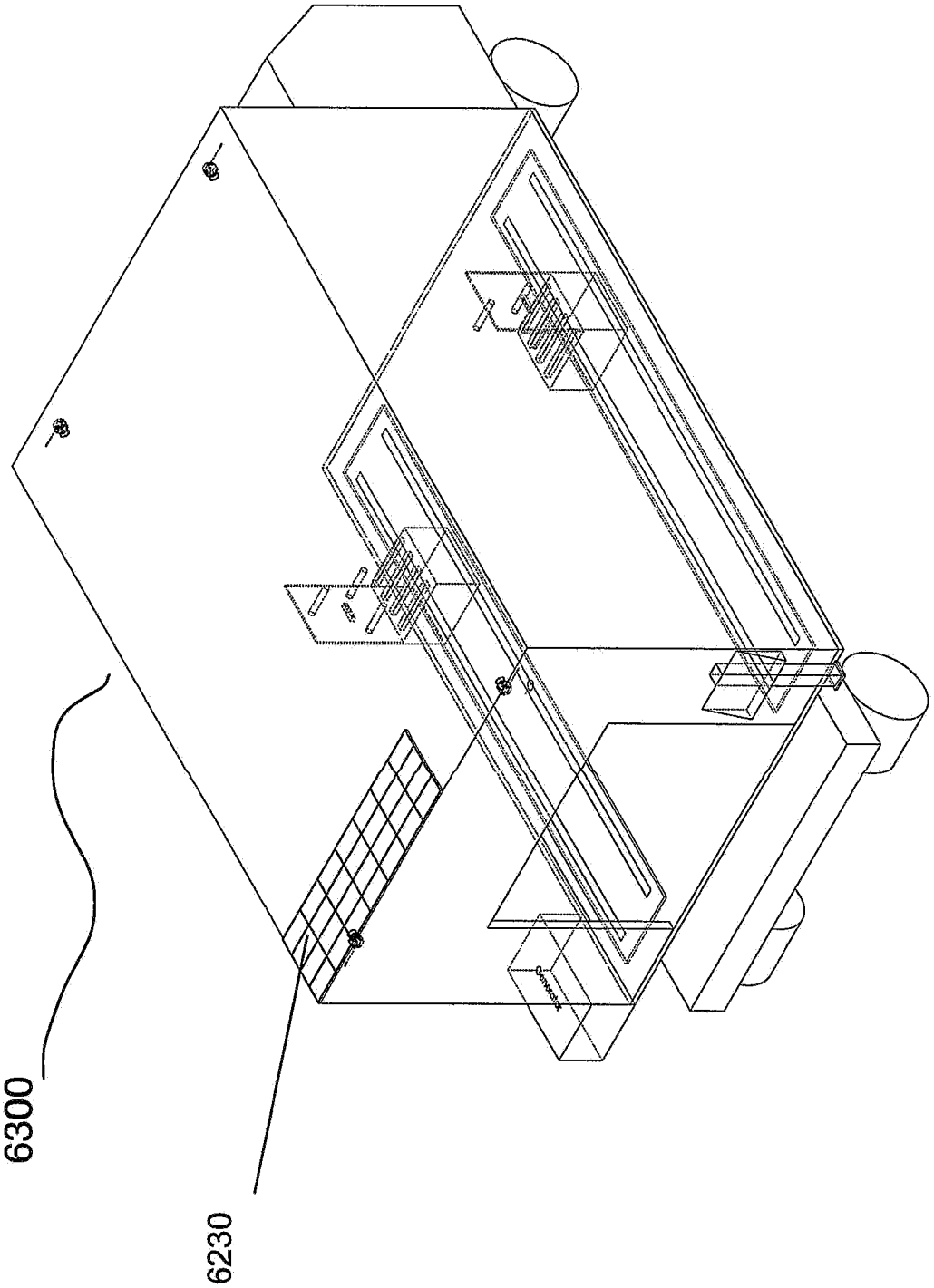


FIG. 137

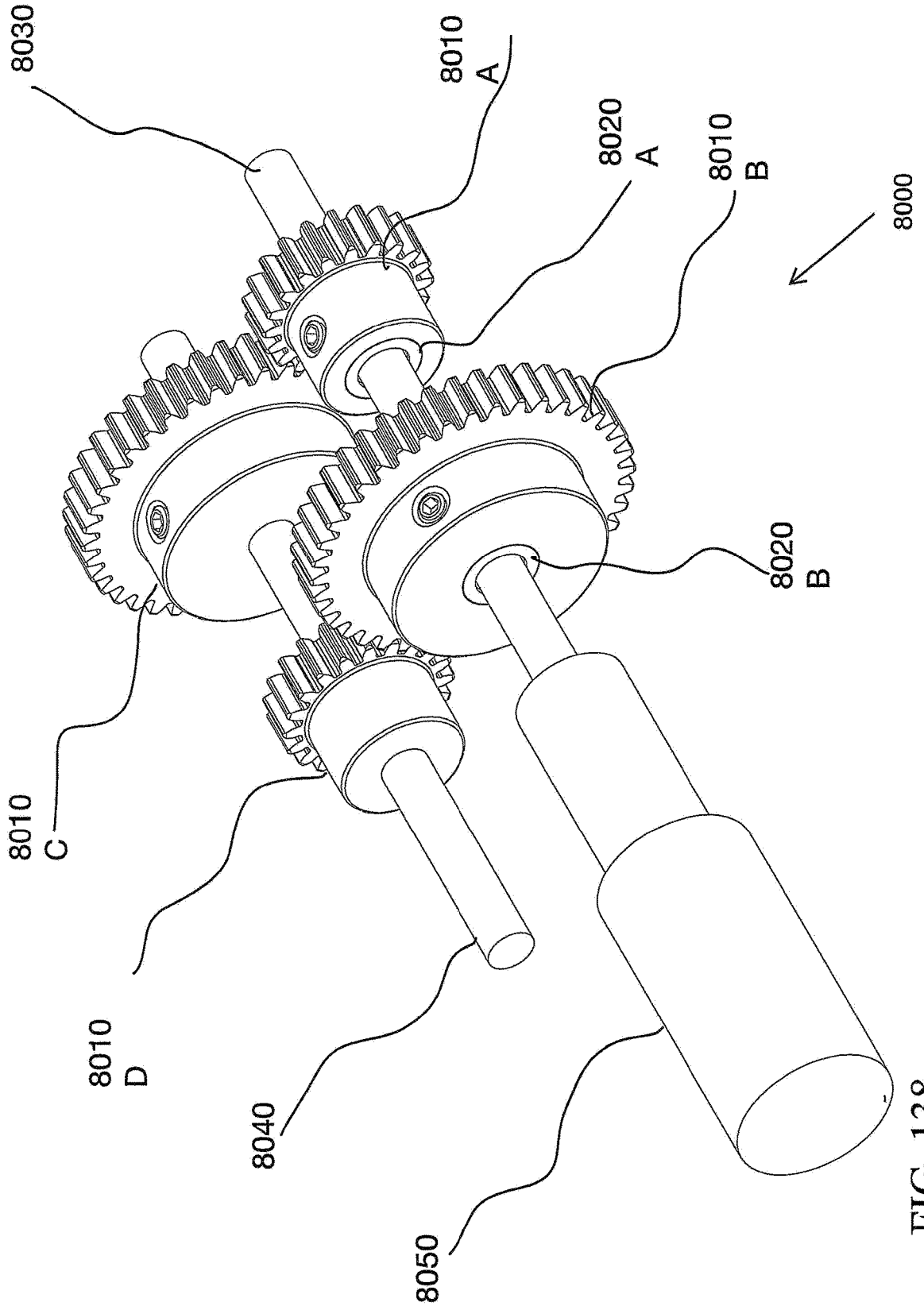


FIG. 138

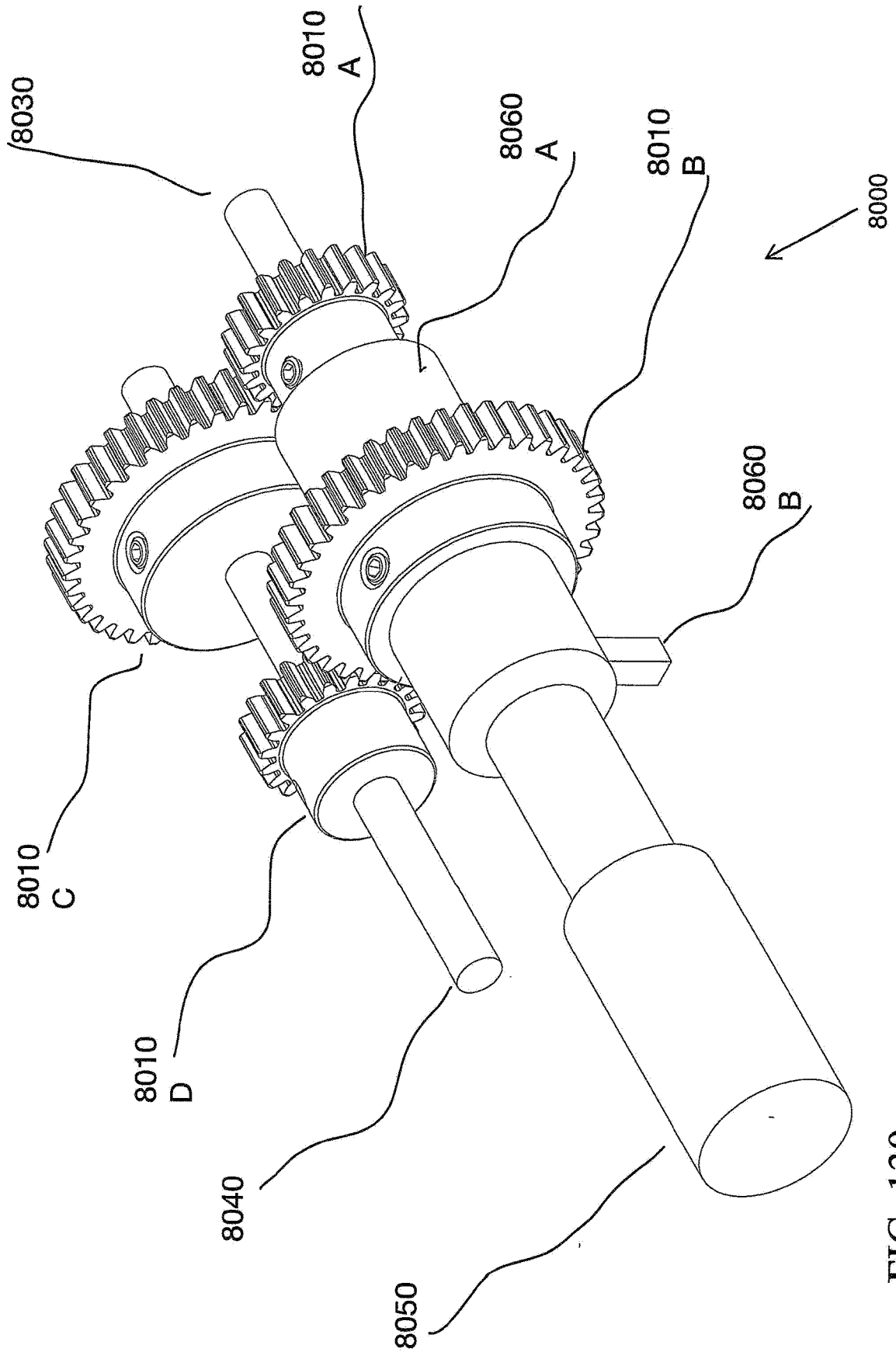


FIG. 139

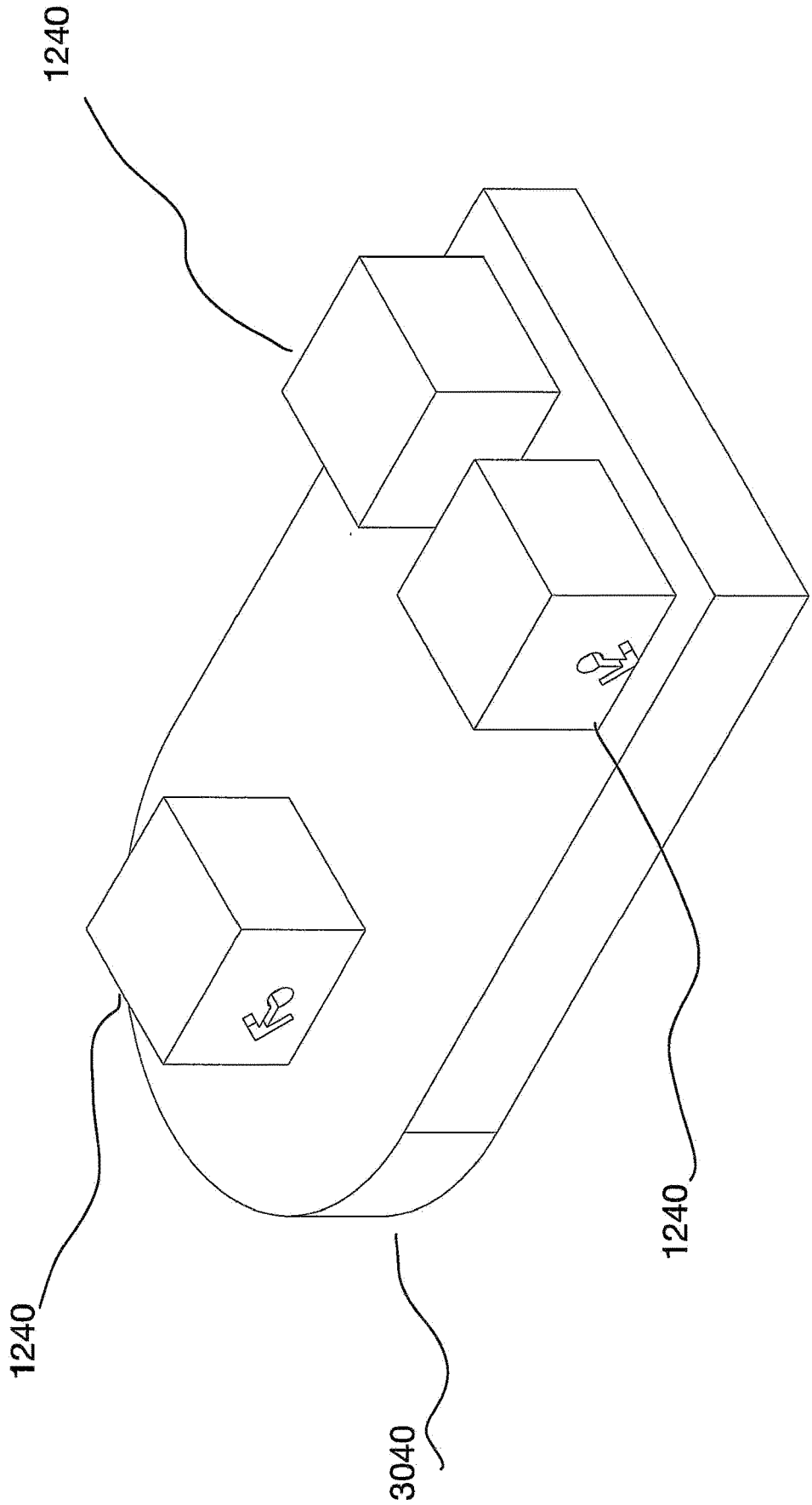


FIG. 140

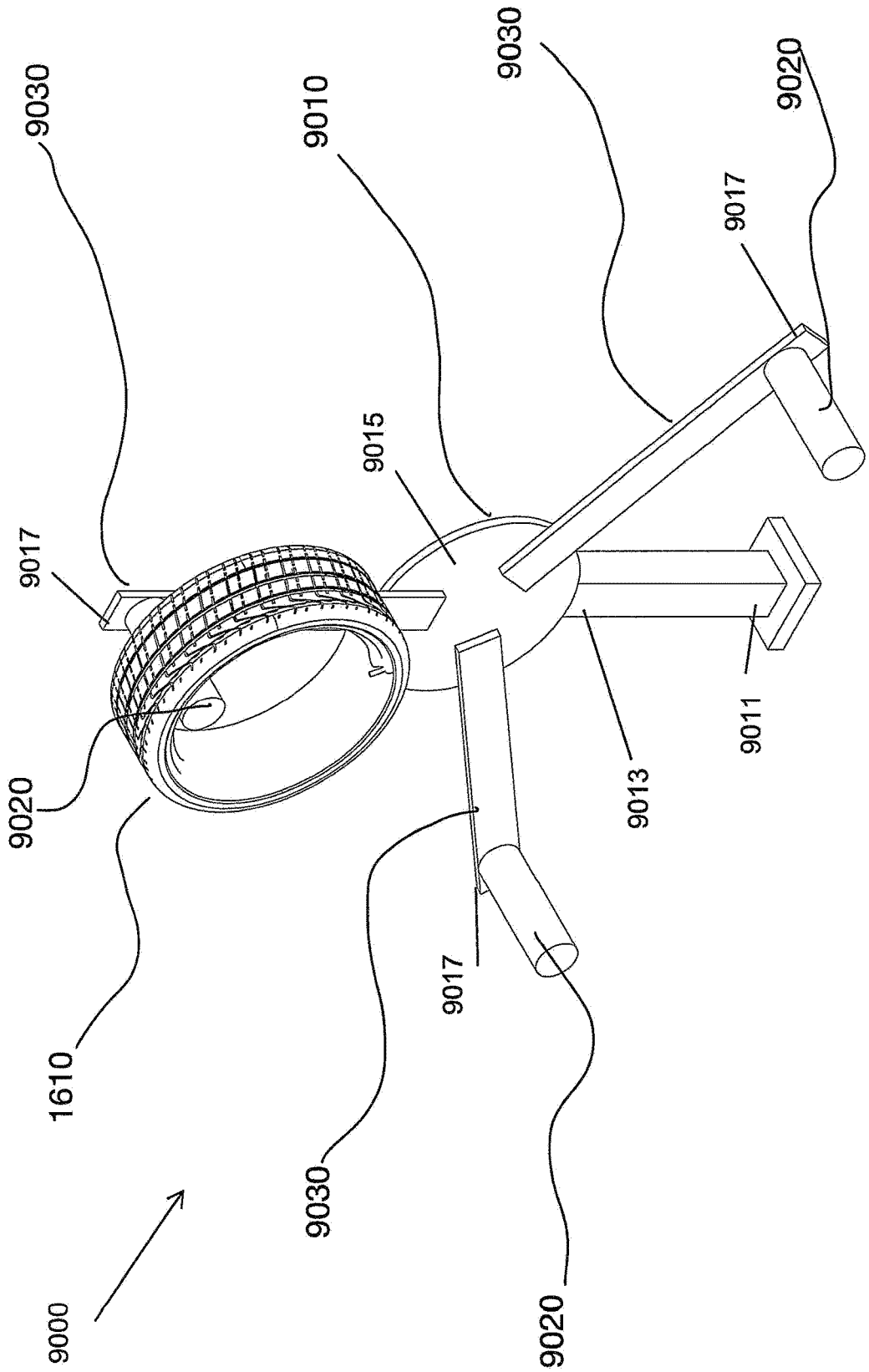

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9015
9017
9020
9013
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FIG. 141

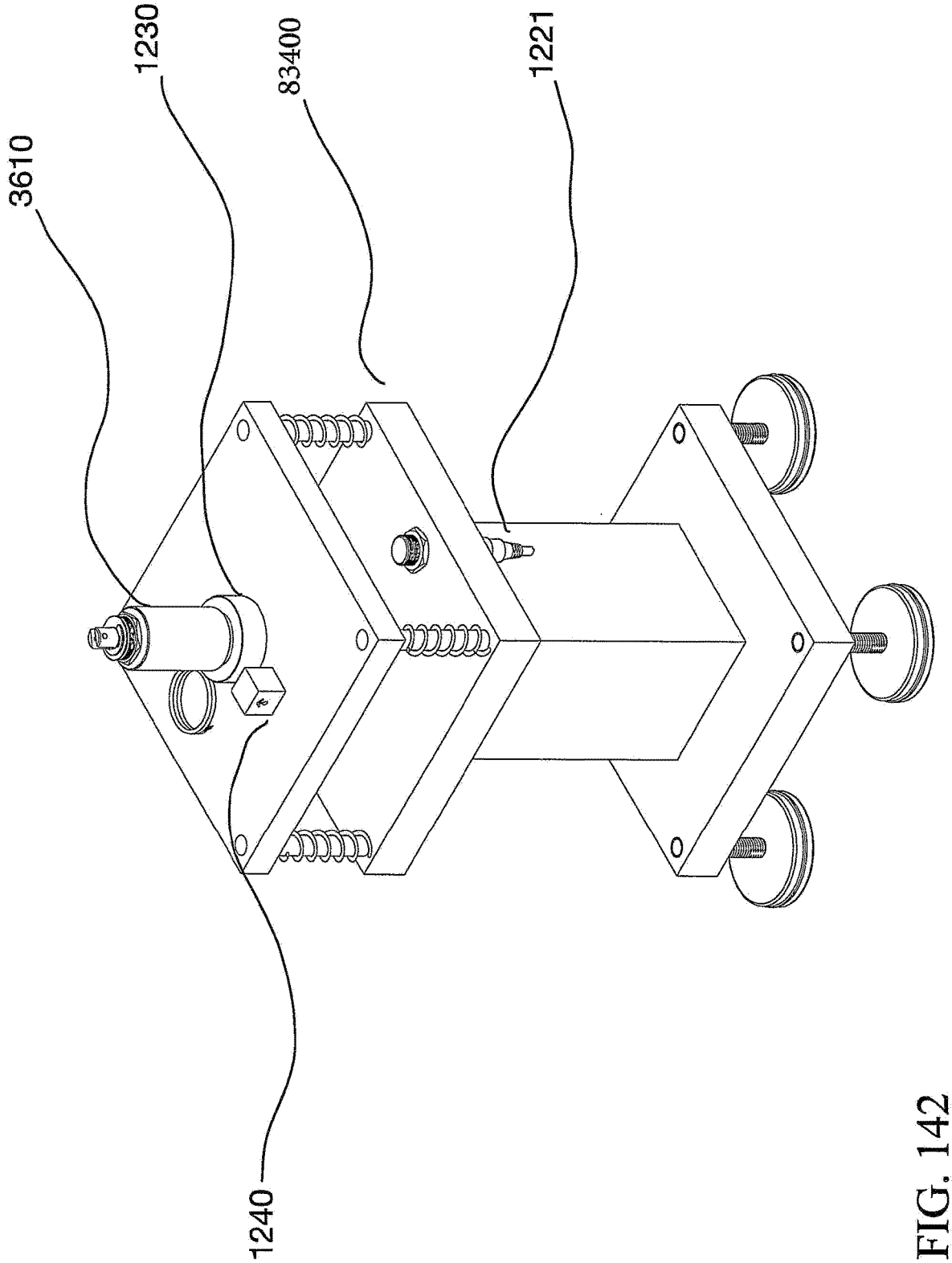


FIG. 142

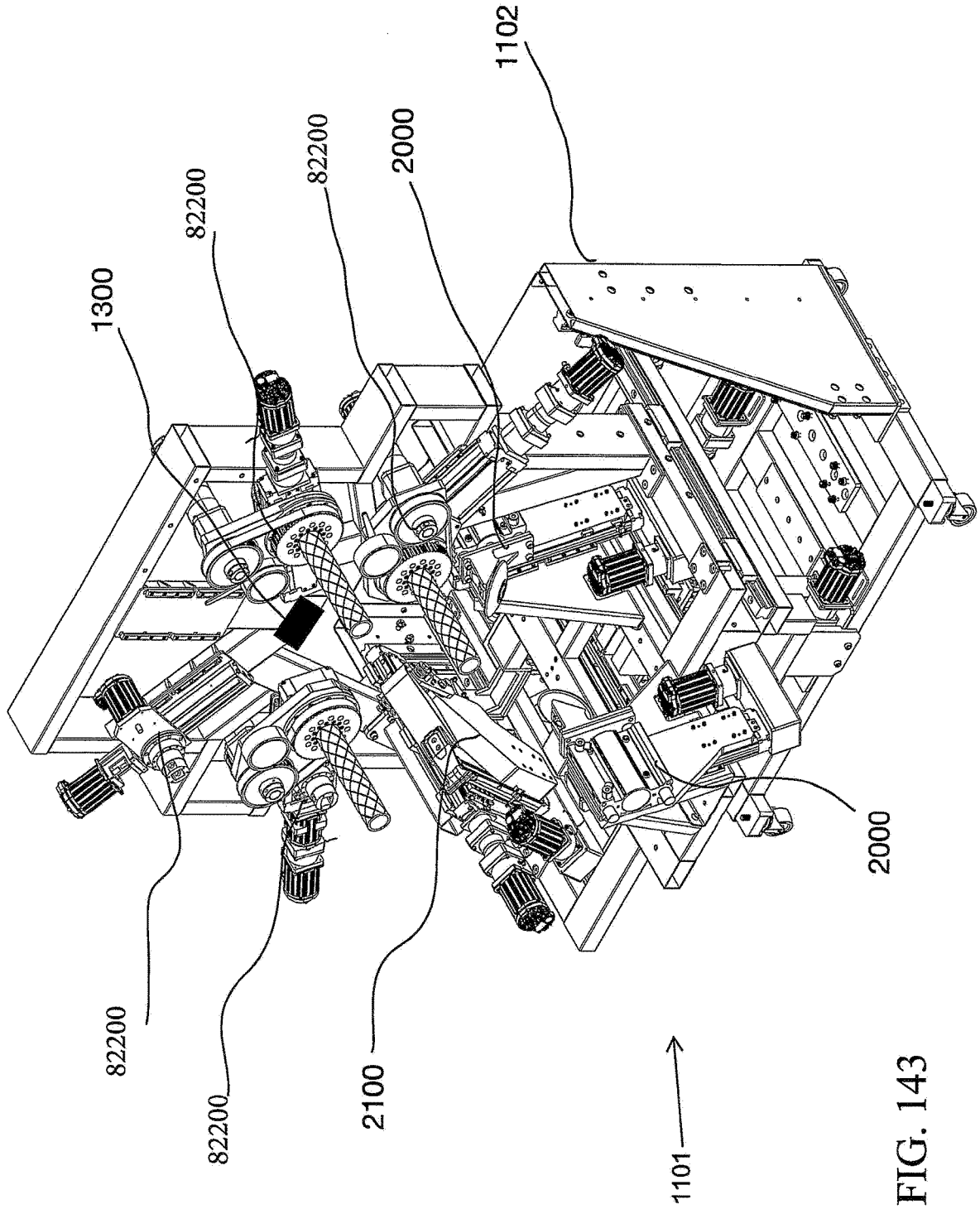


FIG. 143

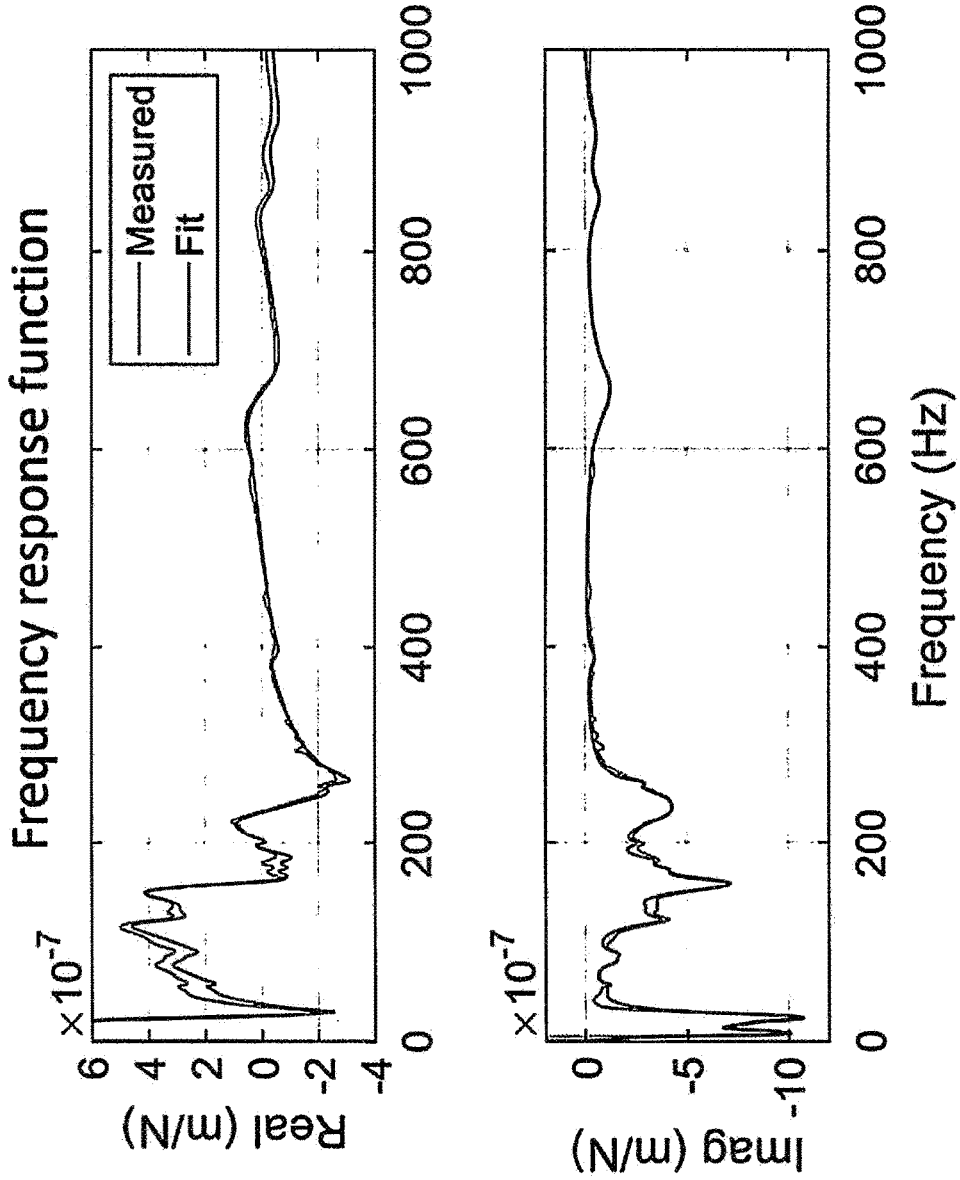

Frequency response function
Measured
Fit
Real (m/N)
Imag (m/N)
×10^-7
6
4
2
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-4
-5
-10
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Frequency (Hz)

FIG. 144

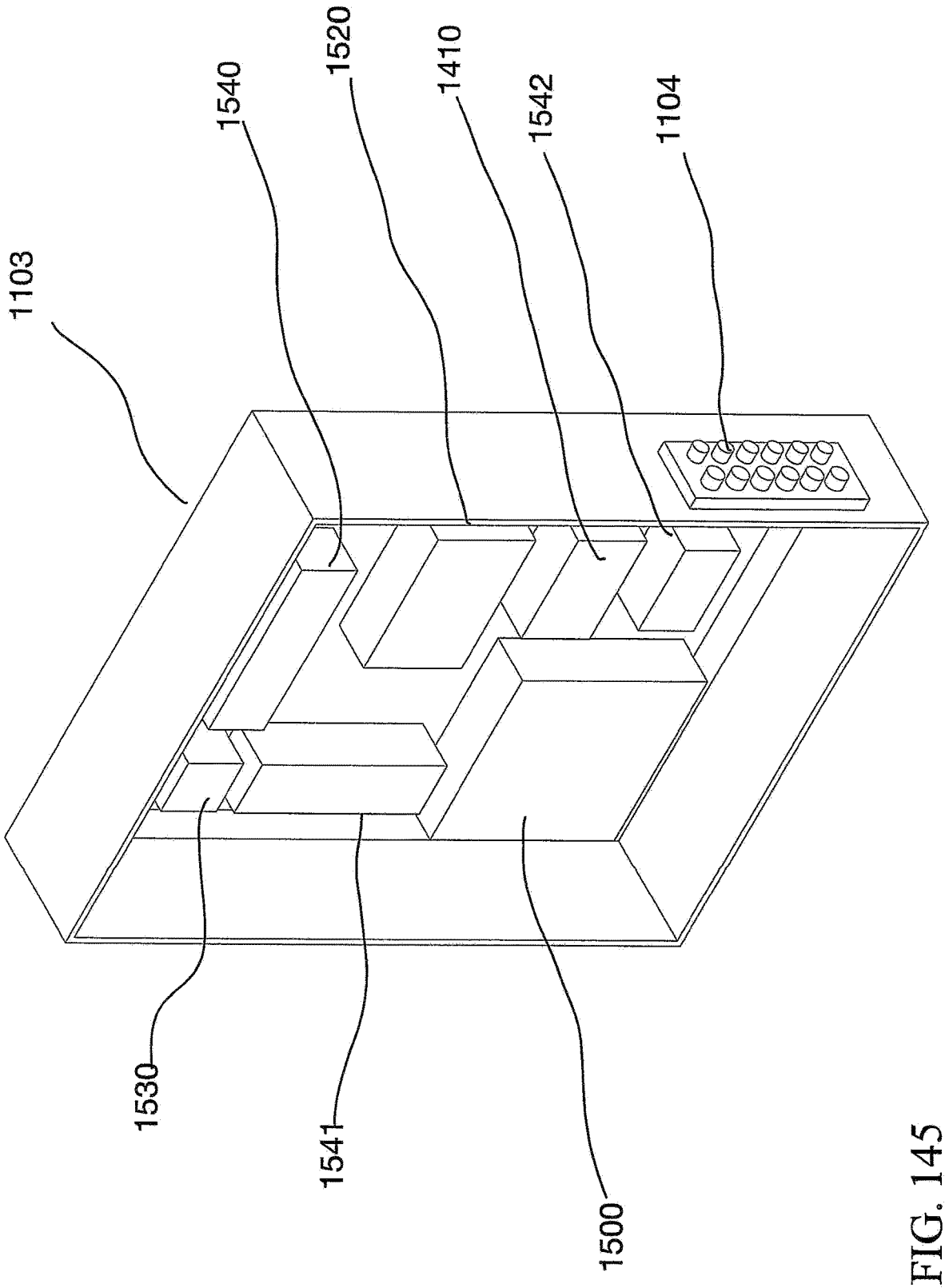


FIG. 145

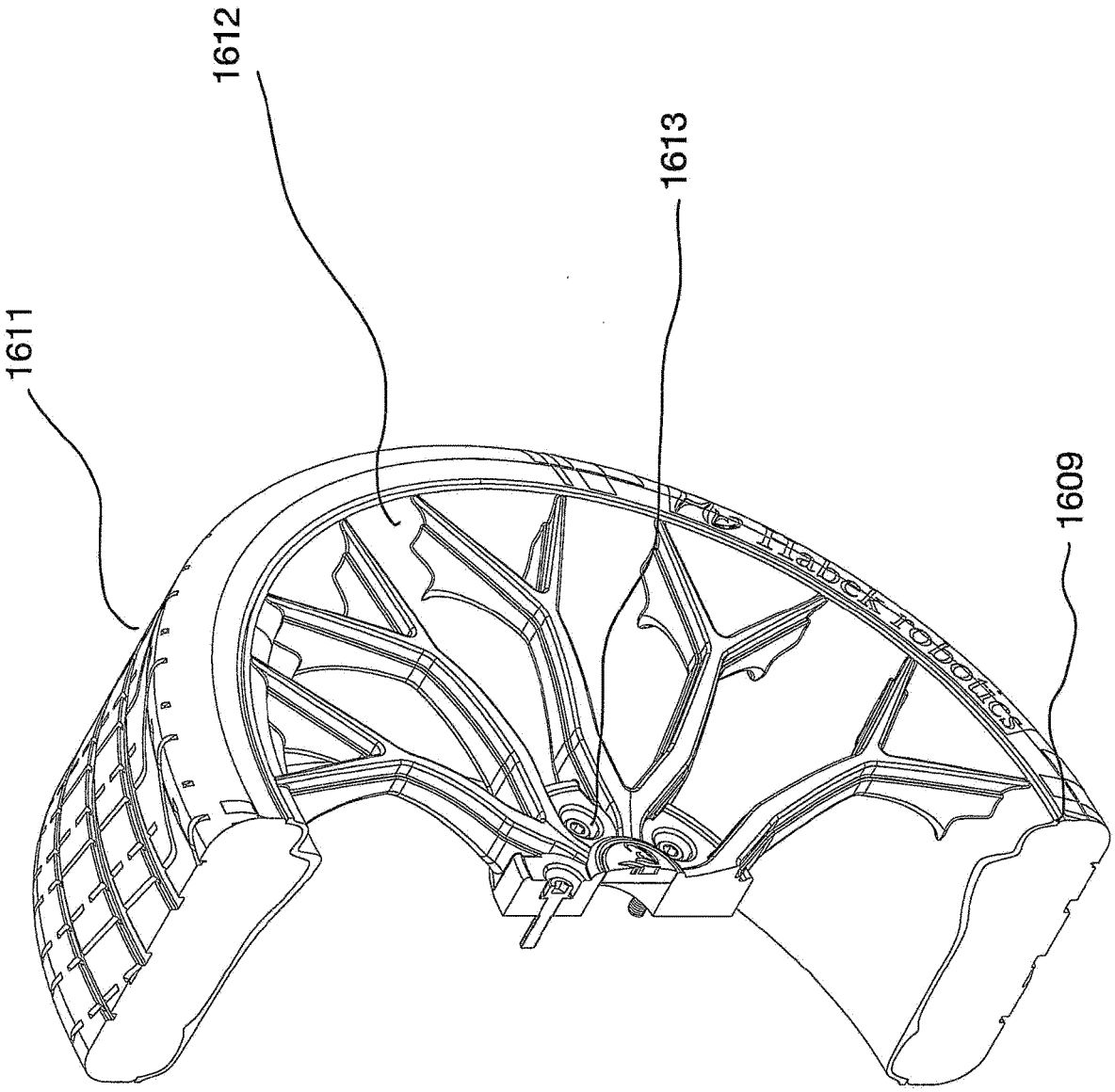


FIG. 146

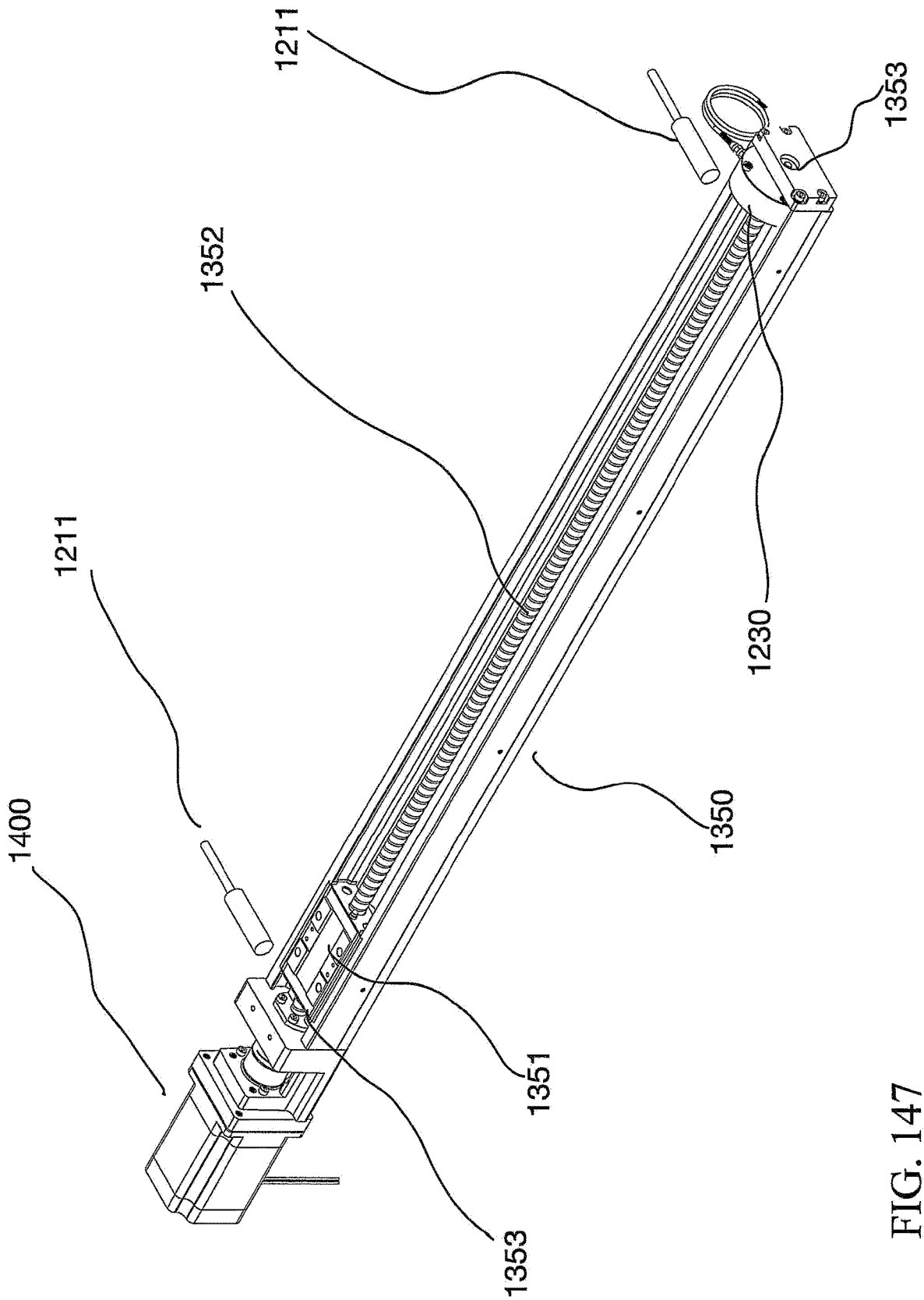


FIG. 147

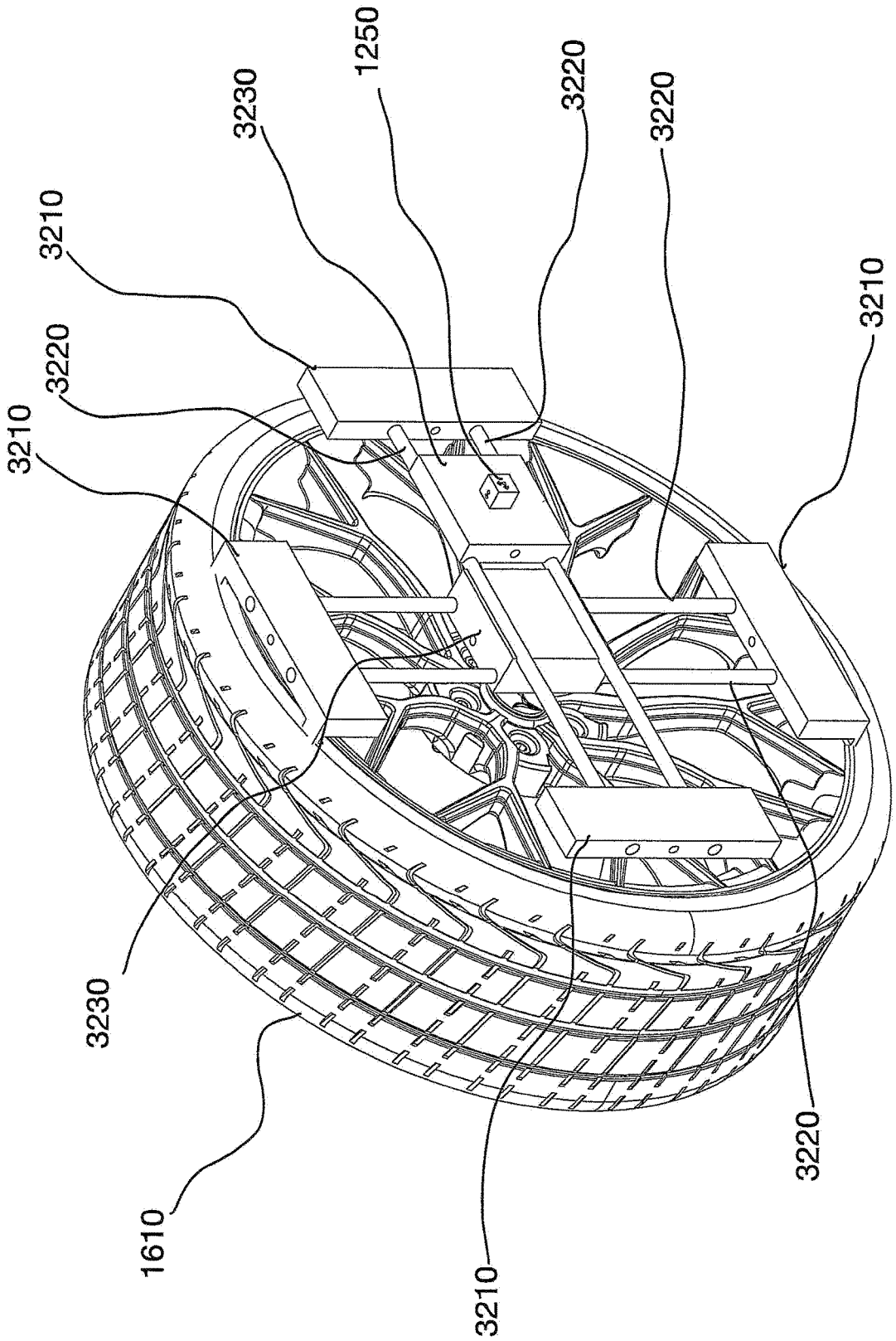


FIG. 148

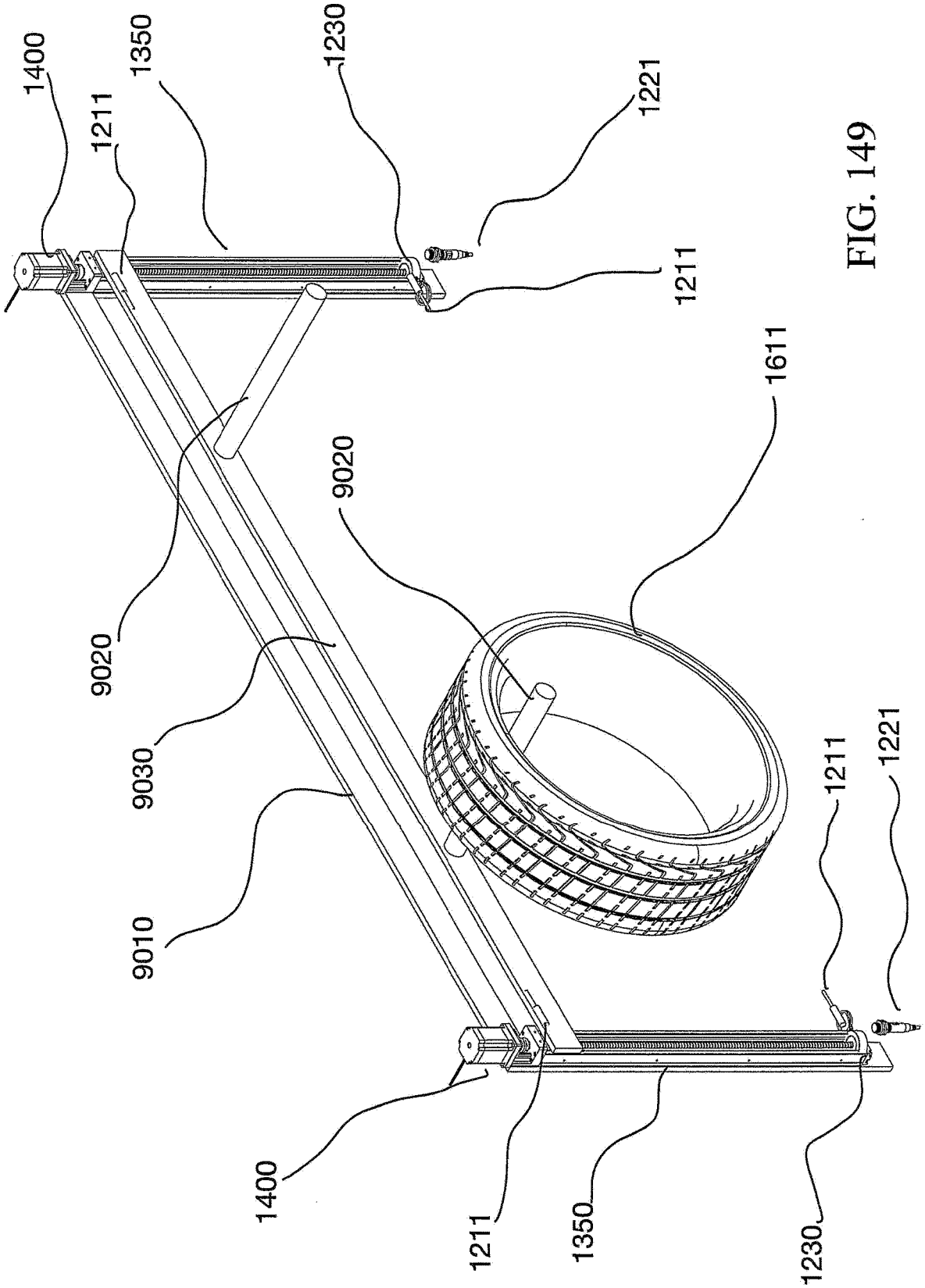

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FIG. 149

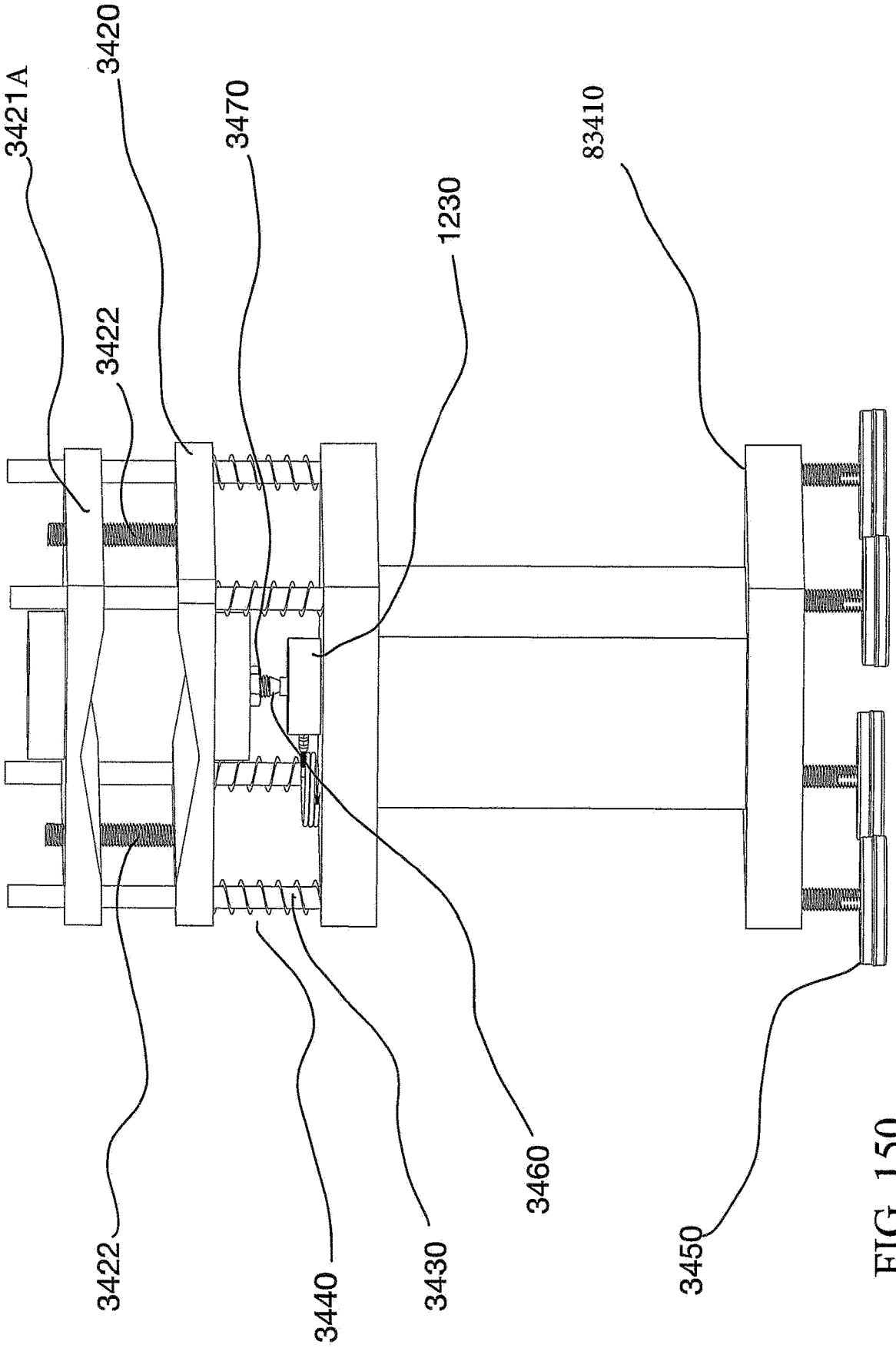


FIG. 150

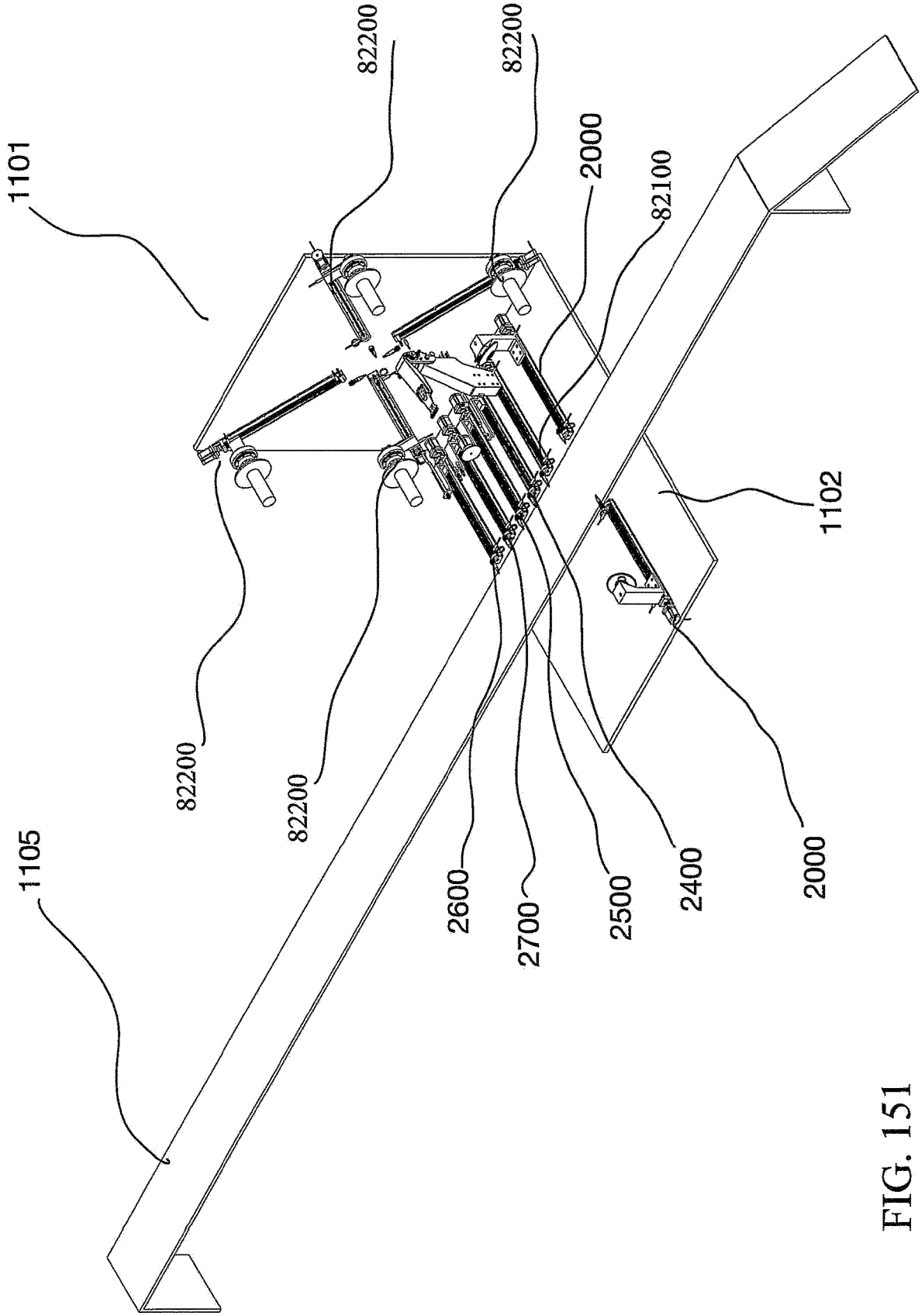

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FIG. 151

AUTONOMOUS TIRE AND WHEEL BALANCER, METHOD THEREFOR AND ROBOTIC AUTOMOTIVE SERVICE SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to U.S. Provisional patent application Ser. No. 63/354,591, filed on Jun. 22, 2022, and titled "Autonomous Tire And Wheel Balancer And Method Therefor", the disclosure of which is hereby incorporated by reference and on which priority is hereby claimed.

BACKGROUND OF THE DISCLOSURE

Field of the Disclosure

[0002] The present disclosure generally relates to vehicle tire changing equipment, and more particularly, to automated vehicle tire changing equipment and systems.

Description of the Related Developments

[0003] Like many industries that generally rely on human labor, there is a shortage of vehicle service technicians to meet demand with respect to, for example, the automobile service industry. Even with an adequate number of employees, throughput and efficiency of an automobile service facility or center may be impacted if one of their vehicle service technicians does not show up for work.

[0004] In addition to maintaining an adequate number of vehicle service technicians, automobile service facilities also face a challenge of finding a suitably qualified technician for any given tasks. For example, senior vehicle service technicians are often too highly paid for a service facility to justify the senior vehicle service technician to perform certain types of work. Moreover, it is not uncommon for some senior vehicle service technicians to refuse work that is below their level of expertise. For example, a senior vehicle service technician may refuse to perform vehicle tire changes. This creates a problem for service facilities in that an appropriate mix of vehicle service technician skill level must generally be maintained to maximize profits and efficiently operate the service facility.

[0005] A constantly changing level of consumer demand for certain automotive services may also compound the problem of efficient service facility operation because at some points in time the service facility may have an appropriate number of vehicle service technicians with an appropriate skill level for a certain task(s), such as vehicle tire changes, while at other times that same number of vehicle service technicians may be unsuitable for fulfilling customer demand with respect to the vehicle tire changes.

[0006] Generally, depending on the size of the service facility, tire changes are performed fully manually, manually with machine assist, or in a semi-automated manner. Fully manual tire changes are labor intensive and involve the use of manual bead breakers, crowbars or mount and demount tools, tire irons, and wheel supports. The amount of labor involved with fully manual tire changes may limit the number of tire changes that can be performed by a vehicle service technician in a given amount of time. The manual with machine assist tire changes reduce the labor involved with the tire change and generally include a machine with hydraulic-powered axes of motion that assist with breaking of the tire bead as well as maneuvering of the tire bead around a flange of the wheel from or to which the tire is being removed or installed. Semi-automated tire machines reduce the labor involved with a tire change even further, thus allowing a service technician to perform more tire changes; however, these semi-automated machines generally require constant vehicle service technician presence making multiple simultaneous tire changes by a single vehicle service technician unfeasible. The number of tire changes (and vehicles processed) that can be performed with the above-noted conventional tire change apparatus/methods is generally limited by the number of machines and corresponding vehicle service technicians available to use those machines.

[0007] In addition to the tire changing process, newly installed tires require the tire/wheel assembly to be balanced. This is also typically performed by a vehicle service technician using a conventional tire balancing machine with the tire/wheel assembly off the vehicle. While tire balancing machines that balance the tire/wheel assembly with the tire/wheel assembly on the vehicle have been used in the past, all-wheel-drive and traction control systems on newer vehicles have all but eliminated these conventional methods of balancing the tire/wheel assembly with the tire/wheel assembly on the vehicle. Tire balancing beads may also be used to dynamically balance a tire/wheel assembly, where the tire balancing beads are inserted into the tire by a vehicle service technician before seating the tire bead on the wheel. In any event, each of these tire balancing methods requires the constant presence of the vehicle service technician, again limiting the number of tires that can be changed in a given time period.

[0008] In some systems, wheel weights (also referred to herein as wheel balancing weights) are applied to a wheel, located off or dismounted from of a vehicle, using robots. These robots employ a rigid end effector that includes a curved surface on which the wheel weights are held. This curved surface has a radius that matches the inside radius of a barrel of the wheel on which barrel the weight is to be affixed. To apply the wheel weight, the robot rotates the end effector so that the weight held on the curved surface contacts the barrel at one edge. The robot rotates the end effector so that the curved surface rotates relative to the barrel so that the curved surface "rolls" along the barrel applying the wheel weight to the barrel in a "rolling" manner (such as in a manner similar to a paint roller depositing paint on a surface). Here, the swinging/rotating movement of the end effector is large and while sufficient for applying a wheel weight to a wheel located off of a vehicle, such rolling on of the wheel weight is prohibitive (due to a lack of the required swing area) with the wheel located on the vehicle. In addition, the "rolling" manner in which the wheel weight is applied may not provide a constant pressure along a length of the wheel weight that may result in debonding of the wheel weight from the wheel.

[0009] The wheel weights are generally applied, e.g., for correcting dynamic balance in accordance with an "inner" and "outer" method where an inner (further away from the centerline of the vehicle) and an outer (towards a centerline of the vehicle) wheel weights are selected for respective placement adjacent the back of the wheel flange and adjacent the inner wheel lip. This contrasts with a method of selecting a single location and single weight, however, the single location and single weight method is less common in

the industry. When applying dynamic balancing weights in an automated system, it is likely that there would be one or a combination of axes, which allow for a fully controlled degree-of-freedom in the axial direction of the wheel, which would allow for the single location and single weight method; however, such control may not be necessary.

[0010] With respect to automated access for placing wheel weights, many vehicles have non-standard flanges as part of the inner lip of the wheel. Without knowing the geometry of these non-standard flanges, placing a tool for installing a wheel weight inside the barrel of a wheel is difficult.

[0011] The manual tire-changing process is not as simple as removing the tire from the rim and placing a new one on. Such a process has many steps that must be followed for success, and a comparable number of tools to complete those steps. In brief, the tire wheel assembly (TWA) must be removed from the car using a lug wrench and placed on a tire changing machine, where a hub adapter is used to tighten the rim for rotation. The valve stem is removed using a tool for protection and to deflate the tire. The beads are broken using dedicated bead breaking rollers. The tire is then lubricated. A bead removal tool is inserted (often with the help of a lever) and the bead is removed. The rim itself is usually then cleaned with a scotch-brite style material by hand. The new tire is then lubed and placed onto the rim. After being pushed into position on the rim, the valve stem is inserted and the tire re-inflated.

[0012] This very brief description accounts for 14 steps and 10 tools, all being handled by an operator who is usually the lowest-trained and compensated employee in a typical mechanic shop environment. Severe limitations exist in this model from a time, safety, and risk perspective. A human operator normally takes about 1 hour to change all the tires on a vehicle (15 min per tire). In that time, the operator is near power tools and semi-automated machinery which poses a safety risk. Finally, many the tools and operations are positioned by the operator by eye. A misaligned tool can cause significant damage to expensive customer rims and tires, posing a business risk every time the operation takes place.

[0013] There are two main modes of vibration due to imbalance in the rotating assemblies of a vehicle: static and dynamic imbalance, also referred to as wheel hop and wheel wobble, respectively. Static imbalance is defined here as imbalance along a plane parallel to the wall of the TWA. Dynamic imbalance is defined here as imbalance in a plane not parallel to the wall of the TWA. Imbalance generated by the rotating assembly is often transmitted, at least in-part, to the driver of the vehicle through the suspension and steering column.

[0014] Vibration in a vehicle is undesirable for several reasons. Vibration in mechanical components of the vehicle can cause premature wear due to the mechanical stresses induced on wheel bearings, the suspension, tie rods, and more. Vibration can also increase tire wear causing increased expense in premature tire replacement. Excessive vibration may require the owner of the vehicle to perform maintenance on a more regular basis to reduce premature wear. Additionally, vibration felt by the driver during operation of the vehicle can be uncomfortable and cause fatigue and loss of concentration.

[0015] Because of the undesirability of imbalance in the vehicle, technology has been developed for balancing TWA assemblies before installing them onto the vehicle. This technology generally involves mounting the TWA on a shaft and rotating it while measuring disturbances on the shaft caused by imbalance. Weights will then be applied to the tire to counteract any measured imbalance, reducing disturbances and thus vibration to an acceptable level. A technician will then take the balanced TWA and mount it on the vehicle.

[0016] This current model of TWA balancing has several inherent risks and limitations. The first limitation is that the process is slow. A technician must remove a TWA from the vehicle, bring it to the balancing machine, run the balancing sequence, apply weights, and then bring the TWA back to the vehicle and remount it. A full TWA balancing sequence for a vehicle with four tires can take anywhere from 45 minutes to several hours depending on the speed and availability of technicians in a shop.

[0017] A second limitation in the current model is that current TWA balancing happens off the vehicle. This turns balancing of the TWA into a significantly simpler problem to solve but introduces drawbacks as it removes the dynamics of the TWA mounting hardware and vehicle from the balancing procedure. This results in a TWA that is well-balanced but is placed into a system (the vehicle) that itself has additional imbalance in the rotating assembly. As such, imbalance still exists within the system and the results can be felt by the operator.

[0018] A third limitation and risk in the process is the technician. Attrition in the workforce has led to shops having less technicians or having to hire sub-par technicians to work with tire balancing. These technicians may not be highly trained in the process, which can often result in a subpar balance. Furthermore, even the best technicians represent a time limitation: breaks, time off, conversations with coworkers, and more mean they work at less-than-optimal efficiency.

[0019] Additionally, TWAs are often heavy and require lifting. Technicians can become injured during the process or damage machines while moving TWAs or operating the balancing sequence, all of which represents significant risk to the businesses operating in the TWA balancing space.

[0020] These risks and limitations paint a clear picture of a market for an automated TWA wheel balancing machine. Such a machine can operate significantly faster than a human technician and work without time off. Furthermore, the machine is not at risk of injury like a human technician and represents significantly less business risk.

OBJECTS AND SUMMARY OF THE DISCLOSURE

[0021] It is an object of the present disclosure to provide a method for on vehicle balancing, the method comprising the steps of effecting rotation of a vehicle's tire wheel assembly about its axis of rotation, providing one or more sensors to measure the one or more imbalance signals, measuring the one or more imbalance signals with the one or more sensors, determining, based on the measurements of the one or more sensors and the magnitude of the one or more tire balancing weights, the locations on the tire wheel assembly to affix the one or more tire balancing weights to balance the one or more of the tire, the wheel, the bearings, the brake components and the vehicle components that impart vibrations to the vehicle; and affixing the one or more tire balancing weights to the determined locations on the tire wheel assembly.

[0022] It is another object of the present invention to provide an instrumented tool for performing tire servicing operations that is engageable with an end effector of a robotic system or mountable to a frame of the robotic system. The instrumented tool includes at least one actuator, a carriage, a drive that effects movement of the carriage between a first position and a second position, tooling mounted to the carriage and one or more sensors.

[0023] These and other objects, features and advantages of the present disclosure will be apparent from the following detailed description of illustrative embodiments thereof, which is to be read in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] FIGS. **1**A-**1**B are schematic illustrations of an automated tire changing system incorporating aspects of the present disclosure;

[0025] FIG. **2**A is another schematic illustration of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0026] FIG. **2**B is still another schematic illustration of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0027] FIG. **2**C is yet another schematic illustration of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0028] FIG. **2**D is another schematic illustration of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0029] FIG. **3** is a schematic block diagram of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0030] FIGS. **4**A and **4**B are schematic illustrations of a wheel weight installation tool of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0031] FIG. **4**C is a schematic illustration of a portion of the wheel weight installation tool of FIGS. **4**A and **4**B in accordance with the present disclosure;

[0032] FIGS. **4**D and **4**E are a schematic illustrations of a portion of the wheel weight installation tool of FIGS. **4**A and **4**B in accordance with the present disclosure;

[0033] FIG. **4**F is a schematic illustration of a portion of the wheel weight installation tool of FIGS. **4**A and **4**B in accordance with the present disclosure;

[0034] FIGS. **5**A-**5**C are schematic illustrations of a wheel weight installation tool of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0035] FIG. **6**A is a schematic illustration of a wheel weight dispenser and wheel weight transport of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0036] FIGS. **6**B and **6**C are schematic illustrations of a portion of the wheel weight dispenser of FIG. **6**A in accordance with the present disclosure;

[0037] FIGS. **7**A-**7**F are schematic illustrations of portions of the wheel weight transport of FIG. **6**A in accordance with the present disclosure;

[0038] FIGS. **8**A-**8**C are schematic illustrations of portions of the wheel weight transport of FIG. **6**A in accordance with the present disclosure;

[0039] FIGS. **9**A-**9**C are schematic illustrations of a wheel assembly proximity sensor of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0040] FIG. **10** is a flow diagram of a wheel weight installation method of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0041] FIG. **11** is a flow diagram of a wheel assembly sensing method of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0042] FIGS. **12**-**15** are flow diagrams of wheel balancing methods of the automated tire changing system of FIGS. **1**A and **1**B in accordance with the present disclosure;

[0043] FIGS. **16**A-**16**D are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0044] FIGS. **17**A, **17**B, and **18** are schematic illustrations of dynamic responses of a wheel in accordance with aspects of the present disclosure;

[0045] FIG. **19** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0046] FIGS. **20**A-**20**D are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0047] FIG. **21** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0048] FIGS. **22**A-**22**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0049] FIG. **23** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0050] FIG. **24** is schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0051] FIG. **25** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0052] FIGS. **26**A-**26**C are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0053] FIG. **27** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0054] FIGS. **28**A-**28**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0055] FIG. **29** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0056] FIGS. **30**A-**30**D are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0057] FIG. **31** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0058] FIGS. **32**A-**33**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0059] FIG. **33** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0060] FIG. **34** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0061] FIG. **35** is schematic illustrations of an automated tire changing system incorporating aspects of the present disclosure;

[0062] FIG. **36** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0063] FIG. **37** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0064] FIGS. **38**A-**38**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0065] FIGS. **39**A-**39**D are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0066] FIGS. **40**A-**40**C are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0067] FIG. **41** is an exemplary flow diagram of a method in accordance with aspects of the present disclosure;

[0068] FIGS. **42**A-**42**C are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0069] FIGS. **43**A-**43**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0070] FIGS. **44**A-**44**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0071] FIGS. **45** and **46**A-**46**D are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0072] FIG. **47** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0073] FIG. **48** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0074] FIG. **49** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0075] FIGS. **50**A-**50**C are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0076] FIGS. **51**A-**51**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0077] FIGS. **52**A-**52**C are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0078] FIG. **53** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0079] FIGS. **54**A-**54**B are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0080] FIGS. **55**A-**55**C are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0081] FIGS. **56**, **57**, and **58** are schematic illustrations of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0082] FIG. **59** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0083] FIG. **60** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0084] FIG. **61** is a schematic illustration of a portion of an automated tire changing system in accordance with aspects of the present disclosure;

[0085] FIG. **62** is a top perspective view of a robotic automotive service system formed in accordance with the present disclosure;

[0086] FIG. **63** is a front perspective view of a bead breaker system formed in accordance with the present disclosure;

[0087] FIG. **64** is a left elevational view of the bead breaker system formed in accordance with the present disclosure;

[0088] FIG. **65** is a graphical motion profile of an exemplary bead breaking maneuver in accordance with the present disclosure;

[0089] FIG. **66** is a top perspective view of a bead tool system formed in accordance with the present disclosure;

[0090] FIG. **67** is an exploded, top perspective view of the bead tool system formed in accordance with the present disclosure;

[0091] FIG. **68** is a top perspective view of an alternative form of a bead tool system formed in accordance with the present disclosure;

[0092] FIG. **69** is a left elevational view of a bead tool end effector formed in accordance with the present disclosure;

[0093] FIG. **70** is a bottom perspective view of the bead tool end effector formed in accordance with the present disclosure;

[0094] FIG. **71** is a graphical motion profile of an exemplary bead removal maneuver in accordance with the present disclosure;

[0095] FIG. **72** is a bottom perspective view of a gripper system formed in accordance with the present disclosure, showing the gripper system adjacent to a TWA;

[0096] FIG. **73** is a top perspective view of the gripper system formed in accordance with the present disclosure;

[0097] FIG. **74** is an exploded, top perspective view of the gripper system formed in accordance with the present disclosure;

[0098] FIG. **75** is a top perspective view of several grippers formed in accordance with the present disclosure;

[0099] FIG. **76** is a cross-sectional, left elevational view of a face gripper formed in accordance with the present disclosure;

[0100] FIG. **77** is a front perspective view of the face gripper formed in accordance with the present disclosure, showing the face gripper engaged with the TWA;

[0101] FIG. **78** is a front perspective view of a lug-nut gripper formed in accordance with the present disclosure;

[0102] FIG. **79** is a front perspective view of a turntable of the gripper system formed in accordance with the present disclosure;

[0103] FIG. **80** is a front elevational view of the TWA, illustrating the relative dimensions thereof;

[0104] FIG. **81** is a top perspective view of an inflation tool system formed in accordance with the present disclosure;

[0105] FIG. **82** is a top perspective view of the inflation tool system formed in accordance with the present disclosure, showing the inflation tool system mated with the valve stem of the TWA;

[0106] FIG. **83** is a top perspective view of an annular seal formed in accordance with the present disclosure;

[0107] FIG. **84** is a top perspective view of a cleaning tool system formed in accordance with the present disclosure;

[0108] FIG. **85** is a top perspective view of a lubrication tool system formed in accordance with the present disclosure;

[0109] FIG. **86** is a top perspective view of a lubrication tool system with a lubricant spray head formed in accordance with the present disclosure;

[0110] FIG. **87** is a top perspective view of a valve tool system formed in accordance with the present disclosure;

[0111] FIG. **88** is a rear elevational view of a balancing system formed in accordance with the present disclosure;

[0112] FIG. **89** is a rear elevational view of another form of the balancing system formed in accordance with the present disclosure;

[0113] FIG. **90** is an illustration of the TWA, showing a set of principal axes and an imbalance thereof;

[0114] FIG. **91** is a top perspective view of a multi-axis accelerometer formed in accordance with the present disclosure;

[0115] FIG. **92** is a top plan view of a sensor mount formed in accordance with the present disclosure;

[0116] FIG. **93** is a top perspective view of another form of a sensor mount formed in accordance with the present disclosure;

[0117] FIG. **94** is a rear elevational view of the balancing system formed in accordance with the present disclosure, showing the multi-axis accelerometer and sensor mount formed in accordance with the present disclosure attached to a vehicle;

[0118] FIG. **95** is a rear elevational view of the balancing system formed in accordance with the present disclosure, showing single-axis accelerometers and a sensor mount formed in accordance with the present disclosure attached to a vehicle;

[0119] FIG. **96** is a top perspective view of another form of a sensor mount formed in accordance with the present disclosure, showing an IMU thereon;

[0120] FIG. **97** is a top perspective view of the sensor mount illustrated in FIG. **96**, showing an IMU and a magnetometer thereon;

[0121] FIG. **98** is a top, rear perspective view of a TWA, showing the multi-axis accelerometer formed in accordance with the present disclosure mounted thereto and in communication with a DAQ;

[0122] FIG. **99** is another top, rear perspective view of a TWA, showing the multi-axis accelerometer formed in accordance with the present disclosure mounted thereto and in communication with a DAQ;

[0123] FIG. **100** is a top, rear perspective view of a TWA, showing a sensor mount formed in accordance with the present disclosure mounted thereto;

[0124] FIG. **101** is a top, rear perspective view of a TWA, showing the multi-axis accelerometer formed in accordance with the present disclosure mounted to the rim of the TWA using a rim clip;

[0125] FIG. **102** is a cross-sectional elevational view of the TWA, showing a tire pressure monitoring system (TPMS) assembly formed in accordance with the present disclosure situated therein;

[0126] FIG. **103** is a cross-sectional elevational view of the tire pressure monitoring system (TPMS) assembly formed in accordance with the present disclosure;

[0127] FIG. **104** is a top perspective view of a gantry balancing system formed in accordance with the present disclosure, showing the gantry balancing system mounted to the TWA;

[0128] FIG. **105** is a top perspective view of another form of a gantry balancing system formed in accordance with the present disclosure, showing the gantry balancing system mounted to the TWA;

[0129] FIG. **106** is a top perspective view of a roller system formed in accordance with the present disclosure;

[0130] FIG. **107** is a top perspective view of the roller system formed in accordance with the present disclosure, showing the roller system underneath the TWA;

[0131] FIG. **108** is a top perspective view of a suspension support structure system formed in accordance with the present disclosure;

[0132] FIG. **109** is an exemplary block diagram of the state of the suspension while the sprung suspension support structure formed in accordance with the present disclosure is engaged

[0133] FIG. **110** left elevational view of the suspension support structure system formed in accordance with the present disclosure;

[0134] FIG. **111** is front perspective view of a vision-based balancing system formed in accordance with the present disclosure;

[0135] FIG. **112** is top perspective view of the vision-based balancing system formed in accordance with the present disclosure, showing fiducials on the vehicle;

[0136] FIG. **113** is top perspective view of another form of the vision-based balancing system formed in accordance with the present disclosure;

[0137] FIG. **114** is a flow diagram of a method for on-car wheel balancing in accordance with the present disclosure;

[0138] FIG. **115** illustrates an example gradient descent curve for wheel balancing;

[0139] FIG. **116** is a graphical illustration showing the relationship between rotational frequency and time of the TWA during a constant speed vs. spin-down test;

[0140] FIG. **117** is a flow diagram of an iterative gradient descent sequence in which an algorithm in accordance with the present disclosure is run;

[0141] FIG. **118** is a flow diagram of an alternative iterative gradient descent sequence in which the algorithm in accordance with the present disclosure runs iteratively without the application of successive balancing weights;

[0142] FIG. **119** is a flow diagram of a fit-based gradient descent sequence in which the measured imbalance is compared by the algorithm in accordance with the present disclosure to a parametrized curve;

[0143] FIG. **120** illustrates a sample curve-fit for the fit-based gradient descent algorithm in accordance with the present disclosure;

[0144] FIG. **121** is a flow diagram of a system identification (SID) process in accordance with the present disclosure;

[0145] FIG. **122** is a flow diagram of a method of using SID for the on-car wheel balancing process in accordance with the present disclosure;

[0146] FIG. **123** is a flow diagram of a machine learning (ML) system architecture for on-vehicle wheel balancing formed in accordance with the present disclosure;

[0147] FIG. **124** is a flow diagram of an exemplary process of wheel balancing using an ML algorithm after the devel-

opment of a wheel-balancing based ML model using the process shown in FIG. **123** of the drawings in accordance with the present disclosure;

[0148] FIG. **125** is a flow diagram of a method for recovering additional training data for the ML model through customer testing in accordance with the present disclosure;

[0149] FIG. **126** shows an exemplary diagram of the contents of a typical signal acquired during the wheel balancing process in accordance with the present disclosure;

[0150] FIG. **127** illustrates a fast-Fourier transform (FFT) of an acquired signal;

[0151] FIG. **128** is top perspective view of a lift system formed in accordance with the present disclosure;

[0152] FIG. **129** is top perspective view of a lift plate system formed in accordance with the present disclosure;

[0153] FIG. **130** is top perspective view of a camera positioning system formed in accordance with the present disclosure;

[0154] FIG. **131** is a graphical illustration of operator controls formed in accordance with the present disclosure;

[0155] FIG. **132** is top perspective view of the robotic automotive service system formed in accordance with the present disclosure;

[0156] FIG. **133** is top perspective view of an alignment tool formed in accordance with the present disclosure;

[0157] FIG. **134** is a bottom perspective view of a vehicle, showing the alignment tool formed in accordance with the present disclosure thereon;

[0158] FIG. **135** is a top perspective view of a self-service station formed in accordance with the present disclosure;

[0159] FIG. **136** is a graphical illustration of an exemplary system interface formed in accordance with the present disclosure;

[0160] FIG. **137** is a top perspective view of a mobile service station formed in accordance with the present disclosure;

[0161] FIG. **138** is a top perspective view of a transmission formed in accordance with the present disclosure;

[0162] FIG. **139** is a top perspective view of another form of a transmission formed in accordance with the present disclosure;

[0163] FIG. **140** is a top perspective view of a sensor mount formed in accordance with the present disclosure;

[0164] FIG. **141** is a top perspective view of a tire handling system formed in accordance with the present disclosure;

[0165] FIG. **142** is a top perspective view of a system dynamics modeling system formed in accordance with the present disclosure;

[0166] FIG. **143** is a top perspective view of a robotic apparatus formed in accordance with the present disclosure;

[0167] FIG. **144** is graphical illustration of an exemplary frequency response curve generated by the system dynamics modeling system formed in accordance with the present disclosure;

[0168] FIG. **145** is a top perspective view of an electrical panel formed in accordance with the present disclosure;

[0169] FIG. **146** is a partial cutaway, top perspective view of a tire rim and the tire bead;

[0170] FIG. **147** is a top perspective view of a linear actuator formed in accordance with the present disclosure;

[0171] FIG. **148** is a top perspective view of another form of a gantry system formed in accordance with the present disclosure;

[0172] FIG. **149** is a top perspective view of another form of a tire handling system formed in accordance with the present disclosure;

[0173] FIG. **150** is a front perspective view of another form of a suspension support structure system formed in accordance with the present disclosure; and

[0174] FIG. **151** is a top perspective view of a another form of a robotic apparatus formed in accordance with the present disclosure.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0175] FIGS. **1A-1B** illustrates an exemplary automated tire changing system **100** in accordance with aspects of the present disclosure. Although the aspects of the present disclosure will be described with reference to the drawings, it should be understood that the aspects of the present disclosure can be embodied in many forms. In addition, any suitable size, shape or type of elements or materials could be used.

[0176] Referring to FIGS. **1A-1B**, the aspects of the tire changing system **100** described herein automate the process of changing tires **111**T on a vehicle **110** (also referred to herein as a road vehicle). As will be described herein the tire changing system **100** provides for changing tires **111**T with the wheel **111**W (also referred to herein as a rim or wheel rim) on (i.e., in situ) the vehicle **110** or by removing the wheel **111**W from the vehicle **110**. In one or more aspects, the tire changing system **100** provides for an operator of the tire changing system **100**, such as a vehicle service technician **199**, to select an in-situ tire change or a tire change by removing the wheel **111**W from the vehicle **110**. The vehicle **110** is any suitable vehicle having a wheel assembly **111** (including a tire **111**T mounted on a wheel **111**W, also referred to herein as a tire-wheel assembly) coupled to and removable from a wheel hub. Suitable examples of a vehicle **110** include, but are not limited to, passenger vehicles, commercial vehicles, and recreational vehicles.

[0177] The aspects of the tire changing system **100** described herein automate tasks associated with changing tires **111**T on the vehicle **110**. A tire change, as described herein, includes at a minimum, removal of an old or used tire **111**TU from the wheel **111**W and replacement of the used tire **111**TU with what may be referred to as a replacement or other (new) tire **111**TN that is installed on the wheel **111**W in place of the removed used tire **111**N. The aspects of the tire changing system **100** provides for a single vehicle service technician **199** to simultaneously monitor the changing of more than one tire on the same or different vehicles addressing the problems noted above. The aspects of the tire changing system **100** described herein generally limit vehicle service technician **199** interaction with the vehicle(s) **110** and/or tire changing apparatus (e.g., tire changing machines, tire balancers, etc.) and substantially eliminates lifting of wheel assemblies **111** by the vehicle service technician **199**. This allows the vehicle service technician **199** to work in a less labor intensive environment and interact with the tire changing system **100** when necessary (e.g., such as to deliver vehicles **110** to/from the tire changing system **100**, provide replacement tires **110**TN or other supplies (valve stems, valve caps, lubricants, cleaning solu-

tions, etc.) to the tire changing system **100**, perform maintenance on components of the tire changing system, etc.). The aspects of the tire changing system **100** also eliminate the need to lift the vehicle **110** to heights that would be ergonomic for the vehicle service technician **199** to remove and install the wheel assembly **111** from and to the vehicle **110**. Here the vehicle **110** only need be lifted (or a normal force be removed from the wheel assembly **111**) to a height that the tire **111**T no longer contacts a traverse surface on which the vehicle **110** was moving so that suitable clearance is provided around the tire **111**T to facilitate removal of the wheel assembly **111** from the vehicle or removal of the tire **111**T from the wheel **111**W.

[0178] Still referring to FIGS. **1**A-**1**B, the tire changing system **100** is configured to change one or more tires with the wheel **111**W remaining on (i.e., in-situ) the vehicle **110** and/or with the wheel **111**W removed from the vehicle **110**. The tire changing system **100** includes at least one tire changing station **101**, noting that multiple tire changing stations may be provided so that multiple vehicles **110** can be processed simultaneously by a single vehicle service technician **199**. The autonomous configuration of the tire changing system provides for the processing of multiple vehicles **110** by a single vehicle service technician **199** and with minimal intervention by the vehicle service technician **199** in the tire changing process. Generally, the tire changing station **101** includes a vehicle component balancing robot apparatus **189** for on vehicle balancing of one or more of a tire **111**T, a wheel **111**W, bearings **111**B (e.g., wheel bearings), brake components **111**RD (e.g., including but not limited to brake drums **111**D and brake rotors **111**R), and vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to a wheel hub **110**H (see FIG. **1**B) of the vehicle **110**). The vehicle component balancing robot apparatus **189** includes a frame **189**F arranged so as to connect with the vehicle **110**. At least one autonomous traverse tire changing bot **120** (referred to herein for convenience as "bot **120**", also referred to herein as a robot) is connected to the frame **189**F. The frame **189**F may be any suitable frame (e.g., a platform, surface, or otherwise) that directly or indirectly connects the bot **120** and vehicle **110** for tire changing operations. It should be understood that reference to an autonomous traverse tire changing bot **120** does not preclude inclusion of more than one autonomous traverse tire changing bot as will be described in greater detail herein. For example, some aspects of the present disclosure (see FIGS. **2**A, **2**B, and **2**D) include more than one separate and/or independent and cooperative bots **120**, cooperating to effect a tire change (though in some aspects a single robot directly effects the tire change). In some aspects, there are multiple bots **120** configured for respective tasks. For example, one bot **120** is configured for wheel assembly **111** or tire **111**T removal, another bot **120** is configured for lug nut/bolt removal, or any other process of the tire change as indicated by, for example, the tools **129**A-**129**Q described herein and described in U.S. Pat. No. 11,446,826 issued on Sep. 20, 2022 and titled "Autonomous Traverse Tire Changing Bot, Autonomous Tire Changing System, and Method Therefor," and U.S. provisional patent application No. 63/354,591 titled "Autonomous Tire and Wheel Balancer and Method Therefor" and filed on Jun. 22, 2022, the disclosures of which are incorporated herein by reference in their entireties.

[0179] As will be described herein, the bot **120** has at least one degree of freedom (such as along traverse path **299** and/or along any one or more axes of motion of the bot **120**) so as to move, in the at least one degree of freedom, relative to the frame **189**F. The bot **120** is configured so that the move, relative to the frame **189**F in the at least one degree of freedom, resolves a predetermined location of the wheel assembly **111** relative to a reference frame RREF of the bot **120**. For example, the bot **120** may be configured to employ one or more of a vision sensor, an ultrasonic sensor, and a proximity sensor (generally referred to herein as proximity sensor **129**N) as described herein for resolving the predetermined location (see FIGS. **1**B and **2**A-**2**D) of the wheel assembly **111** relative to the reference frame RREF of the bot **120**. The predetermined location of the wheel assembly **111** determines a frame of reference of the wheel assembly WREF relative to the reference frame RREF of the bot **120**.

[0180] Referring still to FIGS. **1**A-**1**B, the bot **120** includes a bot frame **125** that includes or is coupled/mounted to a base or carriage **120**C. In one aspect, the carriage **120**C is a stationary carriage having a frame **120**F that facilitates fixing the bot **120** in a stationary location at a tire changing station **101** (such as adjacent a wheel assembly **111** mounted on the vehicle **110**—see FIGS. **2**A-**2**D). In other aspects, the carriage **120**C is any suitable carriage that facilitates traverse of the bot **120** as described herein. For example, as illustrated in FIG. **2**A, the carriage **120**C may be a wheeled carriage that includes a carriage frame **120**F, wheels **120**W (shown in dashed lines) supporting the carriage frame **120**F, and a carriage drive section **121** (shown in dashed lines).

[0181] For exemplary purposes only, the carriage drive section **121** (whether wheeled or otherwise) includes at least one motor **121**M that defines at least one degree of freedom powering at least one of the wheels **120**W (or rotating a ball-screw, etc.) effecting autonomous traverse of the carriage **120**C, along a traverse path **299** (see, e.g., FIGS. **2**A-**2**D), relative to a traverse surface or a floor **198** on which the bot **120** rests in a manner similar to that described in U.S. Pat. No. 11,446,826 issued on Sep. 20, 2022 and titled "Autonomous Traverse Tire Changing Bot, Autonomous Tire Changing System, and Method Therefor," previously incorporated herein by reference in its entirety. As will be described herein, the traverse path **299** along which the bot travels is in one or more aspects, a path around the entire vehicle **110** or a path around a portion of the vehicle **110**, where the traverse path may depend on a number of bots **120** included in the tire changing system **100**. For example, where there are two bots **120** each bot traverses along a respective side (e.g., driver or passenger side) of the vehicle **110**. As another example, where there are two bots **120** on a common side of the vehicle **110** (e.g., either the driver or passenger side) each bot **120** traverses along a respective portion of the common side of the vehicle **110**.

[0182] The traverse path (such as traverse path **299** in FIG. **2**A) may be defined in any suitable manner, such as through non-contact bot guidance on an indeterministic travel surface (i.e., without physical constraints guiding movement of the bot **120**). Where the bot **120** travels on an indeterministic travel surface the wheels **120**W are configured in any suitable manner so as to provide the carriage **120**C with both linear traverse and rotational movement. For example, one or more of the wheels **120**W may be steerable or the wheels may be holonomic wheels (such as Mecanum wheels, Omni wheels, or poly wheels). In other aspects, traverse of the

carriage **120**C may be effected on (where the wheels are replaced or supplemented by) sliding elements such as rails and/or tracks, that include, but are not limited to, guide rod and sleeve bearings, or any other guide system for effecting linear traverse and/or rotational motion of the carriage **120**C. The rails and/or tracks may provide for, including but not limited to, the carriage **120**C being suspended or dependent from an overhead gantry or wall, with traverse of the carriage **120**C in both vertical and horizontal directions (see FIG. **2**B). In other aspects, the carriage **120**C may be mounted on the may be mounted to the floor, mounted to any suitable traverse carriage, or may be mounted on a turret carriage configured to traverse with at least one degree of freedom.

[0183] In one or more aspects, the entire bot **120** may align itself in one or more degrees of freedom with respect to the vehicle **110**, the wheel assembly **111**, the wheel **111**W, the tire **111**T or any other component of the tire changing system **100** to perform a tire changing operation. For exemplary purposes only, a center of rotation of the tire bead breaker tool **129**H (described herein) is substantially aligned with a center of rotation of the wheel assembly **111** and the plane in which the tire bead breaker tool **129**H acts is set so as to be substantially parallel to the rotational axis of the wheel assembly **111**. Where the carriage **120**C includes steerable or holonomic wheels, this positional adjustment of the tire bead breaker tool **129**H is accomplished, at least in part, by controlling the wheels for positioning the bot **120** along one or more of the following directions:

[0184] linear direction **237** extending substantially parallel to both the floor **198** and the vehicle **110** and extending lengthwise (from front to back) relative to the vehicle **110**; and

[0185] linear direction **238** extending substantially perpendicular to the vehicle **110** and substantially parallel to the floor **198**.

The carriage **120**C, whether fixed or wheeled, may also include a movement stage **120**S that coupled to the frame **120**F so as to move in at least direction **238** relative to the frame **120**F. For example, the movement stage **120**S is coupled to the frame **120**F by stage guide rails having any suitable drive that provides the movement stage **120**S with linear movement in direction **238**. The carriage **120**C may include one or more rotational couplings that couple a movement stage **120**S to the frame **120**F. These one or more rotational couplings include any suitable drives for moving the movement stage **120**S in one or more of the following directions:

[0186] rotational direction **239** having an axis of rotation **239**R extending substantially perpendicular to the floor;

[0187] rotational direction **240** having an axis of rotation **240**R extending substantially parallel with the floor **198**; and

[0188] rotational direction **241** having an axis of rotation **241**R extending substantially parallel with the floor **198**.

In some aspects, a vertical drive may be provided to move the movement stage **120**S (and/or the frame **120**F) vertically to raise or lower the movement stage **120**S (and/or the frame **120**F). As such, the movement stage **120**S may be provided with five or six degrees of freedom (in other aspects there may be more than six or less than five degrees of freedom) for aligning the bot **120** with respect to the vehicle **110**, the wheel assembly **111**, the wheel **111**W, the tire **111**T or any other component of the tire changing system **100** to perform a tire changing operation.

The bot frame **125** includes at least one actuator **126** (or arm which may be configured as linear extension/retraction slide, an elongated member, a rod, a linear actuator, a rotary actuator, an articulated actuator, a telescopic actuator or any suitable combination thereof) and a bot drive section **127**. The at least one actuator **126** is a driven actuator that is driven so as to extend along or in the at least one degree of freedom of the bot **120** between a retracted position and an extended position, the extended position locating an (i.e., at least one) end effector **128** (and a distal end **120**D at which the end effector **128** is located) of the actuator **126** proximate a wheel assembly **111**. In one or more aspects, the at least one actuator **126** may be any suitable multi-axis actuator available from such manufacturers as Fanuc Robotics Company, Kuka Automation Company, and Yaskawa Electric Corporation. In one or more aspects the at least one actuator **126** has a bespoke actuator configuration with any suitable number of axes or degrees of freedom. The at least one actuator **126** (whether commercially available or bespoke) has any suitable number of degrees of freedom for effecting a tire change as described herein. For example, the at least one actuator **126** is a one axis actuator, a two axis actuator, a three axis actuator, a five axis actuator, a six axis actuator, a seven axis actuator, nine axis actuator, or an actuator with any other suitable number of axes or degrees of freedom. In one or more aspects, as described herein, the bot **120** has more than one actuator **126**, **126**A where, in one or more aspects, the different actuators have different numbers of axes and/or different tire changing capabilities. The actuator **126** is driven by the bot drive section **127**, where the bot drive section **127** includes at least one motor **127**M that defines a bot actuator degree of freedom, separate and distinct from the at least one degree of freedom powering the traverse path **299** axis of the bot **120** (e.g., the degree of freedom powering the at least one of the wheels **120**W, ball screw rotation, etc.).

[0189] The actuator **126** has an end effector **128** arranged to interface the wheel assembly **111** and the bot **120** moves the end effector **128** to other predetermined locations on the wheel **111**W of the wheel assembly **111**, determined based on resolution of the predetermined location of the wheel assembly **111** relative to the reference frame RREF of the bot **120**. The other predetermined locations on the wheel **111**W are wheel balancing weight locations (see FIGS. **5**A-resolving imbalance of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including but not limited to the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to the wheel hub **110**H (see FIG. **1**B)). As described herein, the end effector **128** interfaces the wheel assembly **111** at the other predetermined locations so as to effect a balancing solution of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD, and the vehicle components **111**C via robotic application of wheel balancing weights **400** with the end effector **128**.

[0190] The end effector **128** includes a wheel or tire engagement tool **129** disposed so that articulation of the at least one actuator **126** with the bot actuator degree of

freedom effects engagement contact of the wheel or tire engagement tool **129** and a wheel **111**W or a tire **111**T mounted on the vehicle **110**. The actuator movement axis/axes AX**1**-AX**6** defined by movement of the at least one actuator **126** with the bot actuator degree of freedom is separate and distinct from the traverse path **299** along which the carriage **120**C (in wheeled form) traverses. As described herein, the aspects of the present disclosure provide for automated control of fully dynamic pose of the carriage **120**C (at least along one drive axis) of the carriage **120**C) so that movement of the at least one actuator **126** (along a different drive axis than the drive axis of the carriage **120**C) engages any suitable tool (such as those described herein) coupled to the end effector **128** of the at least one actuator **126** to a variably positioned wheel **111**W and/or tire **111**T on the vehicle **110**.

[0191] Referring to FIGS. **1**A-**1**B, in accordance with one or more aspects of the present disclosure the wheel or tire engagement tool **129** includes one or more of a wheel assembly grip **129**A, a valve stem cap installation tool **129**B, a valve stem cap removal tool **129**C, a tire deflation tool **129**D, a tire mounting/dismounting tool **129**E, a valve core installation tool **129**F, a valve core removal tool **129**G, a tire bead breaker tool **129**H, a wheel cleaning tool **129**I, a lug wrench **129**J, a tire balancing bead dispenser **129**K, a tire inflation tool **129**L, and a tire balancer **129**M, suitable examples of which are provided in U.S. Pat. No. 11,446,826 issued on Sep. 20, 2022 and titled "Autonomous Traverse Tire Changing Bot, Autonomous Tire Changing System, and Method Therefor," and United States provisional patent application No. 63/354,591 titled "Autonomous Tire and Wheel Balancer and Method Therefor" and filed on Jun. 22, 2022, the disclosures of which were previously incorporated herein by reference in their entireties. In accordance with one or more aspects of the present disclosure the wheel or tire engagement tool **129** also includes a proximity sensor **129**N, a wheel weight installation tool **129**O, a wheel weight gripper **129**P (also referred to herein as a wheel balancing weight grip), a wheel weight dispenser **129**Q, and/or any other suitable tool that effects changing a tire **111**T. The wheel weight installation tool **129**O and wheel weight gripper **129**Q each form a compliant end effector that, as described herein, interfaces the wheel assembly **111** determining a wheel or rim location (e.g., relative to a reference frame RREF of the bot **120**, **120**WR) of the wheel **111**W of the tire wheel assembly **111** and predetermined locations (such as wheel weight locations on the wheel **111**W) so as to effect a balancing solution of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including but not limited to the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to the wheel hub **110**H (see FIG. **1**B)) via robotic application of wheel balancing weights **400** with the compliant end effector. In one or more aspects, the above-noted tools are stored on any suitable tool holder **134** carried by the carriage **120**C or located off-board the bot **120** at a location within the tire changing station **101** that is accessible by the at least one actuator **126**.

[0192] In one or more aspects, the above-noted tools are interchangeable/swappable with each other so that the end effector **128** places one and picks up another different tool for performing tire changing tasks. For example, the bot **120** includes a controller **160** that is configured to command the at least one actuator **126**, based on a task to be performed, to automatically exchange one tool for another, such as through articulation of the at least one actuator **126** the end effector **128** places a tool (e.g., such as the tire bead breaker tool **129**H) at the tool holder **134** and then picks another different tool from the tool holder (e.g., such as tire inflation tool **129**L) for performing a subsequent step in the tire change process.

[0193] In other aspects, the bot **120** includes more than one actuator **126**, **126**A (two actuators are shown in FIGS. **1**A-**1**B for exemplary purposes, but in other aspects there may be more than two actuators). Each of the more than one actuator **126**, **126**A has a different respective actuator movement axis (noting each actuator **126**, **126**A includes respective axes AX**1**-AX**6** of articulation for exemplary purposes only), and a different respective end effector **128**, **128**A disposed for working on the wheel **111**W or tire **111**T mounted on the vehicle **110** (or off the vehicle). Here, in one or more aspects, each actuator **126**, **126**A holds a different one of the tools noted above (e.g., there may an actuator **126** for each tool, noting that in some aspects, the tools are also exchangeable so that one actuator **126** is common to a number of tools that are selectably coupled (such as by employing a tool changer—see FIG. **1**B) to the common actuator **126**, as noted above). Further, the above-noted tools are combined, in some aspects, so that a single combination tool performs several tasks. For example, in one aspect, the wheel weight dispenser **129**Q, the wheel weight gripper **129**P, the wheel weight installation tool **129**O, and/or the proximity sensor **129**N may be combined, where when combined (in any suitable combination) the proximity sensor **129**N provides for one or more of the wheel weight dispenser **129**Q, the wheel weight gripper **129**P and/or the wheel weight installation tool **129**O determining a location of the wheel assembly **111** relative to the reference frame RREF of the robot **120**, **120**WR. In other aspects, one or more of the wheel weight dispenser **129**Q, the wheel weight gripper **129**P and/or the wheel weight installation tool **129**O, and the proximity sensor **129**N may be combined with one or more of the wheel assembly grip **129**A, the a valve stem cap installation tool **129**B, a valve stem cap removal tool **129**C, a tire deflation tool **129**D, a tire mounting/dismounting tool **129**E, a valve core installation tool **129**F, a valve core removal tool **129**G, a tire bead breaker tool **129**H, a wheel cleaning tool **129**I, a lug wrench **129**J, a tire balancing bead dispenser **129**K, a tire inflation tool **129**L, a tire balancer **129**M, and/or any other suitable tool that effects changing a tire **111**T (noting any other combinations of the various tools may be effected and are within the scope of the present disclosure).

[0194] The controller **160** is also configured to control the drives of the bot **120** (e.g., drives of the actuator **126** and carriage **120**C that effect movement of the actuator **126** and carriage **120**C as described herein) to position the carriage **120**C relative to the vehicle **110**, another bot **120** or other component (e.g., tire balancer, tire changing machine, cart, etc.) of the tire changing system **100**. Referring also to FIG. **3**, the controller **160** includes a network application interface **330** and a communication module **331** (configured as a hardware or software module) so that the bot **120** communicates with the control console **310** and/or cloud based services (e.g. such as for bot software updates). The con-

troller **160** is programmed with process control algorithms and state machines **332** to effect the operation of the bot **120** as described herein. A motion application interface **333** and vision application interface **334** are also provided in the controller **160** so that the process control algorithms and state machines **332** interface with motion controllers **335** and vision processors **336** of the bot **120**. The bot **120** includes any suitable onboard communications network **337** (such as an EtherCAT or other suitable network) that communicably couples the cameras, drives, motors, sensors, actuators, switches, etc. (as described herein) of the bot **120** to a respective motion controller **335** or vision processor **336**. While the controller **160** of the bot **120** was described, it should be understood that controllers of the other tire changing system **100** devices **320**A-**320***n* are substantially similar to the controller **160**.

[0195] Referring to FIGS. **1**A-**1**B and **3** a control architecture **300** of the tire changing system **100** will be described. The control architecture of the tire changing system **100** generally includes a business and application logic portion **301**, a control console **310**, and one or more tire changing system devices **320**A-**320***n* (where n is an integer that denotes an upper numerical limit to the number of tire changing system devices in the tire changing system **100**). The control console **310** includes any suitable processors and memory for controlling aspects of the tire changing system **100** as described herein (noting the memory is any suitable memory accessible by the processors such as a memory resident within the tire changing system **100** or a cloud based memory as described herein), and is communicably connected (e.g., wirelessly, through wires, is carried by, or remotely located) to the devices **320**A-**320***n*. The one or more tire changing system devices **320**A-**320***n* are any one or more of the devices described herein (i.e., bots **120**, automated or semi-automated tire changing machines **182**, automated or semi-automated tire balancing machines **183**, tire storage racks/carts **187**, wheel weight dispensers **181**, barriers, etc.). The one or more tire changing system devices **320**A-**320***n* are in one aspect assigned to a single tire changing station **101** (such as where the service facility has a single service bay), or in other aspects, some of the tire changing system devices **320**A-**320***n* are assigned to one tire changing station **101** and other ones of the tire changing system devices **320**A-**320***n* are assigned to another tire changing station **101** (such as where the service facility has more than one service bay).

[0196] As can be seen in FIG. **3**, a portion of the business and application logic portion **301** overlaps with a portion of the control console **310**; however in other aspects there may not be any overlap. For exemplary purposes, a portion of the business and application logic portion **301** is resident in the control console **310**. The business and application logic portion **301** is configured with any suitable operating system (OS) configured (e.g., programmed with non-transitory computer readable code executed on any suitable processor of the control console **310**) to facilitate one or more of local services and cloud based services. The control console **310** includes a database access and management module **302** (which may be configured as a hardware or software module), a cloud interface module **303** (which may be configured as a hardware or software module), an operator graphical user interface **304**, and an application logic module **305** (which may be configured as a hardware or software module) that are shared with the business and application logic portion **301**.

[0197] The operator graphical user interface **304** is configured (e.g., programmed with non-transitory computer readable code executed any suitable processors and memory) to facilitate operator input and control (e.g., both operational control for tire changing services and administrative services (e.g., billing, software updates, database entry, billing, inventory, etc.) control) of the tire changing system **100**. The database access and management module **302** is in communication with operator graphical user interface **304** and any suitable database(s) **360** and facilitates access to and storage of information including, but not limited to tire information, customer information, vehicle information, billing information, and inventory and relationships between the various information (i.e., each customer or vehicle has a respective record that includes respective tire information, respective billing information, etc.). The cloud interface module **303** is configured (e.g., programmed with non-transitory computer readable code executed any suitable processors and memory) to provide an interface between the control console and one or more cloud services. It is noted that reference to cloud services herein pertains to cloud computing which is known as the on-demand availability of computer system resources, especially data storage and computing power, without direct active management by the user and generally refers to data centers available to many users over the Internet. These cloud services include but are not limited to remote access to the tire changing system **100**, point of service payment and billing, and over-the-air software updates to components of the tire changing system **100**. The application logic module **305** is configured to at least interface the operator graphical user interface **304**, the database access and management module **302**, and the cloud interface module **303** with each other.

[0198] The control console **310** also includes a Web application interface **306**, a process monitor module **307** (which may be configured as a hardware or software module), a process control module **308** (which may be configured as a hardware or software module), a device maintenance module **309** (which may be configured as a hardware or software module), and a network application interface to device module **311** (which may be configured as a hardware or software module). The Web application interface **306** is configured (e.g., programmed with non-transitory computer readable code executed any suitable processors and memory) to provide access, e.g., for the operator graphical user interface and/or other modules of the control console, to a web server and/or web browser (e.g., for accessing the cloud services). The process monitor module **307** is configured to (e.g., programmed with non-transitory computer readable code executed any suitable processors and memory) monitor (e.g., by sending data to and receiving data from the devices **320**A-**320***n* indicating a tire change process has started, has ended, or paused due to error) the tire changing process as described herein and provide feedback to the process control module **308**. The process control module **308** is programmed (e.g., programmed with non-transitory computer readable code executed any suitable processors and memory) to issue commands to the devices **320**A-**320***n* controlling the process flow for a tire change so that tire change operations are performed in a predetermined sequence that may depend on the type of tire change and tire

change services requested. The device maintenance module **309** is programmed (e.g., programmed with non-transitory computer readable code executed any suitable processors and memory) to monitor a health of the devices **320**A-**320***n* and provide maintenance alerts to the operator through the operator graphical user interface **304**. The network application interface to device module **1011** is configured to provides a wired or wireless interface between the components of the control console and the devices **320**A-**320***n*.

[0199] In the aspect illustrated in FIGS. **1**A-**1**B the control console **310** is disposed on the floor **198** and is remotely connected (through either a wired or wireless connection) to the devices **320**A-**320***n*. Referring to controller **160** of the bot **120**, for exemplary purposes, the controller **160** (including suitable processors and memory **161** for controlling operations of the bot **120** as described herein) is in communication with the control console **310** and is communicably connected (e.g., wirelessly, through wires, is carried by, or remotely located) to the bot drives so as to effect operation of the bot **120** for wheel changing operations, and in some aspects traverse of the bot **120** along the traverse path **299** effecting dynamic positioning of the at least one actuator **126**. In some aspects, the wheel changing operations employing one or more vision systems **130**, **162** and respective cameras **131**, **163**, **163**A, **163**B, **163**C, **163**D (see also FIG. **2**B) to locate to a variable position of the vehicle **110** with the wheel **111**W or tire **111**T mounted thereon relative to the bot **120**. Suitable examples of vision systems that may be employed herein can be found in U.S. Pat. No. 11,446,826 issued on Sep. 20, 2022 and titled "Autonomous Traverse Tire Changing Bot, Autonomous Tire Changing System, and Method Therefor," previously incorporated herein by reference in its entirety. For example, in a service facility the vehicle service technician **199** drives the vehicle **110** into a service bay. As may be realized, there is nothing to locate the vehicle **110**, in the service bay, at any particular location (e.g., the vehicle may never be located in the same place twice) such as would be the case in a vehicle assembly line where the vehicle is carried by a conveyor and stopped at designated/predetermined positions (with respect to assembly automation) for assembly operations. Moreover, vehicles that are serviced in service facilities have varying wheel bases, varying wheel tracks, varying ride heights, varying camber, varying caster, etc. from vehicle to vehicle (e.g., many different makes and models of vehicles are serviced in the same service bay in any given amount of time one after the other), unlike in a vehicle assembly line where assembly operations are performed on the same make and model vehicle. As such, in service facility operations, within any given service bay (e.g., tire changing station **101**), the vehicle **110** (and the components thereof) has a dynamically varying position (that changes from vehicle to vehicle, or even for the same vehicle each time that vehicle is driven into and parked within the service bay) with respect to the tools/machines within the tire changing station **101**. Here, the positioning of the at least one actuator **126** relative to the variable position of the vehicle **110** with the wheel **111**W or tire **111**T mounted thereon is disposed so that articulation of the at least one actuator **126** engages the wheel or tire engagement tool **129** to the wheel **111**W or tire **111**T on the vehicle **110** in the variable position.

[0200] Referring also to FIGS. **1**A-**1**B, in the example illustrated in FIG. **2**C, the tire changing system **100** includes automated or semi-automated tire changing machine(s) **182** and automated or semi-automated tire balancing machine(s) **183** where the bot **120** is configured to remove a wheel assembly **111** from the vehicle and transport the wheel assembly **111** to the tire changing machine **182**. Here, the end effector **128**, with the wheel or tire engagement tool **129** coupled thereto, on articulation of the at least one actuator **126** is configured to place the wheel **111**W, with the tire **111**T mounted thereto, on the automated (or semi-automated) tire changing machine. In the case of removing the tire **111**T from the wheel **111**W, the bot end effector **128** is configured to remove the tire **111**T (e.g., a used or old tire **111**TU), uninstalled from the wheel **111**W by the automated (or semi-automated) tire changing machine **182**, from the tire changing machine **182**. In the case of installing the tire **111**T to the wheel **111**W, the end effector **128** is configured to place another tire **111**T (e.g., a replacement tire **111**TN) on the automated (or semi-automated) tire changing machine **182** for installation of the other tire **111**TN to the wheel **111**W by the tire changing machine **182**. The end effector **128**, with the wheel or tire engagement tool **129** coupled thereto, on articulation of the at least one actuator **126** is configured to place the wheel **111**W, with the other tire **111**TN mounted thereto, on the automated (or semi-automated) tire balancing machine **183**. Here, in one or more aspects, one of the robotic actuators **126**, **126**A picks wheels weights from a hopper and applies them to the wheel in locations identified by the tire balancing machine **183**. Once balanced the wheel assembly **111** may be installed on the vehicle **110** by the bot **120**.

[0201] As may be realized (and shown in FIGS. **1**A-**1**B, **2**A, and **2**D) the tire changing system **100** is configured, in some aspects, to provide both in situ tire changes with the wheel **111**W mounted in situ on the vehicle **110** and tire changes performed by the tire changing machine(s) **182** and tire balancing machine(s) **183** with the wheel **111**W removed (i.e., located off of) the vehicle **110**. The configuration of the tire changing system **100** between in-situ tire changes and tire changes with the wheel **111**W removed from the vehicle may be effected through the control console **310**. For example, as noted above, the vehicle service technician **199** may select an in-situ tire change and/or a tire change with the wheel **111**W removed from the operator graphical user interface **304**. The operator graphical user interface **304**, in one aspect, is also configured to allow the vehicle service technician **199** to select which tires (e.g., passenger front, passenger rear, drive front, or drive rear) are to be changed in-situ or by removing the wheel **111**W so that in-situ and removed wheel tire changes are performed on a common vehicle.

[0202] The control console **310** is also configured, such as through inputs on the operator graphical user interface **304**, so that the vehicle service technician **199** selects which tire change operations are to be performed. For example, the vehicle service technician **199** may select, and the control console **310** is configured to effect such selection, a type of balancing to be performed on a tire (e.g., wheel weights, tire beads, etc.), whether a valve core is replaced, which tires are to be replaced, the make/model/size of tire to be installed, whether some tire change operations are to be performed manually or in a semi-autonomous manner, etc. In some aspects, there are pre-programmed tire change routines **361** corresponding to a respective type of vehicle (car, truck, sports car, make, model, etc.), a respective type of wheel or tire, and or a respective customer that are stored in a memory

such as database **360**. These pre-programmed tire change routines **1061** are selectable by the vehicle service technician **199** through, for example, the operator graphical user interface **304** and specify a tire change recipe (which tire change processes are to be performed and whether or not one or more tires are changed in-situ or changed by removing the wheel).

[0203] Referring to FIGS. **1**A-**1**B, **2**A-**2**C, and **5**-**8**, in one aspect, the automated tire changing system **100** includes supply carts **187** configured to hold tires **111**T, wheels **111**W, and or wheel assemblies **111**. In one or more aspects, one or more of the supply carts **187** are manual carts that are moved from location to location by, for example, the vehicle service technician **199**. In one or more other aspects, one or more of the carts **187** is an automated cart having a cart drive section **188**, where the cart includes a controller **160'** and memory **161'**, vision system **130'**, positioning sensors **132'**, and navigation system **163'**, which are substantially similar to the controller **160** and memory **161**, vision system **130**, positioning sensors **132**, and navigation system **133** of a wheeled bot **120** (noting that manual and automated carts can be used alongside each other). Here, the cart autonomously navigates throughout the tire changing station **101** in a manner substantially similar to that described above with respect to bot **120**. In still other aspects, one or more of the carts **187** (such as the manual cart) is configured to be towed by a wheeled bot **120** or an automated cart to a predetermined location within the tire changing station **101**.

[0204] As may be realized, the automated tire changing system **100**, in one or more aspects, includes fencing or other barriers **227** (see FIG. **2**B) to substantially isolate the vehicle service technician **199** from the bots **120** and automated supply carts **187** when in operation. In some aspects, the barriers **227** have any suitable interlock devices that terminate power to specific axes of motion or all axes of motion of the bot **120** (and any other automation of the tire changing system **100**) upon opening a door to the barrier **227** and/or entering the barrier **227**. In other aspects, the bots **120** and automated supply carts **187** are configured to collaboratively operate with the vehicle service technician **199** so as to hand off tires **111**T, wheels **111**W, wheel assemblies **111**, etc. to/from the vehicle service technician **199**.

[0205] Referring to FIGS. **1**, **4**A, and **4**B, as described herein, the automated tire changing system **100** is configured to install wheel weights **400** on a wheel **111**W and/or on a wheel assembly **111** (a wheel **111**W with a tire **111**T mounted thereon, also referred to herein as a tire-wheel assembly) with the wheel **111**W and/or wheel assembly **111** mounted on a vehicle **110**. As also described herein, the robot **120** includes an end effector **128** configured to couple with the wheel weight gripper **129**P (FIGS. **4**A and **4**B) and the wheel weight installation tool **129**O (FIGS. **5**A-**5**C), where the wheel weight gripper **129**P and the wheel weight installation tool **129**O are interchangeable/swappable with each other on the end effector **128** as described herein. The end effector **128** and/or the wheel weight gripper **129**P and the wheel weight installation tool **129**O are configured in any suitable manner (such as in a manner similar to that illustrated and described with respect to, e.g., FIGS. **5**A and **9**B but such illustration is only exemplary and the configuration of the end effector and/or the structural connection between the end effector and the wheel weight gripper **129**P and the wheel weight installation tool **129**O is not limited to what is illustrated) such that the wheel weight gripper **129**P and wheel weight installation tool **129**O are inserted into the barrel **450** of the wheel **111**W with the wheel **111**W mounted on the vehicle **110** for application of the wheel weight **400**. In other aspects, the robot **120** includes sufficient articulation to reach around the wheel assembly **111**/wheel **111**W for inserting the wheel weight gripper **129**P and wheel weight installation tool **129**O into the barrel **450** for installation of a wheel weight **400** to the surface **450**S of the barrel **450**. In still other aspects, one or more wheel weight installation robot **120**WR (see FIG. **1**B) may be provided where the wheel weight installation robot is shaped and sized to travel (e.g., in manners similar to those described above with respect to robot **120**) underneath the lifted vehicle **110** and access the barrel **450** of a wheel **111**W for installing (or removing) wheel weights **400**. The wheel weight installation robot **120**WR includes a controller **120"** similar to controller **160** of robot **120**, where the controllers **120**, **120'**, **120"** (and any other suitable controller of the automated tire changing system **100**) may be communicably connected to one another so as to pass information therebetween for cooperative operation of respectively controlled components of the automated tire changing system **100**.

[0206] FIGS. **4**A and **4**B schematically illustrate the wheel weight gripper **129**P coupled to the end effector **128** (or distal end **120**D which comprises the end effector **128**S) of robot **120**. The wheel weight gripper **129**P is a conformable or conforming wheel weight gripper that includes a resilient/compliant structure that conforms, from a relaxed configuration (as illustrated in FIG. **4**A—shown where the flexible grip **420** is substantially straight or planar for exemplary purposes only, but in other aspects the flexible grip may have a curved shape in the relaxed configuration), to a surface of the wheel **111**W onto which the wheel weight **400**, carried by the wheel weight gripper **129**P, is applied. The wheel weight gripper **129**P includes resiliently compliant wheel balancing weight applicator **129**PA having a rigid frame or base **410**, a compliant support **415** (also referred to herein as a resiliently compliant wheel balancing weight applicator), and a flexible grip **420** (also referred to herein as a wheel balancing weight grip). The rigid base **410** is configured for coupling with the end effector **128** in any suitable manner, such as in accordance with the releasable couplings of the end effector **128**. In some aspects, the wheel weight gripper **129**P may be a unitary one piece member, while in other aspects the components of the wheel weight gripper **129**P may be coupled to each other in any suitable manner (e.g., mechanically or chemically). In still other aspects, the wheel weight gripper **129**P may be integral with the end effector **128**. It is noted that the configuration of the wheel weight gripper **129**P described herein is exemplary and the wheel weight gripper **129**P may have any suitable compliant structure for adhering wheel weights to a wheel as described herein.

[0207] The compliant support **415** has a resilient body **415**B that has a first side **415S1** and a second side **415S2**. The first side **415S1** is coupled to the rigid base **410** in any suitable manner (e.g., mechanical or chemical fasteners, welding, brazing, over-molding the resilient body **415**B over/on the rigid base **410** (or vice versa), or any other suitable manner) so that the rigid base **410** and resilient body **415**B are carried together as unit by the robot **120**. The compliant support **415** is illustrated as having an opposing leaf spring or opposing bow configuration for exemplary purposes only and in other aspects has any suitable configu-

ration that provides for conformity and flexing of the flexible grip **420**. In this example, the compliant support includes a first resilient leaf or bow **416** that is coupled at its ends **416**E**1**, **416**E**2** to the first side **415**S**1**. The first leaf **416** has a crown **416**C disposed between the ends **416**E**1**, **416**E**2**. A second resilient leaf or bow **417** has ends **417**E**1**, **417**E**2** and a crown **417**C disposed between the ends **417**E**1**, **417**E**2**. The crown **417**C of the second leaf **417** is coupled to the crown **416**C of the first leaf **416** so as to form the opposing leaf or opposing bow configuration. The ends **417**E**1**, **417**E**2** of the second leaf **317** are coupled to the second side **415**S**2**. In one aspect, the compliant support **415** is formed with the sides **415**S**1**, **415**S**2** of any suitable resilient material (e.g., rubber, plastic, spring steel, etc.) as a single one piece unit (e.g., by molding as a single one piece unit, welding, brazing, etc.).

[0208] The flexible grip **420** is coupled to the second side **415**S**2** of the resilient body **415** in any suitable manner (e.g., mechanical or chemical fasteners, welding, brazing, over-molding the resilient body **415**B over/on the flexible grip **420** (or vice versa), or any other suitable manner) so that the rigid base **410**, the resilient body **415**B, and flexible grip **420** are carried together as unit by the robot **120**. The flexible grip **420** is configured to grip and hold one or more wheel weights **400** against a weight interface surface **420**S of the flexible grip **420** in any suitable manner. For example, the flexible grip **420** includes one or more of adhesives **474**, magnet(s) **471**, vacuum grip(s) **472**, and spring clips **473** (or other suitable clips) that grip the wheel weight and hold the wheel weight against the flexible grip for transport by the robot **120** and for application to a surface **450**S of the barrel **450** of the wheel **111**W. Where vacuum grip(s) **472** are provided, any suitable vacuum source VC is provided on the robot **120** or end effector **128** and is coupled to the vacuum grip(s) **472** such as by hoses or any other suitable conduit.

[0209] Referring also to FIG. **4**C, the magnet(s) **471** of the flexible grip **420** may be segmented permanent magnets (or electromagnets) **471**S arrayed along a length L of the flexible grip **420** where a spacing S between the magnets **471** allows the flexible grip **420** to bend and flex so as to conform to the surface **450**S of the barrel **450**. In other aspects, the flexible grip **420** may be formed of a flexible magnetic material such that magnetic properties are inherent in the flexible grip **420**. Wheels weights made of ferrous material are magnetically attracted to and held by the magnet(s) **471** of the flexible grip **420**.

[0210] Referring also to FIGS. **4**D and **4**E, in one or more aspects, two or more clips **473** are arrayed along the length L of the flexible grip **420** where a spacing S between the clips **473** allows the flexible grip **420** to bend and flex so as to conform to the surface **450**S of the barrel **450**. In other aspects, one clip **473** may be disposed anywhere along the length L and span any suitable portion of the length L so as to grip the wheel weight **400**. Each clip **473** includes a pair of opposing tines **473**T that are resilient and spaced from one another any suitable distance so that the wheel weight **400** passes between the opposing tines **473**T and is held by the opposing tines **473**T with a friction force between the opposing tines **473**T and the wheel weight **400**. The clip(s) **473** provide for gripping of wheel weights constructed with or without ferrous material.

[0211] Referring also to FIG. **4**F, in one or more aspects, two or more vacuum grip(s) **472** are arrayed along the length L of the flexible grip **420** where a spacing S between the vacuum grips **472** allows the flexible grip **420** to bend and flex so as to conform to the surface **450**S of the barrel **450**. In other aspects, one vacuum grip may be disposed substantially midway along the length L so as to grip the wheel weight **400**. Each of the vacuum grip(s) **472** are provided with a suction force sufficient to hold a wheel weight **400** regardless of whether all of the vacuum grips **472** engage the wheel weight **400**. The vacuum grip(s) **473** provide for gripping of wheel weights constructed with or without ferrous material.

[0212] Referring still to FIGS. **4**A and **4**B, with the compliant support **415** in a relaxed state (as illustrated in FIG. **4**A) the weight interface surface **420**S of the flexible grip **420** is substantially flat and forms a plane **488**. As the robot **120** moves the end effector **128** linearly in direction **499** to engage the surface **450**S of the barrel **450** with the wheel weight gripper **129**P for application of the wheel weight **400** to the surface **450**S. With application of the wheel weight **400** to the surface **450**S, the wheel weight **400** is pressed against the surface **450**S where an array of reaction normal force vectors FV are exerted on the wheel weight **400** by the surface **450**S. The substantially evenly distributed compressive force exerted between the wheel weight **400** and the surface **450**S wets the surface **450**S with adhesive **400**A of the wheel weight **400** and/or activates the adhesive **400**A (which may be a pressure sensitive adhesive) to adhere the wheel weight **400** to the surface **450**S. Here, the reaction normal force vectors FV (and the corresponding force vectors exerted on the wheel weight **400** by the weight interface surface **420**S) are arranged to point towards a center of the arc formed by the surface **450**S of the barrel **450** such that the substantially evenly distributed compressive force exerted on the wheel weight **400** by the weight interface surface **420**S and the surface **450**S causes the wheel weight **400** to bend and flex in conformity with the radius of the surface **450**S as shown in FIG. **4**B. These same reaction normal force vectors FV cause the compliant support **415** to be compressed against the rigid base **410** where the opposing leaf spring configuration of the compliant support allows the weight interface surface **420**S to bend and flex in a manner substantially similar to that of the wheel weight **400** (e.g., the weight interface surface **420**S bends and flexes so as to conform with an imaginary cylinder **489** that has a radius concentric with the radius of the surface **450**S) so that an array of force vectors (equal and opposite to the force vectors FV and having the same magnitudes that effect the substantially evenly distributed compressive force) are applied by the weight interface surface **420**S to the wheel weight **400**. The wheel weight gripper **129**P allows the wheel weight **400** to contour to the surface **450**S of the barrel **450** of the wheel **111**W as the wheel weight **400** is pressed against the surface **450**S with a substantially evenly distributed compressive force.

[0213] Referring to FIGS. **1**A, **1**B, and **5**A-**5**C, the bot **120** is connected to the frame **189**F at a proximal end **120**P of the bot **120**. The bot **120** has a distal end **120**D (that comprises the end effector **128**), opposite the proximal end **120**P, where the distal end **120**D is arranged so as to interface with the wheel assembly **111**. As described herein, the bot has an actuator **126**, where the actuator has a wheel weight installation tool or indexer **129**O arranged to index the end effector **128**, in the at least one degree of freedom of the

robot **120**, and position the end effector **128** at different index positions corresponding to wheel weight locations **580**, **581** on the wheel **111**W

[0214] In one or more aspects, the robot **120** has the wheel weight installation tool **129**O that indexes the distal end **120**D between a retracted position (see FIG. **5**A) and at least one extended position (see FIGS. **5**B and **5**C), wherein in the at least one extended position the distal end **120**D interfaces the wheel assembly **111** (as described herein) determining a wheel or rim location of the wheel **111**W of the tire wheel assembly **111** mounted on the vehicle **110**. In other aspects, the wheel weight installation tool **129**O is coupled to the end effector **128** of the robot **120**, for indexing the distal end **120**D between a retracted position (see FIG. **5**A) and at least one extended position (see FIGS. **5**B and **5**C). In the at least one extended position the distal end **120**D interfaces the wheel assembly **111** determining a wheel or rim location of the wheel or rim **111**W of the wheel assembly **111** and predetermined locations so as to effect a balancing solution of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including but not limited to the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to the wheel hub **110**H (see FIG. **1**B)) via robotic application of wheel weights **400** with the end effector **128**. As described herein, the wheel weight(s) **400** are applied to the surface **450**S of the barrel **450**. As noted above, when applying dynamic balancing weights in an automotive system, the wheel weights are most commonly placed at an inner location **580** (further away from the centerline of the vehicle adjacent the back of the wheel flange or spokes) and an outer location **581** (towards a centerline of the vehicle adjacent the inner wheel lip, e.g., about 25.4 mm (about 1 inch) from the inner wheel lip although in other aspects the outer location may be more or less than about 25.4 mm (about 1 inch)). The wheel weight installation tool **129**O positions wheel weights **400** at one or more locations of the wheel **111**W, including but not limited to those locations **580**, **581** described above.

[0215] The wheel weight installation tool **129**O includes a multi-index stage indexer **512**, where each index stage has at least one index position. In the example illustrated in FIGS. **5**A-**5**C, the multi-index stage indexer **512** includes a first stage formed by actuator **510** and a second stage formed by actuator **511**; however, in other aspects there may be more than two stages. At least one stage of the multi-index stage indexer **512** has different index positions or locations (see, for example, locations **580**, **581**) that position the interface corresponding to wheel balancing weight locations on the wheel **111**W so as to effect the balancing solution.

[0216] In some aspects, the wheel weight installation tool **129**O has an index position (see FIG. **5**A) that places the end effector **128** (or distal end **120**D which comprises the end effector **128**S) in contact with the wheel **111**W determining a wheel or rim location on the wheel **111**W, of the wheel assembly **111** mounted on the vehicle **110**. Here, the one or more of the actuators **510**, **511** include any suitable encoders or other distance determining features for determining an extension of the respective actuator. The wheel weight installation tool **129**O may be positioned adjacent the side wall **111**TS (inclusive of the surface ILS of the inner wheel lip) of the wheel assembly **111** and extended so that the end or tip of the wheel weight installation tool **129**O contacts the side wall **111**TS. The encoder or other distance sensor of the respective actuator sends a signal to the controller **160**, **160"** that embodies the extension distance of the respective actuator **510**, **511** so that the distance **578** between a retracted position of the wheel weight installation tool **129**O (see FIG. **5**A) and the sidewall **111**TS is known. The controller **160**, **160"** may employ the distance **578** when controlling extension of the actuators **510**, **511** for placement of wheel weights at one or more of the wheel weight locations **580**, **581**, such as where the actuators have a variably controlled extension.

[0217] In one aspect, the multi-index stage indexer **512** positions wheel weights at one or more of the inner location **580** and the outer location **581**. The multi-index stage indexer **512** is coupled to a frame **566** of the wheel weight installation tool **129**O. The frame **566** has any suitable configuration for coupling with the end effector **128** and that provides for insertion of at least a portion of the wheel weight installation tool **129**O into the barrel **450** (the configuration of the frame **566** illustrated in FIG. **5**A is exemplary only and the frame may have any other suitable configuration). The multi-index stage indexer **512** includes serially arranged actuators **510**, **511** that provide for a staged extension of the wheel weight installation tool from a retracted position (see FIG. **5**A) to one or more of a first extended position (see FIG. **5**B) and a second extended position (see FIG. **5**C). The first extended position corresponds with placement of a wheel weight **400** at the outer location **581**. The second extended position corresponds with placement of a wheel weight **400** at the inner location **580**.

[0218] The actuators **510**, **511** are any suitable actuators including, but not limited to, one or more of electric actuators, pneumatic actuators, hydraulic actuators, magnetic actuators, screw drives, etc. Each actuator **510**, **511** includes a drive portion **510**D, **511**D and a driven portion **510**A, **511**A. The drive portion **510**D of actuator **510** is coupled to the frame **566** in any suitable manner (e.g., such as mechanical and/or chemical fasteners, welding, brazing, etc.). The drive portion **511**D of actuator **511** is coupled to the driven portion **510**A of the actuator **510** in any suitable manner (e.g., such as mechanical and/or chemical fasteners, welding, brazing, etc.) so that the actuator **511** is carried by and moves as a unit with the driven portion **510**A. A wheel weight gripper **529** (which may be substantially similar in configuration to the wheel weight gripper **129**P described above) is coupled to the driven portion **511**A of the actuator **511** in any suitable manner (e.g., such as mechanical and/or chemical fasteners, welding, brazing, etc.) so that the wheel weight gripper **529** moves with the driven portion **511**A.

[0219] Each actuator **510**, **511** has a predetermined stroke (e.g., extension amount) to effect positioning a wheel weight **400** at one of the inner location **580** and outer location **581** with the robot **120** holding the wheel weight installation tool **129**O at a predetermined retracted position location (see FIG. **5**A). In some aspects, the wheel weight installation tool **129**O is a binary wheel weight positioning mechanism where the predetermined stroke may be mechanically limited (e.g., such as by an end of stroke hard stop or contact with the wheel **111**W) for placement at one or more of the locations **580**, **581**; while in other aspects the predetermined stroke may be controlled such as with any suitable controller **160**, **160"** controlling the drive portion **510**D, **511**D to effect,

with an encoder or distance sensors of the drive (see FIG. **5**A), any suitable predetermined extension distance of one or more of the actuators **510**, **511** for placing wheel weights at one or more location including, but not limited to locations **580**, **581**. The predetermined retracted position location may be determined in any suitable manner so that a reference location (such as reference location **577**—see FIG. **5**A) of the wheel weight installation tool is located a predetermined distance **578** from the inner wheel lip **578** and a predetermined distance **579** from the surface **450**S of the barrel **450**. The reference location **577** may be a center point of the weight interface surface **420**S of the flexible grip **420** (see FIG. **4**A) of the wheel weight gripper **529** or any other suitable location of the wheel weight installation tool **129**O that effects placement of the wheel weight gripper **529** in a known location.

[0220] As an example, referring also to FIGS. **1**A and **1**B, the predetermined retracted position location of the wheel weight installation tool **129**O may be determined from data obtained by the one or more of the vision systems **130**, **162** of the tire changing system **100** and/or the proximity sensor **129**N (the proximity sensor being combined with or employed separately from the wheel weight installation tool **129**O) that effects changing of the tire(s) **111**T on the vehicle **110**. To effect a tire change, one or more of the vision systems **130**, **162** maps one or more sides of the vehicle **110** to identify the location of each wheel assembly **111** of the vehicle **110** and identify the tire size in a manner similar to that described in U.S. Pat. No. 11,446,826 issued on Sep. 20, 2022 and titled "Autonomous Traverse Tire Changing Bot, Autonomous Tire Changing System, and Method Therefor," previously incorporated herein by reference in its entirety; while in other aspects the proximity sensor **129**N is employed as described herein for localization of the wheel assembly **111**. The identification of the location of each wheel assembly **111** (within the tire changing station **101**) and tire size informs the controller **160**, **160"** of a position (e.g., the substantially vertical plane) of the inner wheel lip for each wheel assembly **111** and a (vertical or height) position of the surface **450**S of the barrel **450** with respect to the robot **120** coordinate system. With the positions of the inner wheel lip and surface **450**S known, the controller **160** determines, in any suitable manner, the predetermined retracted position location of the wheel weight installation tool **129**O (e.g., in the robot coordinate system) based on the positions of the inner wheel lip and surface **450**S.

[0221] With the wheel weight installation tool **129**O in the predetermined retracted position location (see FIG. **5**A), the controller **160** effects actuation of one or more of the actuators **510**, **511** for placement of a wheel weight **400** at the inner location **580** and the outer location **581** or any other suitable location that resolves and provides for a balancing solution of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including, but not limited, to the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to a wheel hub **110**H (see FIG. **1**B)). Here, the wheel assembly **111** is rotated in any suitable manner (e.g., through automation or manually with the wheel assembly **111** mounted to the vehicle **110**) so that the angular (with respect to tire rotation) wheel weight placement location (as determined by any suitable wheel balancer such as those described in U.S. provisional patent application No. 63/354,591 titled "Autonomous Tire and Wheel Balancer and Method Therefor" and filed on Jun. 22, 2022, the disclosure of which was previously incorporated herein by reference in its entirety) is held substantially aligned with the predetermined retracted position location of the wheel weight installation tool **129**O. As one example, the wheel weight installation tool **129**O may be employed with the one or more wheel weight installation robot **120**WR (see FIG. **1**B) while the robot **120** rotates and holds the wheel assembly **111** with, e.g., the tire balancer **129**M. As another example, the wheel weight installation tool **129**O may be combined with the tire balancer **129**M where the tire balancer rotates the wheel assembly **111** and holds the wheel assembly **111** for installation of the wheel weight **400**. In still other examples, one actuator **126** of the robot **120** may rotate and hold the wheel assembly **111** while another actuator **126**A of the robot **120** (see FIG. **1**B) (or another robot **120**) applies the wheel weight **400**. In other aspects, the robot **120** may be employed with an off-the-car tire balancing machine **183** in a manner similar to that described herein for applying a wheel weight **400** with the wheel weight installation tool **129**O to a wheel assembly **111** mounted on the tire balancing machine **183**.

[0222] With the wheel weight installation tool **129**O disposed at the predetermined retracted position location, the driven portion **510**A of the actuator **510** has a stroke SR**1** (FIG. **5**B) that places the wheel weight gripper **529** (and the wheel weight **400** held thereby) at the outer location **581**. With the wheel weight gripper **529** (and the wheel weight **400** held thereby) at the outer location **581**, the robot **120** moves the wheel weight installation tool **129**O in direction **499** so that the wheel weight **400** is pressed against the surface **4505** of the barrel **450** of the wheel **111**W in a manner similar to that described herein to affix or otherwise bond the wheel weight **400** to the surface **450**S.

[0223] With the wheel weight installation tool **129**O disposed at the predetermined retracted position location, the driven portion **510**A of the actuator **510** has a stroke SR**1**, and the driven portion **511**A of the actuator **511** has a stroke SR**2** (FIG. **5**C), that when combined places the wheel weight gripper **529** (and the wheel weight **400** held thereby) at the inner location **580**. With the wheel weight gripper **529** (and the wheel weight **400** held thereby) at the inner location **580**, the robot **120** moves the wheel weight installation tool **129**O in direction **499** so that the wheel weight **400** is pressed against the surface **450**S of the barrel **450** of the wheel **111**W in a manner similar to that described herein to affix or otherwise bond the wheel weight **400** to the surface **450**S.

[0224] In one or more aspects, the wheel weight installation tool **129**O provides for binary control of the wheel weight **400** position and application of wheel weights **400** at the most commonly employed wheel weight positions of standardized wheels **111**W (e.g., the inner location **580** and the outer location **581** of the wheel **111**W). In one aspect, the strokes SR**1**, SR**2** of the actuators **510**, **511** are such that the wheel weight **400** may be positioned at the inner location **580** and the outer location **581** within a predetermined tolerance for standardized wheels having different widths. For example, different wheel weight installation tools **129**O, **1290**A-**129**O*n* may be provided, where each wheel weight installation tool **129**O effects wheel weight installation for a respective range of wheel widths. For example, one wheel weight installation tool **129**O effects wheel weight installation for wheel widths ranging from about 152.4 mm (about

6 inches) to about 228.6 (about 9 inches), another wheel weight installation tool **129**O effects wheel weight installation for wheel widths ranging from about 241.3 mm (about 9.5 inches) to about 304.8 mm (about 12 inches), etc. (noting that the gradation of ranges may be any suitable gradation and those gradations provided herein are for exemplary purposes only). The strokes SR**1**, SR**2** of the actuators **510**, **511** are limited in any suitable manner such as by stops built into the respective actuators and/or through contact with the wheel **111**W. In other aspects, the strokes SR**1**, SR**2** of the actuators **510**, **511** are such that the wheel weight **400** may be positioned at the inner location **580** and the outer location **581** regardless of the wheel assembly **111** build (e.g., regardless of wheel width). Here, the stroke SR**1** of the actuator **510** is such that, with the wheel weight installation tool **129**O disposed at the predetermined retracted position location, the wheel weight gripper **529** (and the wheel weight **400** held thereby) is positioned at the outer location **581** (about cm (about 1 inch) from the inner wheel lip although in other aspects placement may be more or less than about 25.4 mm (about 1 inch)). The stroke SR**2** of the second actuator **511** is such that extension of the driven portion **511**A is stopped when the wheel weight installation tool **129**O contacts the back of the wheel flange so that contact between the wheel weight installation tool **129**O the back of the wheel flange locates the wheel weight gripper **529** (and the wheel weight **400** held thereby) at the inner location **580**. As may be realized, the wheel weight installation tool **129**O provides for binary placement of wheel weights **400** on a wheel **111**W substantially without feedback, vision systems, or measurement (e.g., wheel width measurement) of the wheel **111**W. In other aspects, as described herein, the wheel weight installation tool provides for placement of wheel weights are locations that include but are not limited to locations **580**, **581**.

[0225] Referring to FIGS. **1**A, **1**B, and **6**A, wheel weights **400** are provided to the wheel weight gripper **129**P and/or the wheel weight installation tool **129**O by a wheel weight dispenser **129**Q, **181**. The wheel weight dispenser is located at any suitable location of the at least one tire changing station **101**. The wheel weight dispenser may be provided as stand-alone wheel weight dispenser **181**, as a tool (see wheel weight dispenser **129**Q) that is coupled to the end effector **128** of a robot **120** (in any suitable manner) or carried (in any suitable manner) by a wheel weight installation robot **120**WR, or integrated/combined with another tool **129**A-**129**P.

[0226] The wheel weight dispenser **129**Q, **181** includes a frame **600** having a spindle or bobbin **610** on which a roll of adhesive wheel weight(s) **699** is supported. Suitable examples of wheel weight material that may be employed with aspects of the disclosure include, but are not limited to, the 3M™ adhesive backed wheel weight rolls provided by the 3M Automotive and Aerospace Solutions Division located in Minnesota USA and the Stickpro™ adhesive wheel weight rolls provided by Plombco located in Quebec Canada.

[0227] A rail **601** is coupled to the frame so as to receive and support wheel weight material **699**M unspooled from the roll of adhesive wheel weight(s) **699**. A wheel weight indexer **620** is coupled to the frame **600**. The wheel weight indexer **620** includes a motor **622** and a roller **621**, where the motor drives rotation of the roller **621**. The roller **621** is positioned on the frame **600** so as to contact the wheel weight material **699**M supported on the rail **601** so that rotation of the roller **621** drives the wheel weight material **699**M along the rail **601** in direction **666** and unspools the wheel weight material **699**M from the roll of adhesive wheel weight(s) **699**. The roller **621** has any suitable configuration for contacting and engaging the wheel weight material **699**M. For example, the roller **621** may be a friction roller that is biased towards the rail **601** in any suitable manner (e.g., a spring, under the weight of the wheel weight indexer **620**, etc.) and against the wheel weight material **699**M for driving and unspooling the wheel weight material **699**M in direction **666**, while in other aspects the roller **621** and the wheel weight indexer **620** may have any suitable configuration for gripping and driving the wheel weight material **699**M in direction **666**.

[0228] The wheel weight dispenser **129**Q, **181** also includes a cutter **640** configured to cut the wheel weight material **699**M into predetermined segments corresponding to a desired amount (e.g., ounces or grams) of weight to be applied to a wheel assembly **111** for balancing of the wheel assembly **111**. The cutter **640** is coupled to the frame **600** in any suitable manner and includes an actuator **642** that drives a cutting blade **641** in direction **691** for cutting the wheel weight material **699**M. The cutting blade **641** is disposed adjacent the roller **621** to cut the wheel weight material **699**M that is driven by and past the roller **621** as described herein.

[0229] The motor **622** includes any suitable motor controller **622**C that is communicably coupled to a controller of the tire changing system **100** (such as of the robot **120**, tire balancing machine **183**, tire balancer **129**M, etc.) so that a desired amount of weight for balancing the wheel assembly **111** (as determined by one or more of the tire balancers **129**M, **183**) is communicated to the motor controller **622**C. The motor **622** may be a stepper motor and/or include any suitable encoders so that, with a known diameter of the roller **621**, the motor controller **622**C operates the motor **622** to dispense or otherwise drive a length of wheel weight material **699**ML past the roller **621**, where the length of wheel weight material **699**ML corresponds to the desired amount of wheel weight for balancing the wheel assembly **111**.

[1] Referring also to FIG. **6**C, where the wheel weight material **699**M is unsegmented any desired amount of wheel weight material **699**M may be dispensed past the roller and cut by the cutting blade **641** to match the desired amount of wheel weight. As can be seen in FIG. **6**C, unsegmented wheel weight material **699**M is driven past the roller so that a predetermined length **699**ML of the wheel material is located downstream (relative to the roller **621** and direction **666** of travel of the wheel weight material **699**M) of the cutting blade **641**. The cutting blade **641** is lowered by the actuator **642** against the rail **601** to cut the predetermined length **699**ML of wheel weight material **699**ML.

[0230] Referring also to FIG. **6**B, where the wheel weight material **699**M is segmented, each segment **699**MS is of a predetermined weight common to all of the segments **699**MS of the roll **699** and of a predetermined length **699**SS common to all of the segments of the roll **699**. The controller **622**C is configured to drive the wheel weight material **699**M by incremental distances substantially equal to the segment length **699**SS so that a number of segments **699**MS are dispensed downstream of the cutting blade **641**, where the number (e.g., one or more) of segments **699**MS (e.g., the predetermined length of wheel weight material **699**ML) is

substantially equal to the desired amount of wheel weight. Here, the incremental distance, which the wheel weight material is driven, maintains substantial alignment between the cutting blade **641** and cut lines that are scribed between and delineate one segment **699**MS from another adjacent segment **699**MS. With the desired number of segments **699**MS disposed downstream of the cutting blade **641**, the cutting blade **641** is lowered by the actuator **642** against the rail **601** to cut the predetermined length of wheel weight material **699**ML.

[0231] The wheel weight dispenser **181**, **129**Q includes a take up spool **630** coupled to the frame **900** and configured in any suitable manner to peel the adhesive backing **699**B from the wheel weight material **699**M and spool the adhesive backing **699**B onto a roll **635** for disposal. An adhesive film real **631** may be coupled to the frame **600** and include roller(s) **632** that press an adhesive film (e.g., unrolled from the adhesive film reel) against the adhesive backing **699**B of the wheel weight material **699**M so that the adhesive film adheres to the adhesive backing **699**B. The adhesive film may be wound/wrapped around the roll **635** so that as the adhesive film is redirected by the roller **632** from being pressed against the wheel weight material **699**M to the roll **635**, the adhesive film peels a leading edge of the adhesive backing **699**B from the wheel weight material **699**M so as to peel the adhesive backing **699**B from the wheel weight material **699**M and spool the adhesive film with the adhesive backing **699**B adhered thereto around the roll **635**. The take up spool **630** (and the adhesive film reel) is driven in rotation by the motor **622** simultaneously with and at the substantially the same rate as the roller **621**. As an example, the motor **622** includes an output on which output the roller **621** is mounted. Any suitable transmission couples the output of the motor **622** to a drive shaft of the take up spool **630**. As illustrated in FIG. **6**A, the transmission includes a pair of gears TG**1**, TG**2**. The gear TG**1** is coupled to the output of the motor **622** and rotates as a unit with the roller **621**. The gear TG**2** is coupled to the drive shaft of the take up spool **630** so as to rotate as a unit with the take up spool **630**. The gears TG**1**, TG**2** are meshed with each other so that as the roller **621** rotates to drive the wheel weight material **699**M in direction **666**, the take up spool **630** also rotates to take up the adhesive backing **699**B peeled from the wheel weight material **699**M at the same rate the wheel weight material is advanced by the roller **621**. While the transmission is described as including gears TG**1**, TG**2**, the transmission may have any suitable configuration (e.g., gears, belts and pulleys, chains and sprockets, etc.) that effects the simultaneous and same rate rotation of the roller **621** and take up spool **630**. As may be realized, rotation of the adhesive film reel may be driven by/controlled with a gear of the above-mentioned transmission where the gear is meshed with gear TG**1**, meshed with the gear TG**2**, or driven by one or gear TG**1**, TG**2** via an idler gear. The take up spool **630** may include any suitable tensioning device, clutch or other tensioning/slipping device that effects peeling of the adhesive backing **699**B substantially without ripping/tearing the adhesive backing **699**B or otherwise stopping the functioning of wheel weight dispenser. In other aspects, the adhesive backing **699**B may be removed from the wheel weight material **699**M with a friction-based system such as a friction roller (see FIG. **6**A). In still other aspects, the adhesive backing **699**B removed from the wheel weight material **699**M may be directed (e.g., in any suitable manner such as by rollers, gravity, etc.) into a collection or waste container (see FIG. **6**A) or is otherwise removed from the wheel weight material **699**M then unmanaged.

[0232] As illustrated in FIG. **6**A, the cut lengths of wheel weight material **699**ML are dispensed onto a wheel weight transport **700** configured to transport the cut lengths of wheel weight material **699**ML to a pick station **799** (see FIGS. **7**B and **8**B) accessible by the wheel weight gripper **129**P and/or the wheel weight installation tool **129**O. The wheel weight gripper **129**P and/or the wheel weight installation tool **129**O picks the cut lengths of wheel weight material **699**ML from the pick station **799** for coupling the cut length of wheel weight material **699**ML to a wheel **111**W as described herein.

[0233] Where, the wheel weight dispenser (e.g., wheel weight dispenser **129**Q) is carried by the robot **120** or wheel weight installation robot **120**WR the wheel weight transport **700** and wheel weight dispenser **129**Q may be coupled to the frame **566** of the wheel weight installation tool **129**O so as to position the a cut length of wheel weights **699**ML (referred to herein as a wheel weight **400**) at the retracted position of the wheel weight gripper **529** (here, another degree of freedom may be provided on the wheel weight dispenser to provide relative movement between the wheel weight gripper **529** and a wheel weight **400** disposed at the pick station **799** and effect picking of the wheel weight **400** by the wheel weight gripper **529** from the pick station **799**). In other aspects, the wheel weight dispenser and wheel weight transport **700** may be carried by one robot **120** or robot actuator **126** while the wheel weight gripper **129**P or wheel weight installation tool **129**O is carried by another robot **120** or robot actuator **126**A so that the pick station **799** is accessible by the wheel weight gripper **129**P or wheel weight installation tool **129**O.

[0234] Where a stationary wheel weight dispenser (e.g., wheel weight dispenser **181**) is employed, the wheel weight transport **700** may receive the wheel weight **400** from the wheel weight dispenser **181** and transport the wheel weight **400** to any suitable location of the tire changing station **101** that is accessible by the wheel weight gripper **129**P and/or the wheel weight installation tool **129**O. The wheel weight transport **700** may be configured so that a single wheel weight dispenser **181** provides wheel weights to (i.e., is common to) multiple pick stations **799** (see FIG. **799**) or a single pick station. There may be one or more wheel weight dispenser(s) **181** (see FIG. **2**A) where each wheel weight dispenser feeds a respective wheel weight transport **700** having one or more pick stations **799**.

[0235] Referring to FIGS. **1**A, **1**B, **6**A, **7**A-**7**F, and **8**A-**8**C, the wheel weight transport **700** includes rail(s) **710**, a conveyance **730**, a drive **720**, and the pick station **799**. In the example illustrated, the rail(s) **710** may include opposing rails **710**A, **710**B each having a weight support surface **711**. The rails **710**A, **710**B may or may not include a respective weight guide surface **712**. The rails **710**A, **710**B are spaced apart from each other by any suitable distance or gap **770** so as to support the wheel weight **400** but span the adhesive **699**A (see FIG. **7**C). In other aspects, there may be a single rail **710**C (see FIG. **8**C) that may or may not include weight guide surfaces **712**. The wheel weight **400** slides along the rails **710**A, **710**B, **710**C in sliding contact with the rails **710**A, **710**B, **710**C or the wheel weight **400** may be disposed on a platen **400**P that slides along the rail(s) and on which the wheel weight **400** is carried. In some aspects, the

adhesive backing **699**B may be stripped from the adhesive **699**A of the wheel weight **400** (in a manner similar to that described above with respect to the FIGS. **6**A-**6**C) at a pick station **799** of the wheel weight transport **700** (e.g., the pick station includes the adhesive film reel **631** roller **632**, spool **630**, and roll **635**); while in other aspects, the adhesive backing **699**B is stripped from the adhesive **699**A of the wheel weight **400** prior to conveyance of the wheel weight **400** by the wheel weight transport **700** as described herein with respect to FIGS. **6**A-**6**C. Where the wheel weight is conveyed with the adhesive backing **699**B removed, the adhesive **699**A may be disposed in a gap **770** between the rails **710**A, **710**B or a above/within a recess **770**A of the platen **400**P.

[0236] The rails **710**A, **710**B, **710**C may have one or more of linear portions (see FIG. **7**A) and curved portions (see FIG. **7**D) that transport the wheel weight **400** to any suitable location of the tire changing station **101**. In one aspect, the weight guide surface **712** of the rails **710**A, **710**B maintains alignment of the wheel weight **400** (and platen **400**P where the wheel weight **400** is disposed on the platen **400**P for transport) with the direction of travel **666** along the rails **710**A, **710**B (e.g., the wheel weight **400** is aligned so that the wheel weight **400** and/or platen **400**P travels with its longitudinal axis substantially aligned with the direction of travel, where the longitudinal axis is generally a longest length of the weight and/or platen). In another aspect, one or more of the rails **710**A, **710**B include a respective array of magnets **710**AR that are arrayed along the length of the respective rail **710**A, **710**B or is constructed of a magnetic material so that a magnetic coupling between one or more of the rails **710**A, **710**B and one or more of the wheel weight **400** and platen **400**P maintains alignment of the wheel weight **400** with the direction of travel **666**. In still other aspects, one or more of the rails **710**A, **710**B includes both the weight guide surface **712** and the array of magnets **710**AR/magnetic material where a combination of contact between the wheel weight **400** and or platen **400**P and the weight guide surface **712** and the magnetic coupling between the wheel weight **400** and/or platen **400**P and the rail(s) **710**A, **710**B maintains alignment of the wheel weight **400** and/or platen **400**P with the direction of travel **666**. In other aspects, the platen **400**P includes a magnet where the wheel weight **400** is aligned to the platen **400**P via the magnet and the platen **400**P is mechanically aligned to the rails **710**A, **710**B. In still other aspects, the wheel weight **400** may be mechanically aligned to the rails **710**A, **710**B in any suitable manner, such as by clips, slots, etc.

[0237] The conveyance **730** is any suitable conveyance configured to convey the wheel weight **400** along the rails **710**A, **710**B. The conveyance **730** may be for example, a belt **730**B, a chain **730**C, or any other suitable conveyance. Where the conveyance is a belt **730** or chain **730**C the belt **730**B may be an articulated belt having articulated links **730**AL (see FIG. **7**D) that configured the belt **730**B to round corners formed by the curved portions of the rails **710**A, **710**B. The conveyance **730** is driven by any suitable drive **720** (including a motor and suitable transmission such as gears, sprockets, pulleys etc.). As another example, the conveyance **730** may be a linear motor **730**M (which has an integral drive). The linear motor includes an electromagnetic driver track **730**EMT and a carrier **730**EMC. The carrier **730**EMC may form the platen **400**P (or otherwise drive the platen **400**P) on which the wheel weight **400** is carried and may be magnetically levitated by and driven along the electromagnetic driver track **730**EMT, while in other aspects, the carrier **730**EMC (forming the platen **400**P or otherwise driving the platen **400**P as described herein) travels on rails and is driven by and along the electromagnetic driver track **730**EMT.

[0238] In one or more aspects, the conveyance includes one or more of drive tabs **730**T (see FIGS. **7**A, **7**B, **7**D, **7**E, and **7**F) that engage and push the wheel weight **400** and/or platen **400**P along the rail(s) **710**A, **710**B, **710**C with movement of the conveyance **730** in direction **777**. In other aspects, the conveyance includes magnetic portions **730**M that form a magnetic coupling with the wheel weight **400** and/or platen **400**P, where the magnetic coupling pulls the wheel weight **400** and/or platen **400**P along the rail(s) **710**A, **710**B, **710**C with movement of the conveyance **730** in direction **777**. In still other aspects, the conveyance may include both tabs **730**T and magnetic portions **730**M that complement each other to push and/or pull the wheel weight **400** and/or platen **400**P along the rail(s) **710**A, **710**B, **710**C.

[0239] The pick station **799** is formed by a portion of the rail(s) **710**A, **710**B, **710**C downstream from a terminus of the conveyance **730** (see FIGS. **7**B and **8**B). The conveyance **730** an "endless" conveyance (see FIGS. **7**B, **7**F, **8**B, and **8**C) that recirculates itself to convey one or more wheel weights **400** to the pick station **799**. In the example illustrated, the conveyance **730** is redirected for recirculation by one or more rollers **733** (or a sprocket, pulley, etc.) where, as the tab **730**T and/or magnetic portion **730**M travels around the roller **733** the tab **730**T and/or magnetic portion **730**M disengages from the wheel weight so that the wheel weight **400** is positioned at the pick station **799**.

[0240] In operation, referring also to FIG. **10**, the wheel weight dispenser **181**, **129**Q cuts a length of wheel weights **699**ML in accordance with a desired amount of wheel weights to effect balancing a wheel assembly (FIG. **10**, Block **1000**). The wheel weight dispenser **1181**, **129**Q pushes the cut length of wheel weights **699**ML (e.g., the wheel weight **400** is dispensed) onto the rails **710** (FIG. **10**, Block **1010**). With the conveyance **730** being driven by the drive **720**, a tab **730**T and/or magnetic portion **730**M couples with the wheel weight **400** and conveys the wheel weight along the rails **710** to the pick station **799** (FIG. **10**, Block **1020**). At the pick station **799**, the tab **730**T and/or magnetic portion **730**M disengages/decouples from the wheel weight **400** effecting positioning of the wheel weight **400** at the pick station **799** (FIG. **10**, Block **1030**). The wheel weight **400** is picked from the pick station **799** (FIG. **10**, Block **1040**) by the wheel weight gripper **129**P or the wheel weight installation tool **129**O in the manner described herein and the wheel weight **400** is affixed/coupled to the surface **450**S of the barrel **450** of the wheel **111**W (FIG. **10**, Block **1050**) as described herein.

[0241] Referring to FIGS. **1**A, **1**B, **9**A, **9**B, and **9**C, the proximity sensor **129**N is coupled to the end effector **128** of the robot **120**, **120**WR in any suitable manner so that the proximity sensor **129**N is positioned to interface with the surfaces of the wheel assembly **111**W closest to the centerline of the vehicle such as the surface ILS of the inner wheel lip and the sidewall **111**TS of the tire **111**T, although in other aspects the proximity sensor may interface with any suitable surface(s) of the wheel assembly **111**. The proximity sensor **129**N is any suitable sensor including, but not limited to, one or more of a contact sensor (such as a limit switch or other

suitable contact sensor), optical sensor, and ultrasonic sensor, where the proximity sensor (via movement of the bot **120**) resolves the predetermined location of the tire-wheel assembly relative to the reference frame RREF of the bot **120**.

[0242] As described above and in U.S. Pat. No. 11,446,826 issued on Sep. 20, 2022 and titled "Autonomous Traverse Tire Changing Bot, Autonomous Tire Changing System, and Method Therefor," previously incorporated herein by reference in its entirety, the position and diameter of the tire **111**T may be known to the controller **160** from one or more of the vision systems **130**, **162**. Here, the one or more vision systems **130**, **162** may be employed in combination with the proximity sensor to resolve the predetermined location of the tire-wheel assembly relative to the reference frame RREF of the bot **120**, the one or more vision systems **130**, **162** alone may be employed to resolve the predetermined location of the tire-wheel assembly relative to the reference frame RREF of the bot **120**, or the proximity sensor **129**N alone may be employed to resolve the predetermined location of the tire-wheel assembly relative to the reference frame RREF of the bot **120**.

[0243] Where the proximity sensor **129**N is employed to, at least in part, resolve the predetermined location of the tire-wheel assembly relative to the reference frame RREF of the bot **120** the proximity sensor **129**N is moved by the bot **120** in one or more degrees of freedom so as to sense or otherwise detect the vehicle **110**.

[0244] With reference to the proximity sensor **129**N being an optical sensor, the optical sensor may be a line scan sensor, a camera, a beam sensor or any other suitable optical sensor. The optical sensor may be moved to detect one or more predetermined features of the vehicle **110** (such as bumpers, wheel wells, etc.) that effect localization of a wheel assembly **111**.

[0245] In some aspects, datum features **266** may be attached (such as by an operator) to the vehicle **110** or to the frame **189**F adjacent the vehicle at predetermined locations relative to the vehicle **110**, where the datum features resolve a location of the wheel assembly **111** relative to the reference frame RREF of the bot **120**. As an example, where the proximity sensor is a line scan or beam sensor, one or more datum features **266** may be placed (with a vertical or horizontal orientation depending on the structural configuration of the proximity sensor **129**N mount to the bot **120**) in any suitable manner along a line that has a known position relative to the reference frame RREF of the bot **120** (see FIG. **2**B). The datum features **266** may be placed adjacent (e.g., substantially aligned with a center of) a wheel assembly **111**, and the bot **120** moves the proximity sensor **129**N along the line so as to detect the datum feature **266**. The datum feature includes any suitable pattern (e.g., optical pattern, raised features, etc.) that is detected by the optical sensor, where when the pattern is detected the bot **120** (via the controller **160**, **160"**) correlates the location of the datum feature **266** (and the wheel assembly **111** to which the datum feature is aligned) to the reference frame RREF of the bot **120**. Knowing the location of the wheel assembly **111** along the traverse path **299** (via detection of the datum feature **266**), the bot **120** may move the beam sensor to a position so as to sense the wheel assembly **111** and move the beam sensor in direction **997** from adjacent a (floor) surface of the frame **189**F towards the wheel assembly **111** to resolve the location of the wheel assembly **111** relative to the reference frame RREF (see FIG. **9**C). As may be realized, the bot **120** may scan (vertically as in FIG. **9**C) in one or more locations along the line to determine a low point of the wheel assembly **111**) using any suitable geometric algorithms.

[0246] Where the sensor is a camera, the bot **120** may move the camera along a side of the vehicle **110** where any suitable vision algorithms (e.g., of controller **160**, **160"**) are employed to detect the wheel assembly **111** and resolve the location of the wheel assembly relative to the reference frame RREF of the bot **120**.

[0247] With reference to the proximity sensor **129**N being a sonic sensor, the sonic sensor may be employed in a manner similar to that of the line scan or beam sensor noted above. As may be realized, vertical and/or horizontal scanning of the wheel assembly **111** with the ultrasonic or optical sensors determines a location (e.g., the bounds) of the inner wheel lip and the location of the barrel **450** of the wheel **111**W (see FIG. **9**C)

[0248] With reference to the proximity sensor **129**N being a contact sensor, the bot **120** may probe the workspace of the tire changing station **101** with the bot **120** moving the proximity sensor **129**N so as to detect the vehicle **110** via contact between the proximity sensor **129**N and the vehicle **110**. The bot **120** may be configured (e.g., via controller **160**, **160"**) to detect, via probing, one or more corners of the vehicle **110**, where the location of the wheel assembly **111** is resolved by employing known dimensions of the vehicle **110** (e.g., stored any suitable memory accessible by controller **160**, **160"**) and the location of the corner of the vehicle as detected in the reference frame RREF of the bot **120**.

[0249] Referring to FIGS. **1**A, **1**B, **9**A, **9**B, and **11**, based on the position and diameter information of the tire **111**T (as determined in any suitable manner such as those described herein by one or more of the vision system **130**, **162** and the (optical, ultrasonic, and/or contact) proximity sensor), an exemplary inner wheel lip localization will be described with respect to the proximity sensor **129**N including a contact sensor. The inner wheel lip localization effects determination of an open location of the wheel **111**W into which the end effector **128** extends to affix a wheel weight **400** to the wheel **111**W. The robot **120**, **120**WR (under control of controller **160**, **160"**) positions the proximity sensor **129**N adjacent the side wall **111**TS of the tire **111**T (FIG. **11**, Block **1100**) and is iteratively moved into an out of contact with the wheel assembly **111**W in what may be referred to as limit-switch homing method. For example, with the proximity sensor **129**N positioned adjacent the side wall **111**TS (e.g., inside a diameter **999** of the tire **111**T and adjacent the tire tread **111**TT—see FIG. **9**B), the robot **120**, **120**WR moves the proximity sensor **129**N towards the side wall **111**TS (e.g., towards the side of the wheel assembly **111**) in direction **998**A (FIG. **11**, Block **1110**). When the proximity sensor **129**N contacts the side wall **111**TS of the tire **111**, the proximity sensor **129**N sends a signal to the controller **160** (or any other suitable controller including, but not limited to, controller **160"**), where the signal embodies or otherwise indicates a proximity of the proximity sensor **129**N (e.g., in this example substantial contact) with the side wall **111**TS (FIG. **11**, Block **1120**). With contact being made between the proximity sensor **129**N and the side wall **111**TS, the robot **120**, **120**WR moves (e.g., "backs away") the proximity sensor **129**N (FIG. **11**, Block **1130**) a predetermined distance (e.g., about 5 mm (about 0.2 inches) or more

or less than about 5 mm (about 0.2 inches)) in direction **998**B away from the side wall **111**TS.

[0250] With the proximity sensor **129**N backed away from the side wall **111**TS, the robot **120**, **120**WR indexes the proximity sensor **129**N in direction **997** (towards a center of the tire **111**T) by a predetermined distance (e.g., about 5 mm (about 0.2 inches) or more or less than about 5 mm (about 0.2 inches)) (FIG. **11**, Block **1140**). Blocks **1110**-**1140** of FIG. **11** are repeated until the proximity sensor **129**N is moved past (as determined by the controller **160**, **160"** from data obtained from any suitable encoders of the robot **120**, **120**WR or as determined in any other suitable manner) an expected contact distance (e.g., the proximity sensor **129**N iteratively contacts the wheel assembly **111** (including the side wall **111**TS and surface ILS of the inner wheel lip) along a substantially radial line in direction **997** until the proximity sensor moves in direction **997** past the surface ILS and into the barrel **450** of the wheel **111**W. The expected contact distance may be determined, by the controller **160**, **160"** from data obtained from any suitable encoders of the robot **120**, **120**WR (or in any other suitable manner), as the distance the proximity sensor **129**N is moved in the initial approach (FIG. **11**, Block **1110**) to contact the side wall **111**TS. The expected contact distance may have a predetermined tolerance (e.g., a tolerance of about +/−5 mm (about +/−0.2 inches) or a tolerance greater or less than about +/−5 mm (about +/−0.2 inches)) to account for variations in the side wall **111**TS and transitions between the side wall **111**TS and the surface ILS.

[0251] An inner lip clearance position is identified (FIG. **11**, Block **1150**) by the controller **160**, **160"** in the robot **120**, **120**WR coordinate system as the location in direction **997** which the proximity sensor **129**N moved past the expected contact distance. The inner lip clearance position is the location in direction **997** at which the robot **120**, **120**WR may insert the wheel weight gripper **129**P or wheel weight installation tool **129**O into the barrel **450** substantially without obstruction from the wheel **111**W and/or tire **111**T for applying a wheel weight **400** to the wheel **111**W or wheel assembly **111**. The proximity sensor **129**N is backed away from the wheel assembly **111** (FIG. **11**, Block **1160**) so that the wheel weight **400** may be installed.

[0252] Referring to FIGS. **1**A-**9**C and **12** an exemplary vehicle component balancing method for on vehicle balancing of one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including, but not limited to, the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to a wheel hub **110**H (see FIG. **1**B) of the road vehicle **110**) will be described. In accordance with the method, a vehicle component balancing robot apparatus **189** for on vehicle balancing of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD, and the vehicle components **111**C is provided (FIG. **12**, Block **1200**). The vehicle component balancing robot apparatus **189** has a frame **189**F, as described herein, arranged so as to connect with the vehicle **110**. A predetermined location of the tire-wheel assembly relative to a reference frame of the bot **120** is resolved (FIG. **12**, Block **1210**) by moving the bot **120** relative to the frame **189**F in at least one degree of freedom (as described herein), where the robot is connected to the frame **189**F (such as by the rails or wheels described herein) and has the at least one degree of freedom (such as along traverse path **299** and/or along any one or more axes of motion of the bot **120**). The end effector **128** of the bot **120** is interfaced with the wheel assembly **111** (FIG. **12**, Block **1220**) and the bot **120** moves the end effector to other predetermined locations (such as, for example, the wheel weight installation locations described herein) on the wheel **111**W of the wheel assembly **111** (FIG. **12**, Block **1230**), where the other predetermined locations are determined based on resolution of the predetermined location of the wheel assembly **111** relative to a reference frame RREF of the bot **120**.

[0253] Referring to FIGS. **1**A-**9**C and **13** an exemplary vehicle component balancing method for on vehicle balancing of one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including, but not limited to, the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to a wheel hub **110**H (see FIG. **1**B) of the road vehicle **110**) will be described. The method includes providing a vehicle component balancing robot apparatus **189** for on vehicle balancing of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD, and the vehicle components **111**C (FIG. **13**, Block **1300**), where the vehicle component balancing robot apparatus **189** has a frame **189**F arranged so as to connect with the vehicle **110**. A distal end **120**D of a robot **120**, of the vehicle component balancing robot apparatus **189**, is interfaced with the wheel assembly **111** (FIG. **13**, Block **1310**), where the robot **120** is connected to the frame **189**F at a proximal end **120**P of the robot **120**, the proximal end **120**P being opposite the distal end **120**D. The distal end **120**D is indexed, with an indexer (also referred to as a wheel weigh installation tool) **129**O of the robot **120**, between a retracted position (see FIG. **5**A) and at least one extended position (see FIGS. **5**B and **5**C) (FIG. **13**, Block **1320**), wherein in the at least one extended position the distal end **120**D interfaces the wheel assembly **111** determining a rim or wheel location of the wheel **111**W of the wheel assembly **111** mounted on the vehicle **110**.

[0254] Referring to FIGS. **1**A-**9**C and **14** an exemplary vehicle component balancing method for on vehicle balancing of one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including, but not limited to, the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to a wheel hub **110**H (see FIG. **1**B) of the road vehicle **110**) will be described. The method includes providing a vehicle component balancing robot apparatus **189** for on vehicle balancing of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD, and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to a wheel hub **110**H (see FIG. **1**B)) (FIG. **14**, Block **1400**), where the vehicle component balancing robot apparatus **189** has a frame **189**F arranged so as to connect with the vehicle **110**. A distal end **120**D of a robot **120** (of the vehicle component balancing robot apparatus **189**) is indexed with the wheel assembly **111** (FIG. **14**, Block **1410**),

where the robot **120** is connected to the frame **189**F at a proximal end **120**P of the robot, the proximal end **120**P being opposite the distal end **120**D. The distal end **120**D is indexed, with an indexer of the robot, between a retracted position (see FIG. **5**A) and at least one extended position (see FIGS. **5**B and **5**C), wherein in the at least one extended position the distal end **120**D interfaces the wheel assembly **111** determining a wheel or rim location of the wheel or rim **111**W of the wheel assembly **111** and predetermined locations (such as wheel weigh locations) so as to effect a balancing solution of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD, and the vehicle components **111**C via robotic application of wheel balancing weights **400** with the distal end **120**D (FIG. **14**, Block **1420**).

[0255] Referring to FIGS. **1**A-**9**C and **15** an exemplary vehicle component balancing method for on vehicle balancing of one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD (e.g., including, but not limited to, the brake drums **111**D and the brake rotors **111**R), and the vehicle components **111**C that impart, e.g., with the vehicle **110** in motion, vibrations to the vehicle **110** (e.g., such as by, but not limited to, imparting eccentric forces to a wheel hub **110**H (see FIG. **1**B) of the road vehicle **110**) will be described. The method includes providing a vehicle component balancing robot apparatus **189** for on vehicle balancing of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD, and the vehicle components **111**C (FIG. **15**, Block **1500**), the vehicle component balancing robot apparatus **189** having a frame **189**F arranged so as to connect with the vehicle **110**. A compliant end effector (such as wheel weight gripper **129**P or wheel weight installation tool **129**O), of a robot **120** (of the vehicle component balancing robot apparatus **189**), is interfaced with the wheel assembly **111** (FIG. **15**, Block **1510**), where the robot **120** is connected to the frame **189**F at a proximal end **120**P of the robot **120**, and the compliant end effector is disposed opposite the proximal end **120**P. The method includes determining, with the compliant end effector interfacing the wheel assembly **111**, a rim or wheel location of the wheel or rim **111**W of the wheel assembly **111** and predetermined locations (such as wheel weight locations) so as to effect a balancing solution of the one or more of the tire **111**T, the wheel **111**W, the bearings **111**B, the brake components **111**RD, and the vehicle components **111**C via robotic application of wheel balancing weights **400** with the compliant end effector (FIG. **15**, Block **1520**).

[0256] In accordance with one or more aspects of the present disclosure, a vehicle component balancing robot apparatus, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle, is provided. The apparatus includes: a frame arranged so as to connect with the vehicle; and a robot connected to the frame, the robot having at least one degree of freedom so as to move, in the at least one degree of freedom, relative to the frame, and is configured so that the move, relative to the frame in the at least one degree of freedom, resolves a predetermined location of a tire-wheel assembly of the vehicle relative to a reference frame of the robot; wherein the robot has at least one end effector arranged to interface the tire-wheel assembly and the robot moves the at least one end effector to other predetermined locations on a wheel rim of the tire-wheel assembly, determined based on resolution of the predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0257] In accordance with one or more aspects of the present disclosure, the predetermined location determines a frame of reference of the tire-wheel assembly relative to the reference frame of the robot.

[0258] In accordance with one or more aspects of the present disclosure, the other predetermined locations on the wheel rim are wheel balancing weight locations resolving imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0259] In accordance with one or more aspects of the present disclosure, the at least one end effector interfaces the tire-wheel assembly at the other predetermined locations so as to effect a balancing solution of one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the at least one end effector.

[0260] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator, driven so as to extend in the at least one degree of freedom between a retracted position and an extended position, the extended position locating the at least one end effector proximate the tire-wheel assembly.

[0261] In accordance with one or more aspects of the present disclosure, the actuator has an indexer arranged to index the at least one end effector, in the at least one degree of freedom, and position the at least one end effector at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0262] In accordance with one or more aspects of the present disclosure, the indexer has an index position that places the at least one end effector in contact with the wheel rim determining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0263] In accordance with one or more aspects of the present disclosure, the at least one end effector has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0264] In accordance with one or more aspects of the present disclosure, the at least one end effector includes an indexer that effects placement of a wheel balancing weight at one or more locations on the wheel rim.

[0265] In accordance with one or more aspects of the present disclosure, the one or more locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0266] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having at least a first extension position and a second extension position.

[0267] In accordance with one or more aspects of the present disclosure, the wheel balancing weight installation tool includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0268] In accordance with one or more aspects of the present disclosure, the at least one end effector includes a conforming wheel balancing weight gripper that conforms,

from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0269] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip configured to grip and hold a wheel balancing weight.

[0270] In accordance with one or more aspects of the present disclosure, the flexible grip includes one or more of magnets, vacuum grips, and clips.

[0271] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes one or more sensors configured to resolve the predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0272] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0273] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0274] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one end effector extends to affix a wheel weight to the wheel.

[0275] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes a wheel balancing weight dispenser connected to the frame.

[0276] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes a wheel weight transport configured to convey and position wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0277] In accordance with one or more aspects of the present disclosure, the wheel weight transport is configured to convey adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0278] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser is configured to remove the adhesive backing from the wheel balancing weights for transport on the wheel weight transport.

[0279] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes an automated weight-measuring roller and a cutting blade, the automated weight-measuring roller being configured to unroll and index a predetermined amount of weight past the cutting blade and the cutting blade is configured to cut the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0280] In accordance with one or more aspects of the present disclosure, a vehicle component balancing method, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle, is provided. The method includes: providing a vehicle component balancing robot apparatus for on vehicle balancing of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle, the vehicle component balancing robot apparatus having a frame arranged so as to connect with the vehicle; resolving a predetermined location of a tire-wheel assembly of the vehicle relative to a reference frame of a robot by moving the robot relative to the frame in at least one degree of freedom, where the robot is connected to the frame and has the at least one degree of freedom; interfacing at least one end effector of the robot with the tire-wheel assembly; and moving, with the robot, the at least one end effector to other predetermined locations on a wheel rim of the tire-wheel assembly, determined based on resolution of the predetermined location of the tire-wheel assembly relative to a reference frame of the robot.

[0281] In accordance with one or more aspects of the present disclosure, the predetermined location determines a frame of reference of the tire-wheel assembly relative to the reference frame of the robot.

[0282] In accordance with one or more aspects of the present disclosure, the other predetermined locations on the wheel rim are wheel balancing weight locations resolving imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0283] In accordance with one or more aspects of the present disclosure, the at least one end effector interfaces the tire-wheel assembly at the other predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the at least one end effector.

[0284] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator that is driven so as to extend in the at least one degree of freedom between a retracted position and an extended position, the extended position locating the at least one end effector proximate the tire-wheel assembly.

[0285] In accordance with one or more aspects of the present disclosure, the actuator has an indexer that indexed the at least one end effector, in the at least one degree of freedom, and position the at least one end effector at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0286] In accordance with one or more aspects of the present disclosure, the indexer has an index position that places the at least one end effector in contact with the wheel rim determining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0287] In accordance with one or more aspects of the present disclosure, the at least one end effector has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0288] In accordance with one or more aspects of the present disclosure, the method further includes, with an indexer of the at least one end effector, placement of a wheel balancing weight at one or more locations on the wheel rim.

[0289] In accordance with one or more aspects of the present disclosure, the one or more locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0290] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having a first extension position and a second extension position.

[0291] In accordance with one or more aspects of the present disclosure, the wheel balancing weight is applied with a conforming wheel balancing weight gripper of the wheel balancing weight installation tool, where the conforming wheel balancing weight gripper conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0292] In accordance with one or more aspects of the present disclosure, the wheel balancing weight is applied with a conforming wheel balancing weight gripper of the at least one end effector that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0293] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip that grips and holds a wheel balancing weight.

[0294] In accordance with one or more aspects of the present disclosure, the flexible grip holds the wheel balancing weight with one or more of magnets, vacuum grips, and clips of the flexible grip.

[0295] In accordance with one or more aspects of the present disclosure, the method further includes resolving the predetermined location of the tire-wheel assembly relative to the reference frame of the robot with one or more sensors of the vehicle component balancing robot apparatus.

[0296] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0297] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, the method further comprising moving, with the robot, the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0298] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, the method further comprising moving, with the robot, the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one end effector extends to affix a wheel weight to the wheel.

[0299] In accordance with one or more aspects of the present disclosure, a wheel balancing weight dispenser is connected to the frame for dispensing wheel weights to the robot.

[0300] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser has a wheel weight transport that conveys and positions wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0301] In accordance with one or more aspects of the present disclosure, the wheel weight transport conveys adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0302] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser removes the adhesive backing from the wheel balancing weights prior to or after transport of the wheel weights on the wheel weight transport.

[0303] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes an automated weight-measuring roller and a cutting blade, method further comprises unrolling and indexing, with the automated weight-measuring roller, a predetermined amount of weight past the cutting blade and cutting, with the cutting blade, the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0304] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser removes the adhesive backing from the wheel balancing weights prior to or after cutting of the predetermined amount of weight.

[0305] In accordance with one or more aspects of the present disclosure, a vehicle component balancing robot apparatus, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle, is provided. The apparatus comprising: a frame arranged so as to connect with the vehicle; and a robot connected to the frame at a proximal end of the robot, and the robot has a distal end, opposite the proximal end, the distal end being arranged so as to interface with a tire-wheel assembly of the vehicle; wherein the robot has an indexer that indexes the distal end between a retracted position and at least one extended position, wherein in the at least one extended position the distal end interfaces the tire-wheel assembly determining a rim location of the wheel rim of the tire wheel assembly and predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the distal end.

[0306] In accordance with one or more aspects of the present disclosure, the indexer is a multi-index stage indexer, each index stage having at least one index position.

[0307] In accordance with one or more aspects of the present disclosure, at least one index stage has different index positions that position the interface corresponding to wheel balancing weight locations on the wheel rim so as to effect the balancing solution.

[0308] In accordance with one or more aspects of the present disclosure, the robot has at least one degree of freedom and is configured to move the distal end in the one degree of freedom relative to the frame so that the move resolves another predetermined location of the tire-wheel assembly relative to a reference frame of the robot; and the distal end is arranged to interface the tire-wheel assembly and the robot moves the distal end to the predetermined locations on a wheel rim of the tire-wheel assembly, deter-

mined based on resolution of the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0309] In accordance with one or more aspects of the present disclosure, the other predetermined location determines a frame of reference of the tire-wheel assembly relative to the reference frame of the robot.

[0310] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim are wheel balancing weight locations resolving imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0311] In accordance with one or more aspects of the present disclosure, the distal end interfaces the tire-wheel assembly at the predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the at least one end effector.

[0312] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator, the driven actuator has the distal end and the actuator is driven so as to extend in at least one degree of freedom of the robot between a retracted position and an extended position, the extended position locating the distal end proximate the tire-wheel assembly.

[0313] In accordance with one or more aspects of the present disclosure, the actuator has the indexer arranged to index the distal end, in the at least one degree of freedom, and position the distal end at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0314] In accordance with one or more aspects of the present disclosure, the indexer has an index position that places the distal end in contact with the wheel rim determining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0315] In accordance with one or more aspects of the present disclosure, the distal end has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0316] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes one or more sensors configured to resolve the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0317] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0318] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the distal end, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0319] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one end effector extends to affix a wheel weight to the wheel.

[0320] In accordance with one or more aspects of the present disclosure, the indexer effects placement of a wheel balancing weight at the predetermined locations on the wheel rim.

[0321] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0322] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having a first extension position and a second extension position.

[0323] In accordance with one or more aspects of the present disclosure, the indexer includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0324] In accordance with one or more aspects of the present disclosure, the distal end includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0325] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip configured to grip and hold a wheel balancing weight.

[0326] In accordance with one or more aspects of the present disclosure, the flexible grip includes one or more of magnets, vacuum grips, and clips.

[0327] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes a wheel balancing weight dispenser connected to the frame, the wheel balancing weight dispenser includes a wheel weight transport configured to convey and position wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0328] In accordance with one or more aspects of the present disclosure, the wheel weight transport is configured to convey adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0329] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser is configured to remove the adhesive backing from the wheel balancing weights for transport on the wheel weight transport.

[0330] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes an automated weight-measuring roller and a cutting blade, the automated weight-measuring roller being configured to unroll and index a predetermined amount of weight past the cutting blade and the cutting blade is configured to cut the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0331] In accordance with one or more aspects of the present disclosure, a vehicle component balancing method, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that

impart vibrations to the vehicle, is provided. The method comprising: providing a vehicle component balancing robot apparatus for on vehicle balancing of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle, the vehicle component balancing robot apparatus having a frame arranged so as to connect with the vehicle; and interfacing a distal end of a robot with a tire-wheel assembly of the vehicle, where the robot is connected to the frame at a proximal end of the robot, opposite the distal end; indexing, with an indexer of the robot, the distal end between a retracted position and at least one extended position, wherein in the at least one extended position the distal end interfaces the tire-wheel assembly determining a rim location of the wheel rim of the tire wheel assembly and predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the distal end.

[0332] In accordance with one or more aspects of the present disclosure, the indexer is a multi-index stage indexer, each index stage having at least one index position.

[0333] In accordance with one or more aspects of the present disclosure, at least one index stage has different index positions that position the interface corresponding to wheel balancing weight locations on the wheel rim so as to effect the balancing solution.

[0334] In accordance with one or more aspects of the present disclosure, the robot has at least one degree of freedom and moves the distal end in the one degree of freedom relative to the frame so that the move resolves another predetermined location of the tire-wheel assembly relative to a reference frame of the robot; and the distal end is arranged to interface the tire-wheel assembly and the robot moves the distal end to the predetermined locations on a wheel rim of the tire-wheel assembly, determined based on resolution of the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0335] In accordance with one or more aspects of the present disclosure, the other predetermined location determines a frame of reference of the tire-wheel assembly relative to the reference frame of the robot.

[0336] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim are wheel balancing weight locations resolving imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0337] In accordance with one or more aspects of the present disclosure, the distal end interfaces the tire-wheel assembly at the predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the distal end.

[0338] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator, the driven actuator has the distal end and the actuator is driven so as to extend in at least one degree of freedom of the robot between a retracted position and an extended position, the extended position locating the distal end proximate the tire-wheel assembly.

[0339] In accordance with one or more aspects of the present disclosure, the actuator has the indexer and indexes the distal end, in the at least one degree of freedom, and positions the distal end at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0340] In accordance with one or more aspects of the present disclosure, the indexer has an index position that places the distal end in contact with the wheel rim determining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0341] In accordance with one or more aspects of the present disclosure, the distal end has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0342] In accordance with one or more aspects of the present disclosure, the method further includes resolving, with one or more sensors, the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0343] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0344] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the distal end, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0345] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one end effector extends to affix a wheel weight to the wheel.

[0346] In accordance with one or more aspects of the present disclosure, the indexer effects placement of a wheel balancing weight at the predetermined locations on the wheel rim.

[0347] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0348] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having a first extension position and a second extension position.

[0349] In accordance with one or more aspects of the present disclosure, the indexer includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0350] In accordance with one or more aspects of the present disclosure, the distal end includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0351] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip configured to grip and hold a wheel balancing weight.

[0352] In accordance with one or more aspects of the present disclosure, the flexible grip includes one or more of magnets, vacuum grips, and clips.

[0353] In accordance with one or more aspects of the present disclosure, the method further includes, with a wheel balancing weight dispenser connected to the frame where the wheel balancing weight dispenser includes a wheel weight transport, conveying and positioning wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0354] In accordance with one or more aspects of the present disclosure, the wheel weight transport conveys adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0355] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser removes the adhesive backing from the wheel balancing weights for transport on the wheel weight transport.

[0356] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes an automated weight-measuring roller and a cutting blade, where the automated weight-measuring roller unrolls and indexes a predetermined amount of weight past the cutting blade and the cutting blade cuts the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0357] In accordance with one or more aspects of the present disclosure, a vehicle component balancing robot apparatus, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle, is provided. The apparatus comprising: a frame arranged so as to connect with the vehicle; and a robot connected to the frame at a proximal end of the robot, and the robot has a distal end, opposite the proximal end, the distal end being arranged so as to interface with a tire-wheel assembly of the vehicle; wherein the robot has an indexer that indexes the distal end between a retracted position and at least one extended position, wherein in the at least one extended position the distal end interfaces the tire-wheel assembly determining a rim location of the wheel rim of the tire wheel assembly mounted on the vehicle.

[0358] In accordance with one or more aspects of the present disclosure, the indexer is a multi-index stage indexer, each index stage having at least one index position.

[0359] In accordance with one or more aspects of the present disclosure, at least one index stage has different index positions that position the interface corresponding to wheel balancing weight locations on the wheel rim so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0360] In accordance with one or more aspects of the present disclosure, the distal end interfaces the tire-wheel assembly so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the distal end.

[0361] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator, the driven actuator has the distal end and the actuator is driven so as to extend in at least one degree of freedom of the robot between a retracted position and an extended position, the extended position locating the distal end proximate the tire-wheel assembly.

[0362] In accordance with one or more aspects of the present disclosure, the actuator has the indexer arranged to index the distal end, in the at least one degree of freedom, and position the distal end at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0363] In accordance with one or more aspects of the present disclosure, the indexer has an index position that places the distal end in contact with the wheel rim determining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0364] In accordance with one or more aspects of the present disclosure, the distal end has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0365] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes one or more sensors configured to resolve the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0366] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0367] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the distal end, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0368] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one end effector extends to affix a wheel weight to the wheel.

[0369] In accordance with one or more aspects of the present disclosure, the indexer effects placement of a wheel balancing weight at one or more locations on the wheel rim.

[0370] In accordance with one or more aspects of the present disclosure, the one or more locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0371] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having a first extension position and a second extension position.

[0372] In accordance with one or more aspects of the present disclosure, the indexer includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0373] In accordance with one or more aspects of the present disclosure, the distal end includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0374] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip configured to grip and hold a wheel balancing weight.

[0375] In accordance with one or more aspects of the present disclosure, the flexible grip includes one or more of magnets, vacuum grips, and clips.

[0376] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes a wheel balancing weight dispenser connected to the frame, the wheel balancing weight dispenser includes a wheel weight transport configured to convey and position wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0377] In accordance with one or more aspects of the present disclosure, the wheel weight transport is configured to convey adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0378] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser is configured to remove the adhesive backing from the wheel balancing weights for transport on the wheel weight transport.

[0379] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes an automated weight-measuring roller and a cutting blade, the automated weight-measuring roller being configured to unroll and index a predetermined amount of weight past the cutting blade and the cutting blade is configured to cut the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0380] In accordance with one or more aspects of the present disclosure, a vehicle component balancing method, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle, is provided. The method includes: providing a vehicle component balancing robot apparatus for on vehicle balancing of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle, the vehicle component balancing robot apparatus having a frame arranged so as to connect with the vehicle; interfacing a distal end of a robot with a tire-wheel assembly of the vehicle, where the robot is connected to the frame at a proximal end of the robot, opposite the distal end; and indexing, with an indexer of the robot, the distal end between a retracted position and at least one extended position, wherein in the at least one extended position the distal end interfaces the tire-wheel assembly determining a rim location of the wheel rim of the tire wheel assembly mounted on the vehicle.

[0381] In accordance with one or more aspects of the present disclosure, the indexer is a multi-index stage indexer, each index stage having at least one index position.

[0382] In accordance with one or more aspects of the present disclosure, at least one index stage has different index positions that position the interface corresponding to wheel balancing weight locations on the wheel rim so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0383] In accordance with one or more aspects of the present disclosure, the distal end interfaces the tire-wheel assembly at the predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the distal end.

[0384] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator, the driven actuator has the distal end and the actuator is driven so as to extend in at least one degree of freedom of the robot between a retracted position and an extended position, the extended position locating the distal end proximate the tire-wheel assembly.

[0385] In accordance with one or more aspects of the present disclosure, the actuator has the indexer and indexes the distal end, in the at least one degree of freedom, and positions the distal end at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0386] In accordance with one or more aspects of the present disclosure, the indexer has an index position that places the distal end in contact with the wheel rim determining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0387] In accordance with one or more aspects of the present disclosure, the distal end has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0388] In accordance with one or more aspects of the present disclosure, the method further includes resolving, with one or more sensors, the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0389] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0390] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the distal end, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0391] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one end effector extends to affix a wheel weight to the wheel.

[0392] In accordance with one or more aspects of the present disclosure, the indexer effects placement of a wheel balancing weight at the predetermined locations on the wheel rim.

[0393] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0394] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having a first extension position and a second extension position.

[0395] In accordance with one or more aspects of the present disclosure, the indexer includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0396] In accordance with one or more aspects of the present disclosure, the distal end includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0397] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip configured to grip and hold a wheel balancing weight.

[0398] In accordance with one or more aspects of the present disclosure, the flexible grip includes one or more of magnets, vacuum grips, and clips.

[0399] In accordance with one or more aspects of the present disclosure, the method further includes, with a wheel balancing weight dispenser connected to the frame where the wheel balancing weight dispenser includes a wheel weight transport, conveying and positioning wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0400] In accordance with one or more aspects of the present disclosure, the wheel weight transport conveys adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0401] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser removes the adhesive backing from the wheel balancing weights for transport on the wheel weight transport.

[0402] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes an automated weight-measuring roller and a cutting blade, where the automated weight-measuring roller unrolls and indexes a predetermined amount of weight past the cutting blade and the cutting blade cuts the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0403] In accordance with one or more aspects of the present disclosure, a vehicle component balancing robot apparatus, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle, is provided. The apparatus comprising: a frame arranged so as to connect with the vehicle; and a robot connected to the frame at a proximal end of the robot, and the robot has at least one compliant end effector, opposite the proximal end, the at least one compliant end effector being arranged so as to interface with a tire-wheel assembly of the vehicle; wherein the at least one compliant end effector interfaces the tire-wheel assembly determining a rim location of the wheel rim of the tire wheel assembly and predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the at least one compliant end effector.

[0404] In accordance with one or more aspects of the present disclosure, the at least one compliant end effector comprises an indexer that indexes the at least one compliant end effector between a retracted position and at least one extended position.

[0405] In accordance with one or more aspects of the present disclosure, the indexer is a multi-stage indexer and at least one index stage has different index positions that position the interface corresponding to wheel balancing weight locations on the wheel rim so as to effect the balancing solution.

[0406] In accordance with one or more aspects of the present disclosure, the robot has an actuator that has the indexer arranged to index the at least one compliant end effector, in at least one degree of freedom, and position the at least one compliant end effector at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0407] In accordance with one or more aspects of the present disclosure, the indexer has an index position that places the at least one compliant end effector in contact with the wheel rim determining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0408] In accordance with one or more aspects of the present disclosure, the indexer effects placement of a wheel balancing weight at the predetermined locations on the wheel rim.

[0409] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0410] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having a first extension position and a second extension position.

[0411] In accordance with one or more aspects of the present disclosure, the robot has at least one degree of freedom and is configured to move the at least one compliant end effector in the one degree of freedom relative to the frame so that the move resolves another predetermined location of the tire-wheel assembly relative to a reference frame of the robot; and the at least one compliant end effector is arranged to interface the tire-wheel assembly and the robot moves the at least one compliant end effector to the predetermined locations on a wheel rim of the tire-wheel assembly, determined based on resolution of the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0412] In accordance with one or more aspects of the present disclosure, the other predetermined location determines a frame of reference of the tire-wheel assembly relative to the reference frame of the robot.

[0413] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim are wheel balancing weight locations resolving imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0414] In accordance with one or more aspects of the present disclosure, the at least one compliant end effector interfaces the tire-wheel assembly at the predetermined locations so as to effect the balancing solution of the one or

more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the at least one compliant end effector.

[0415] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes one or more sensors configured to resolve the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0416] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0417] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one compliant end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0418] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one compliant end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one compliant end effector extends to affix a wheel weight to the wheel.

[0419] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator, the driven actuator has the at least one compliant end effector and the actuator is driven so as to extend in at least one degree of freedom of the robot between a retracted position and an extended position, the extended position locating the at least one compliant end effector proximate the tire-wheel assembly.

[0420] In accordance with one or more aspects of the present disclosure, the at least one compliant end effector has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0421] In accordance with one or more aspects of the present disclosure, the at least one compliant end effector includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0422] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip configured to grip and hold a wheel balancing weight.

[0423] In accordance with one or more aspects of the present disclosure, the flexible grip includes one or more of magnets, vacuum grips, and clips.

[0424] In accordance with one or more aspects of the present disclosure, the vehicle component balancing robot apparatus further includes a wheel balancing weight dispenser connected to the frame, the wheel balancing weight dispenser includes a wheel weight transport configured to convey and position wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0425] In accordance with one or more aspects of the present disclosure, the wheel weight transport is configured to convey adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0426] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser is configured to remove the adhesive backing from the wheel balancing weights for transport on the wheel weight transport.

[0427] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser includes an automated weight-measuring roller and a cutting blade, the automated weight-measuring roller being configured to unroll and index a predetermined amount of weight past the cutting blade and the cutting blade is configured to cut the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0428] In accordance with one or more aspects of the present disclosure, a vehicle component balancing method, for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components that impart vibrations to the vehicle, is provided. The method comprising: providing a vehicle component balancing robot apparatus for on vehicle balancing of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle, the vehicle component balancing robot apparatus having a frame arranged so as to connect with the vehicle; interfacing at least one compliant end effector of a robot with a tire-wheel assembly of the vehicle, the robot being connected to the frame at a proximal end of the robot, and the at least one compliant end effector is disposed opposite the proximal end; and determining, with the at least one compliant end effector interfacing the tire-wheel assembly, a rim location of the wheel rim of the tire wheel assembly and predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the at least one compliant end effector.

[0429] In accordance with one or more aspects of the present disclosure, the method further includes, with an indexer of the at least one compliant end effector, indexing the at least one compliant end effector between a retracted position and at least one extended position.

[0430] In accordance with one or more aspects of the present disclosure, the indexer is a multi-stage indexer and at least one index stage has different index positions that position the interface corresponding to wheel balancing weight locations on the wheel rim so as to effect the balancing solution.

[0431] In accordance with one or more aspects of the present disclosure, the robot has an actuator that has the indexer arranged to index the at least one compliant end effector, in at least one degree of freedom, and position the at least one compliant end effector at different index positions corresponding to wheel balancing weight locations on the wheel rim.

[0432] In accordance with one or more aspects of the present disclosure, the method further includes, with an index position of the indexer, placing the at least one compliant end effector in contact with the wheel rim deter-

mining a rim location on the wheel rim, of the tire-wheel assembly mounted on the vehicle.

[0433] In accordance with one or more aspects of the present disclosure, the indexer effects placement of a wheel balancing weight at the predetermined locations on the wheel rim.

[0434] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim include a location adjacent a back of a wheel flange and another location adjacent an inner wheel lip.

[0435] In accordance with one or more aspects of the present disclosure, the indexer includes at least one actuator having a first extension position and a second extension position.

[0436] In accordance with one or more aspects of the present disclosure, the robot has at least one degree of freedom and moves the at least one compliant end effector in the one degree of freedom relative to the frame so that the move resolves another predetermined location of the tire-wheel assembly relative to a reference frame of the robot; and the at least one compliant end effector interfaces the tire-wheel assembly and the robot moves the at least one compliant end effector to the predetermined locations on a wheel rim of the tire-wheel assembly, determined based on resolution of the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0437] In accordance with one or more aspects of the present disclosure, the other predetermined location determines a frame of reference of the tire-wheel assembly relative to the reference frame of the robot.

[0438] In accordance with one or more aspects of the present disclosure, the predetermined locations on the wheel rim are wheel balancing weight locations resolving imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0439] In accordance with one or more aspects of the present disclosure, the at least one compliant end effector interfaces the tire-wheel assembly at the predetermined locations so as to effect a balancing solution of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle via robotic application of wheel balancing weights with the at least one compliant end effector.

[0440] In accordance with one or more aspects of the present disclosure, the method further includes, with one or more sensors, resolving the other predetermined location of the tire-wheel assembly relative to the reference frame of the robot.

[0441] In accordance with one or more aspects of the present disclosure, the one or more sensors includes one or more of an optical sensor, an ultrasonic sensor, and a proximity sensor.

[0442] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one compliant end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an inner lip location of the tire-wheel assembly.

[0443] In accordance with one or more aspects of the present disclosure, the one or more sensors includes a proximity sensor coupled to the at least one compliant end effector, where the robot moves the proximity sensor to iteratively contact a side of the tire-wheel assembly and effect determination of an open location of the wheel into which the at least one compliant end effector extends to affix a wheel weight to the wheel.

[0444] In accordance with one or more aspects of the present disclosure, the robot has a driven actuator, the driven actuator has the at least one compliant end effector and the actuator is driven so as to extend in at least one degree of freedom of the robot between a retracted position and an extended position, the extended position locating the at least one compliant end effector proximate the tire-wheel assembly.

[0445] In accordance with one or more aspects of the present disclosure, the at least one compliant end effector has a wheel balancing weight grip, and a resiliently compliant wheel balancing weight applicator.

[0446] In accordance with one or more aspects of the present disclosure, the at least one compliant end effector includes a conforming wheel balancing weight gripper that conforms, from a relaxed configuration, to a contour of a surface of the wheel rim onto which the wheel balancing weight is applied.

[0447] In accordance with one or more aspects of the present disclosure, the conforming wheel balancing weight gripper includes a flexible grip that grips and holds a wheel balancing weight.

[0448] In accordance with one or more aspects of the present disclosure, the flexible grip includes one or more of magnets, vacuum grips, and clips.

[0449] In accordance with one or more aspects of the present disclosure, the method further includes, with a wheel weight transport of a wheel balancing weight dispenser connected to the frame, conveying and positioning wheel balancing weights at an interface location where the robot picks the wheel balancing weights from the wheel weight transport.

[0450] In accordance with one or more aspects of the present disclosure, the wheel weight transport conveys adhesive wheel balancing weights sans an adhesive backing of the wheel balancing weights.

[0451] In accordance with one or more aspects of the present disclosure, the wheel balancing weight dispenser removes the adhesive backing from the wheel balancing weights for transport on the wheel weight transport.

[0452] In accordance with one or more aspects of the present disclosure, the method further includes, with an automated weight-measuring roller and a cutting blade of the wheel balancing weight dispenser, unrolling and indexing a predetermined amount of weight past the cutting blade and cutting the predetermined amount of weight to form a wheel balancing weight of a predetermined weight that resolves imbalance of the one or more of the tire, the wheel, the bearings, the brake components, and the vehicle components that impart vibrations to the vehicle.

[0453] Referring to FIGS. **16**A and **20**A, for exemplary purposes, the tire balancer **129**M has any suitable configuration for balancing the wheel assembly **111**. For non-limiting exemplary purposes only, tire balancer **129**M includes an end effector mount **129**MM that couples the tire balancer **129**M to the end effector **128** of the at least one robotic arm **126** (see FIG. **20**A). The tire balancer **129**M is configured to balance the tire **111**T and the wheel **111**W assembly **111** with the tire **111**T and wheel **111**W (i.e., wheel assembly **111**) spinning at wheel operating speeds of about

60 mph or greater (in other aspects the operating speeds may be less than about 60 mph) so as to effect dynamic balancing or road force balancing of the wheel assembly **111**. In one aspect, the tire balancer **129**M is configured to balance the wheel assembly **111** off of the vehicle **110** and may be substantially similar to a conventional tire balancer but carried by the at least one robotic arm **126**; while in other aspects, the tire balancer **129**M is configured to balance the wheel assembly **111** on or in situ the vehicle **110** and includes rollers (e.g., a drive roller **300** configured to spin the wheel assembly **111** about a respective wheel hub of the vehicle **110** and a road force roller **305** configured to apply a simulated road force to the tire **111**T with the wheel assembly **111** spinning. At least the drive roller **300** drives rotation of the wheel assembly **111** for determining where to place wheel weights **3188** (see, e.g., FIGS. **44**A and **56**). The wheel weights **3188** are applied to the wheel **111**W in any suitable manner such as with a wheel weight dispenser (such as one of the robotic arm **126**, **126**A that picks wheels weights from a hopper and applies them to the wheel in locations identified by the tire balancer **129**M) to place the wheels weights onto the wheel **111**W. In other aspects the tire balancer **129**M has any suitable configuration and/or components for balancing the wheel assembly **111**.

[0454] Still referring to FIG. **16**A and also to FIGS. **16**B-**16**C a tire balancer **129**M**1** is illustrated. The tire balancer **129**M**1** is configured as a dynamic tire balancer that includes a frame **310**, a drive roller **300** mounted to the frame **310**, and a road force roller **310** mounted to the frame **310**. A suitable drive motor(s) DM are mounted to the frame for driving rotation of the drive roller **300** to effect rotation/spinning of the wheel assembly **111**. As described above, the frame **310** includes an end effector mount **129**MM that couples the frame **129**M**1** to the end effector **128** of the at least one robotic arm **126**. The robot arm **126** is configured to move the drive roller **300** and road force roller **305** into contact with the tire **111**T. The robot arm **126**, in one aspect, includes any suitable force feedback sensors (pressure sensors, current sensors, etc.) for detecting an amount of force applied by robot arm **126** on the tire **111**T by the drive roller **300** and road force roller **305**; while in other aspects the motors are provided to raise/move the drive roller **300** and the road force roller **305** relative to the frame **310** and into substantial contact with the tire **111**T, where force feedback sensors are coupled to the frame **310**, the drive roller **300**, and the road force roller **305** for detecting a force exerted on the tire by the drive roller **300** and road force roller **305**.

[0455] The tire balancer **129**M**1** may include a remote motion detection module **320** that includes a mounting plate **321** and motion sensors **322**A, **322**B, **322**C. The mounting plate **321** is configured in any suitable manner, such as with fasteners **321**FF (e.g., clips, magnets, spring or crank tension rods, etc.), to couple with the wheel **111**W so that a center **321**CC of the mounting plate **321** is substantially coaxial with a center of rotation WHB of the wheel assembly **111**. The mounting plate **321** may include sockets **335** that have are equal in number to and have the same pattern diameter SPD as the lugs **765** of the wheel **111**W to which the mounting plate **321** is coupled. The sockets **335** are configured to frictionally engage the lugs **765** to effect centering of the mounting plate **321** with respect to the wheel **111**W. In some aspects, the frictional coupling of the sockets **335** with the lugs **765** retains the mounting plate **321** on the wheel assembly **111** during balancing of the wheel assembly **111**; while in other aspects, the frictional engagement between the sockets **335** and lugs **765** at least in part retains (e.g., supplemented by other retaining means such as the clips, magnets, tension rods, etc.) the mounting plate **321** on the wheel assembly **111** during balancing of the wheel assembly. The mounting plate **321** is, in one aspect, configured to couple with the outer face of the wheel **111**W (i.e., opposite the wheel hub of the vehicle **110**) so that coupling and uncoupling of the mounting plate **321** to the wheel **111**W is substantially unobstructed.

[0456] The motion sensors **322**A, **322**B, **322**C are coupled to the mounting plate **321** in any suitable arrangement so that the remote motion detection module **320** is rotationally balanced and the balancing of the wheel assembly **111** is unaffected by the presence of the remote motion detection module **320** on the wheel assembly **111**. In this aspect, there are three motion sensors **322**A, **322**B, **322**C where each motion sensor is an accelerometer; however, in other aspects there may be any suitable type and number of motion sensors. Here, at least one of the motion sensors **322**A, **322**B, **322**C is arranged on the mounting plate **321** and is configured to detect radial accelerations R (e.g., up and down vibrations or "hop") of the wheel assembly **111** (see FIG. **16**C). At least one of the motion sensors **322**A, **322**B, **322**C is arranged on the mounting plate **321** and is configured to detect positive axial accelerations +Z (relative to the wheel hub/spindle to which the wheel assembly **111** is coupled) of the wheel assembly **111** (see FIG. **16**C). At least one of the motion sensors **322**A, **322**B, **322**C is arranged on the mounting plate **321** and is configured to detect negative axial accelerations −Z (relative to the wheel hub/spindle to which the wheel assembly **111** is coupled) of the wheel assembly **111** (see FIG. **16**C). The positive and negative axial accelerations may be referred to as "wobble" (e.g., sideways motion) of the wheel assembly **111**. In other aspects, one or more of the motion sensors **322**A, **322**B, **322**C may be a multi-axis sensors configured to detect any suitable combination of the radial accelerations R, the positive axial accelerations +z, and the negative axial accelerations −Z. In still other aspects, a single multi-axis motion sensor is provided to detect the radial accelerations R, the positive axial accelerations +z, and the negative axial accelerations −Z while inert weights are provided on the mounting plate **321** to balance the weight of the single multi-axis motion sensor.

[0457] The motion sensors **322**A, **322**B, **322**C are configured as wireless motion sensors that communication with any suitable wheel balancer controller **129**CNT. The motions sensors **322**A, **322**B, **322**C communicate sensor signals that embody the detected accelerations to the controller **129**CNT over any suitable wireless communication protocol/connection WCP, including but not limited to Bluetooth®, Zigbee®, cellular, Wi-Fi, or any other long or short range communication protocol. In one aspect, the controller **129**CNT is coupled to the frame **310** and is in communication with one or more of a device **1020**A-**1020***n* controller **160** (e.g., such as a bot **120** controller, a wheel weight dispenser/applicator controller, etc.) and the control console **1010**; while in other aspects the controller **129**CNT is integral to a device controller **160** (see FIG. **20**A) or the control console **1010** so as to communicate with other components of the tire changing system **100** (e.g., the tire

balancer **129**M, wheel weight dispenser/applicator, operator GUI **1004**, etc.) to effect balancing of the wheel assembly **111** as described herein.

[0458] While the tire balancer **129**M**1** was described above, as having an end effector mount **129**MM for coupling the tire balancer **129**M**1** to the at least one robotic arm **126**, in other aspects, the tire balancer **129**M**1** may be a stand-alone floor unit (substantially similar to that shown and described herein with respect to FIG. **30**D) or the tire balancer **129**M**1** may be a component of tire changing system **100**, **100**A (see FIGS. **1**A, **1**B and **35**) where the vehicle **110** is driven into the alignment cell and onto the tire balancer **129**M**1** (which is generally referred to in FIGS. **1** and **35** as tire balancer **129**MS).

[0459] Referring to FIGS. **16**A-**19**, in operation the tire balancer **129**M**1** is positioned relative to the wheel assembly **111** (with the wheel assembly **111** in situ the vehicle **110**) in any suitable manner (FIG. **19**, Block **600**), such as by the at least one robotic arm **126** so that the drive roller **300** and road force roller **305** are in substantial contact with the tire **111**T. The controller **129**CNT operates the drive motor(s) DM so that the drive roller **300** drivingly rotates the wheel assembly **111** with the drive force roller **305** applying a simulated road force to the wheel assembly **111**. The wheel assembly **111** is rotated and one or more of the radial accelerations R, positive axial accelerations +Z, and negative axial accelerations −Z are detected by the motion sensor(s) **322**A, **322**B, **322**C (FIG. **19**, Block **610**).

[0460] An amount of weight and a position of the weight is determined based on the detected accelerations (FIG. **19**, Block **620**). For example, in one aspect, the wheel assembly **111** is initially spun without wheel weights applied to obtain baseline accelerations, such as illustrated in FIG. **17**A. A known mass **400** is applied to the wheel assembly **111** at a known location **401** relative to the balancing planes R (X, Y), Z (see FIG. **16**C). The wheel assembly is spun with the known mass **400** applied and the accelerations are detected (see FIG. **17**B) and compared with the baseline accelerations in any suitable manner to determine the amount and location of weight to be applied to the wheel assembly **111** for balancing the wheel assembly. In another aspect, the amount of weight for balancing the wheel assembly **111** is determined by measuring a mass m of the wheel assembly **111** while lifting the wheel assembly **111** (e.g., from a drooped position—i.e., with the vehicle **110** lifted off of the ground and the vehicle suspension components **500** fully relaxed/drooped down) based on a deflection d of the wheel assembly from the drooped position, assuming a steady spring constant k of the vehicle suspension components **500**; noting that the spring constant k can be determined by measuring the force F required to lift the wheel assembly **111** from the dropped position back to a ride height position (i.e., a position of the wheel as determined by the vehicle suspension components **500** with the vehicle **110** resting with all wheels on the ground) where:

$$F=-mg/d \quad \text{[eq. 1]}$$

and

$$E=(k\times d^2)/2 \quad \text{[eq. 2]}$$

where E is the spring potential energy and g is the force of gravity. The location of the weight may be determined by application of the determined weight to the wheel **111**W, spinning the wheel, and measuring the accelerations in a manner similar to that noted above. In other aspects, the amount of weight and location of the weight may be determined in any suitable manner.

With the amount of weight and the position of the weight determined the weight is applied to the wheel **111**W (FIG. **19**, Block **630**) in any suitable manner (e.g., with automated equipment or manually), such as described herein.

Referring to FIGS. **20**A-**20**C, a wheel balancer **129**M**2** is illustrated. The wheel balancer **129**M**2** is coupled to the end effector **128** of the at least one robotic arm **126** with an end effector mount **129**MM in a manner similar to that described above. In this aspect, the wheel balancer **129**M**2** includes a wheel shroud or housing **700** that is coupled to the end effector mount **129**MM by a shaft **705**. The wheel shroud **700** has the form of an open top can or cup that includes a base **700**B, to which the shaft **705** is coupled, and a peripheral wall **700**B that extends from the base **700**B in a direction opposite the shaft **705**. The end effector mount **129**MM includes any suitable drive motor **710** that is coupled to and drives the shaft **705** (and the wheel shroud **700** coupled thereto) about a longitudinal axis **705**LAX of the shaft **705**; while in other aspects, the motor **710** may be located between the shaft **705** and the wheel shroud **700** so that the shaft **705** is rotationally fixed to the end effector mount **129**MM and the wheel shroud **700** is driven in rotation, by the motor **710** relative to the shaft **705**.

The wheel shroud **700** includes a road force roller **305** that is coupled to the peripheral wall **700**P of the wheel shroud **700** so as to be movable in a radial direction **777**. The wheel shroud **700** includes any suitable motor **720** that is configured to move the road force roller **305** in the radial direction **777** so that the road force roller **305** selectively engages and disengages the tire **111**T.

The wheel shroud **700** may also include one or more dynamic balance rollers **735**A, **735**B that are coupled to the peripheral wall **700**P of the wheel shroud **700** so as to be movable in a radial direction **777**. The wheel shroud **700** includes any suitable motor **721** that is configured to move the one or more dynamic balance rollers **735**A, **735**B in the radial direction **777** so that the one or more dynamic balance rollers **735**A, **735**B selectively engage and disengage the tire **111**T.

Where the one or more dynamic balance rollers **735**A, **735**B are provided with the road force roller **305**, the one or more dynamic balance rollers **735**A, **735**B and the road force roller **305** are independently deployable for engagement with the tire **111**T to provide for road force balancing of the wheel assembly **111**, dynamical balancing of the wheel assembly, or both (a combination of) road force balancing and dynamic balancing.

The wheel shroud **700** includes a centering protrusion **760** that extends from base **700**P and is substantially coaxial (i.e., extends along the longitudinal axis **705**LAX) with the shaft **705**. The centering protrusion **760** has any suitable configuration for engaging the wheel **111**W, to center the wheel assembly **111** within the wheel shroud **700** or to center the wheel shroud **700** with the wheel assembly **111** (e.g., the center of the wheel **111**W is substantially aligned/coaxial with the shaft **705** longitudinal axis **705**LAX). For example, referring also to FIG. **20**D, the centering protrusion **760** includes sockets **761** arranged in a pattern that substantially matches the lug **765** pattern of the wheel **111**W. The sockets **761** have a socket pattern (e.g., socket number and socket-pattern diameter SPD) and are configured to engage the lugs

765 and center the wheel assembly 111 with the wheel shroud 700 as noted above. The centering protrusion 760 (or a socket portion thereof) may be removable from the base 700B and interchangeable with other centering protrusions 760 (or socket portions). Each interchangeable centering protrusion 760 corresponds with a different lug 765 pattern (e.g., lug number and bolt-pattern diameter BPD) so that the tire balancer 129M2 may be employed with different wheels 111W having different lug 765 patterns corresponding to a socket pattern of a respective one of the interchangeable centering protrusions 760.

The centering protrusion 760 may be coupled to the base 700B so as to rotate relative to the base. The rotatable coupling between the base 700B and the centering protrusion 760 provides for centering of the wheel shroud 700 relative to the wheel assembly 111 while allowing rotation of the wheel shroud 700 with the wheel assembly 111 remaining rotationally stationary/fixed. A releasable lock 760L may be coupled to the base 700P to selectively lock rotation of the centering protrusion 760 to the base 700P so that the wheel shroud 700 and the centering protrusion 760 rotate as a unit for engaging the centering protrusion 760 with the lugs 765 and so that the wheel shroud 700 rotates independent of the centering protrusion 760. The tire balancer 760 may include a vision system 760V that images the wheel lug 765 pattern and a fiducial 760F of the centering protrusion 760 (the fiducial 760F having a known relationship relative to the socket pattern) and is configured to effect an aligning rotation of the wheel shroud 700 (and the centering protrusion) so that the centering protrusion 760 engages the lugs 765. In other aspects, alignment of the centering protrusion 760 with the lugs 765 (or any other suitable portion of the wheel 111W) may be effected in any suitable manner for centering the wheel shroud 700 relative to the wheel assembly 111 or vice versa.

The tire balancer 129M2 includes one or more sensors to effect balancing of the wheel assembly 111. For example, one or more force sensors 723 are disposed on the shaft 705 to detect deflections of the wheel shroud 700 as the wheel shroud rotates around the wheel assembly. The one or more force sensors 723 may be any suitable force sensor(s) including but not limited to torque cells and/or strain gauges. The one or more force sensors 723 are in communication with the controller 129CNT in any suitable manner (such as through the wireless protocol/connection WCP) where the controller is configured to (e.g., with any suitable non-transitory program code) determine an amount of movement, in one or more of the radial R, +Z, and −Z directions, of the wheel assembly 111 based on contact of the wheel assembly 111 with one or more of the road force roller 305 and the one or more dynamic balance rollers 735A, 735B.

The wheel balancer 129M2 may also include one or more of a wheel lateral runout sensor 780 and a wheel radial runout sensor 781. The wheel lateral runout sensor 780 is any suitable sensors (optical, contact, capacitive, etc.) that is coupled to the base 700B and is positioned to detect the amount of sideways motion (lateral runout or the amount of "wobble") in of the wheel 111W (and/or tire 111T) as the wheel shroud 700 rotates around the wheel assembly 111. The wheel radial runout sensor 781 is any suitable sensors (optical, contact, capacitive, etc.) that is coupled to the base 700B and is positioned to detect a radius RAD of the wheel 111W (and/or tire 111T) for effecting a determination as to whether the radius of the wheel 111W (and/or tire 111T) is not consistent from the wheel 111W center of rotation to any given point on the rim (this radial out of round condition causes the wheel assembly to vibrate up and down or "hop" as the wheel assembly 111 spins on, e.g., a road surface). The one or more of the wheel lateral runout sensor 780 and the wheel radial runout sensor 781 are connected to (i.e., in communication with) the controller 129CNT in any suitable manner (such as through the wireless protocol/connection WCP) where the controller is configured to (e.g., with any suitable non-transitory program code) determine one or more of the lateral and radial runout of the wheel 111W based on sensor data from the one or more of the wheel lateral runout sensor 780 and the wheel radial runout sensor 781.

As may be realized, the components of the tire balancer 129M2 coupled to the wheel shroud 700 are positioned relative to each other, with or without suitable counterweighting) so that the wheel shroud 700 is rotationally balanced. Rotationally balancing the wheel shroud 700 effects balancing of the wheel assembly 111 substantially without undue influence from (i.e., independent of) variations in dynamic loading that may otherwise result from rotating the wheel shroud 700 relative to the wheel assembly 111.

The controller 129CNT is configured to determine an amount of weight to be applied to the wheel assembly 111 and a location of the weight on the wheel 111W so that with the weight applied to the wheel 111W the wheel assembly is balanced. In one aspect, the amount of and position of the weight is determined based on sensor data from the one or more force sensor 723; while in other aspects, the amount of and position of the weight is determined based on the sensor data from the one or more force sensor 723 and at least one of the one or more of the wheel lateral runout sensor 780 and the wheel radial runout sensor 781.

While the tire balancer 129M2 was described above, as having an end effector mount 129MM for coupling the tire balancer 129M1 to the at least one robotic arm 126, in other aspects, the tire balancer 129M2 may be a stand-alone floor unit (substantially similar to that shown and described herein with respect to FIG. 30D) or the tire balancer 129M2 may be a component of tire changing system 100, 100A (see FIGS. 1A, 1B and 35) where the vehicle 110 is driven into the alignment cell and onto the tire balancer 129M2 (which is generally referred to in FIGS. 1 and 35 as tire balancer 129MS).

Still referring to FIGS. 20A-20D and also to FIG. 21, an exemplary operation of the tire balancer 129M2 will be described. The at least one robotic arm 126 positions the wheel shroud 700 around the wheel assembly 111, with the wheel assembly in situ the vehicle 110 (FIG. 21, Block 800) so that the centering protrusion 760 engages the lugs 765 and the wheel shroud 700 is substantially centered with respect to the wheel assembly 111. One or more of the road force roller 305 and dynamic balance rollers 735A, 735B are moved radially, by their respective motors 720, 721, so as to engage (e.g., substantially contact) the tire 111T (FIG. 21, Block 810 and/or FIG. 21, Block 820). The wheel shroud 700 is rotated, by the motor 710, relative to the wheel assembly (FIG. 21, Block 830) and the wheel balance metrics (e.g., one or more of the radial runout, lateral runout, and shaft deflections) are obtained from the sensors (e.g., respective ones of the force sensor 723, the radial runout sensor 781, and lateral runout sensor 780) (FIG. 21, Block

840). The amount of weight to be coupled to the wheel 111W and the location of weight to be coupled to the wheel are determined (FIG. 21, Block 850) by the controller 129CNT in any suitable manner, where the weight is coupled to the wheel assembly (FIG. 21, Block 860) in any suitable manner (such as by a human operator or automation) so that the wheel assembly 111 is balanced.

Referring now to FIGS. 22A and 22B, a tire balancer 129M3 is illustrated. The tire balancer may be substantially similar to tire balancer 129M1; however, in this aspect the tire balancer 129M3 employs passive fiducials 821A, 821B, 821C on the mounting plate 321 (of the remote motion detection module 320) and one or more detectors 950, 960 on the frame 310. The passive fiducials 922A, 922B, 922C are arranged on the mounting plate 321 in a manner similar to that described above with respect to motion sensors 322A, 322B, 322C. The passive fiducials 922A, 922B, 922C may be any suitable fiducial configured to be sensed by an optical, capacitive, and/or inductive sensor. For example, the passive fiducials 922A, 922B, 922C may be reflectors and/or metallic pads that extend or otherwise protrude from the sensed face 999; however, in other aspects the passive fiducials may be recessed at least partially within the mounting plate 321 so as to be substantially flush with or protrude from the sensed face 999; while in still other aspects, the passive fiducials may be stickers (having minimal thickness) that are adhered to the sensed face 999 in any suitable manner.

[2] The detectors 950 are mounted to a detector mount 950P that is coupled to the frame 310 so as to face the sensed face 999 of the mounting plate 321 with the mounting plate 321 coupled to the wheel assembly 111 and with the frame 310 positioned relative to the wheel assembly 111 to effect rotation of the wheel assembly 111. The detectors 950 include one or more optical sensor, capacitive sensor, inductive sensor, and/or any other suitable sensor (collectively referred to herein as sensors 950S) configured to detect the passive fiducials 922A, 922B, 922C.

Each passive fiducial 922A, 922B, 922C is positioned on the mounting plate 321 at a predetermined radial distance 924 from a center MPC of the mounting plate 321. With the mounting plate 321 coupled to the wheel assembly 111 and with the frame 310 positioned relative to the wheel assembly 111 to effect rotation of the wheel assembly 111, a center DTC of the detectors 950 is substantially aligned (e.g., coaxial) with the center MPC of the mounting plate 321. The sensors 950S (two sensors 950S1, 950S1 are shown for illustrative purposes) are arranged to be the distance 924 from the center DTC so as to be radially aligned with the passive fiducials 922A, 922B, 922C.

The detectors 950 and the mounting plate 321 are configured to detect wheel hop (e.g., up and down vibration) during balancing of the wheel assembly 111. The detectors are coupled to the controller over any suitable wireless communication protocol/connection WCP so as to transmit sensor data to the controller for determining an amount of wheel hop.

The detectors 960 include at least one optical sensor such as laser scanners, vision systems (e.g., cameras), diffuse sensors, reflective sensors, through-beams sensors or any other suitable sensor for sensing the tire 111T. The detectors 960 are coupled to the frame 310 so as to face the tread 111TD of the tire 111T and have a width that is greater than the width of the tire 111T so as to detect lateral (e.g., +Z and/or −Z) movement of the tire 111T as the tire is spun by the drive roller 300. In other aspects, a distance sensor 960DS, such as a laser distance sensor, the capacitive sensor, and/or the inductive sensor (noting the distance sensors may be integral with or the same as the detectors 950S in the case of capacitive and inductive sensors) may be coupled to the detector mount 950P so that the lateral movement of the wheel assembly 111 is detected by the interface between the distance sensor 960DS and the sensed faced 999 and/or passive fiducials 922A, 922B, 922C of the mounting plate 321.

While the tire balancer 129M3 was described above, as having an end effector mount 129MM for coupling the tire balancer 129M3 to the at least one robotic arm 126, in other aspects, the tire balancer 129M3 may be a stand-alone floor unit (substantially similar to that shown and described herein with respect to FIG. 30D) or the tire balancer 129M3 may be a component of tire changing system 100, 100A (see FIGS. 1A, 1B and 35) where the vehicle 110 is driven into the alignment cell and onto the tire balancer 129M3 (which is generally referred to in FIGS. 1 and 35 as tire balancer 129MS).

Still referring to FIGS. 22A and 22B and also to 10, an exemplary operation of the tire balancer 129M3 will be described. The tire balancer 129M3 is positioned relative to the wheel assembly 111 (with the wheel assembly 111 in situ the vehicle 110) in any suitable manner (FIG. 23, Block 200), such as by the at least one robotic arm 126 so that the drive roller 300 and road force roller 305 are in substantial contact with the tire 111T. The controller 129CNT operates the drive motor(s) DM to that the drive roller 300 drivingly rotates the wheel assembly 111 (FIG. 23, Block 210) with the drive force roller 305 applying a simulated road force to the wheel assembly 111.

With the wheel assembly 111 rotating the detectors 950 detect fiducial misalignment between the detectors 950 and the fiducials in the radial acceleration R direction (FIG. 23, Block 220). The detectors send sensor signals, embodying the fiducial alignment data, to the controller 129CNT.

With the wheel assembly 111 rotating the detectors 960 detect lateral movement of the tire 111T (and the wheel assembly 111), relative to the detectors 960, in the axial acceleration direction (e.g., +Z and/or −Z directions) (FIG. 23, Block 220). The detectors 960 send sensor signals, embodying the lateral movement data, to the controller 129CNT.

An amount of weight and a position of the weight is determined based on the detected fiducial misalignment and/or the detected lateral movement (FIG. 23, Block 240). For example, the controller 129CNT includes an empirically derived table EDT that correlates amounts of weights and positions of those weights on the wheel assembly 111 to the detected fiducial misalignment and/or the detected lateral movement. There may be an empirically derived table EDT for each different tire 111T and wheel 111W combinations such that based on the detected fiducial misalignment and/or the detected lateral movement and the tire/wheel combination the controller 129CNT searches the empirically derived tables EDT to determine from the corresponding empirically derived table EDT the amount and position of the weights to be affixed to the wheel assembly 111. In other aspects, the amount and position of the weights to be affixed to the wheel assembly 111 may be determined in any suitable manner such as analytically as a function of detected axial and radial

movement of the wheel assembly **111** or a wheel assembly weight distribution (e.g., as determined by the detected axial and radial movement of the wheel assembly **111** knowing the material properties and sizes of the tire and wheel).

With the amount of weight and the position of the weight determined the weight is applied to the wheel **111**W (FIG. **23**, Block **250**) in any suitable manner (e.g., with automated equipment or manually), such as described herein.

Referring to FIG. **24**, a tire balancer **129**M**4** is illustrated. The tire balancer **129**M**4** includes a frame **1100** that is in one aspect configured with an end effector mount **129**MM for coupling with the robotic arm **126**; while in other aspects the frame **1100** is configured for placement on a floor of a tire changing station (such as shown in FIG. **35**). The frame **1100** may be substantially similar to frame **310** and include at least a drive roller **300** and its corresponding drive motor DM. The frame **1100** may also include a road force roller **305**.

Any suitable vibration sensor **1115** is coupled to the frame **1100**. The vibration sensor **1115** may be one or more accelerometers, a non-contact optical displacement sensor, or any other suitable sensor configured to sense vibrations of the wheel assembly **111** and/or vehicle suspension components **500** and send signals embodying the detected vibrations to the controller **129**CNT over a wired or wireless connection/protocol WCP. The vibration sensor **1115** may be coupled to the frame **1100** in any suitable manner, such as by a lift **1125** that raises and lowers the vibration sensor **1115** relative to the frame. The lift **1125**, under control of controller **129**CNT, is raised to place the vibration sensor in contact with, for example, the any suitable portion of the vehicle suspension components **500** (e.g., such as a control arm). The lift **1125** and/or vibration sensor **1115** may include any suitable contact, optical, capacitive, resistive, etc. sensor configured to detect contact between the vibration sensor **1115** and the vehicle suspension components **500** so as to signals to the controller with respect to stopping travel of the lift once contact is made.

The vibration sensor **1115** includes any suitable magnets, clamps, etc. that engage the vehicle suspension components **500** to hold the vibration sensor **1115** to the vehicle suspension components **500**. In one aspect, the vibration sensor **1115** may be releasable from the lift, such that with the vibration sensor **1115** is held contact with the vehicle suspension components **500** (e.g., via magnet, clamp, etc.), the vibration sensor **1115** is automatically disengaged from the lift **1125** and the lift **1125** is lowered so as not to dampen any vibration caused by wheel assembly imbalance; in other aspects, the lift **115** may have a spring rate/force sufficient to raise the vibration sensor **1115** into contact with the vehicle suspension components **500** but such spring rate/force is negligible with respect to vibration induced by wheel assembly imbalance. In other aspects the vibration sensor **1115** may be manually coupled to the vehicle suspension components **500** in any suitable manner (e.g., magnetically, mechanical fasteners/clamps, etc.).

Still referring to FIG. **24**, and also to FIG. **25**, in operation the tire balancer **129**M**4** and the wheel assembly **111** are positioned relative to one another (FIG. **25**, Block **1200**). In one aspect, the robotic arm positions the tire balancer **129**M**4** relative to the wheel assembly **111** such as with the vehicle **110** on a lift **170**; while in other aspects, the vehicle **110** is driven onto the rollers **300**, **305** of the tire balancer **129**M**4**.

The vibration sensor **1115** is engaged with the vehicle suspension components **500** (FIG. **25**, Block **1210**) in the manner described above. The wheel assembly **111** is rotated (e.g., by the drive roller **300**) (FIG. **25**, Block **1220**) and wheel balance metrics are obtained at least in part from the vibration sensor (FIG. **25**, Block **1230**), e.g., the vibration sensor **1115** senses vibrations in the vehicle suspension components **500** that are indicative of wheel assembly **111** imbalance. The vibration sensor **1115** sends signals to the controller **129**CNT embodying the wheel balance metrics and the controller **129**CNT is configured to determine, based on the wheel balance metrics (e.g., including vibrations, wheel rotation position, etc.) an amount of wheel weight and a position of the wheel weight **3188** (see, e.g., FIGS. **44**A and **56**) on the wheel **111**W (FIG. **25**, Block **1240**) to effect balancing of the wheel assembly **111**. The wheel weight **3188** may be applied (FIG. **25**, Block **1250**) with any suitable automation or manually.

Referring to FIGS. **26**A-**26**C, a tire balancer **129**M**5** is illustrated. The tire balancer **129**M**5** may be substantially similar to tire balancer **129**M**1**; however in this aspect the tire balancer **129**M**5** employs an optical sensing system (e.g., that includes one or more of an optical runout sensor **1310** and at least one optical point sensor **1320**, **1321**) to detect one or more of high and low points of radial runout of the wheel assembly **111**, radial runout of the wheel assembly **111**, and lateral runout of the wheel assembly **111**. While the tire balancer **129**M**5** is illustrated as having drive roller **300** and road force roller **305**, in other aspects, tire balancer **129**M**5** may include an idle (non-driven) roller **300**D in place of the drive force roller **305**, or in other aspects, the rollers may form or be part of a dynamometer.

The tire balancer **129**M**5** includes optical scanner **1310**. The optical runout sensor **1310** is configured to detect both radial runout and lateral runout of the wheel assembly **111**; while in other aspects, there may be separate optical scanners for respectively detecting the radial runout and lateral runout. For exemplary purposes, the optical runout sensor **1310** may be any suitable three-dimensional scanner including, but not limited to, LIDAR (light detection and ranging), ViDAR (video or visual detection and ranging), and time-of-flight cameras. The optical runout sensor **1310** is coupled to the frame **310** in any suitable manner so as to be disposed beneath the tire **111**T with the wheel assembly **111** disposed on the rollers **300**, **305**. In one aspect, the optical runout sensor **1310** is disposed substantially between the rollers **300**, **305** but in other aspects may be positioned at any suitable location on the frame **310** so as to image the thread (e.g., tire width) of the tire **111**T. The optical runout sensor **1310** has a width (or field of view) FOV**13** that is greater than the width TW of the tire. The optical runout sensor **1310** provides detection signals (both ranging and position signals) to the controller **129**CNT and the controller **219**CNT is configured to determine (based on the detection signals) the radial and lateral runout of the wheel assembly **111**.

The tire balancer **129**M**5** includes one or more optical point sensors **1320**, **1321** that are coupled to the frame **310** in any suitable locations so as to image at least one lateral side of the wheel assembly **111**. For example, optical point sensor **1320** is disposed on one lateral side of the wheel assembly **111** while optical point sensor **1321** is disposed on the opposite lateral side of the wheel assembly **111** (see FIG. **26**B); while in other aspect, there may be but one optical point sensor located on the frame **310** so as to be positioned

on but one lateral side of the wheel assembly. Each of the optical point sensors **1320**, **1321** has a field of view FOV**13**A, FOV**13**B that is shaped and sized to as to image or otherwise detect a sidewall **111**TS of the tire **111**T and at least a rim **111**R of the wheel **111**W. Each of the optical point sensors **1320**, **1321** provides detection signals to the controller **129**CNT and the controller **219**CNT is configured to determine (based on the detection signals) the high and low points of the radial runout of the wheel assembly **111**.

The optical runout sensor **1310** and the one or more optical point sensors **1320**, **1321** are communicably connected to the controller **129**CNT in any suitable manner, such as through a wireless connection (such as wireless communication protocol WCP) and/or a wired connection.

While the tire balancer **129**M**5** was described above, as having an end effector mount **129**MM for coupling the tire balancer **129**M**5** to the at least one robotic arm **126**, in other aspects, the tire balancer **129**M**5** may be a stand-alone floor unit (substantially similar to that shown and described herein with respect to FIG. **30**D) or the tire balancer **129**M**5** may be a component of tire changing system **100**, **100**A (see FIGS. **1**A, **1**B and **35**) where the vehicle **110** is driven into the alignment cell and onto the tire balancer **129**M**5** (which is generally referred to in FIGS. **1** and **35** as tire balancer **129**MS).

Still referring to FIGS. **26**A-**26**C and also to FIG. **27**, an exemplary operation of the tire balancer **129**M**5** will be described. The tire balancer **129**M**5** is positioned relative to the wheel assembly **111** or vice versa (with the wheel assembly **111** in situ the vehicle **110**) in any suitable manner (FIG. **27**, Block **1400**), such as by the at least one robotic arm **126** so that the drive roller **300** and road force roller **305** are in substantial contact with the tire **111**T. In other aspects, the tire balancer **129**M**5** may be a component of tire changing system **100**, **100**A (see FIGS. **1**A, **1**B and **35**) where the vehicle **110** is driven into the alignment cell and onto the tire balancer **129**M**5**. The controller **129**CNT operates the drive motor(s) DM so that the drive roller **300** drivingly rotates the wheel assembly **111** (FIG. **27**, Block **1410**) with the drive force roller **305** applying a simulated road force to the wheel assembly **111**.

With the wheel assembly **111** rotating the optical runout sensor **1310** detects movement of the wheel assembly **111** in one or more of the radial acceleration R direction and the axial acceleration direction (e.g., +Z and/or −Z directions) (FIG. **27**, Block **1425**). The optical runout sensor **1310** sends sensor signals, embodying data corresponding to the detected movement of the wheel assembly **111** in the radial and axial acceleration directions, to the controller **129**CNT.

With the wheel assembly **111** rotating the at least one optical point sensor **1320**, **1321** detect(s) the high and low points of the radial runout of the wheel assembly **111** (FIG. **27**, Block **1420**). The at least one optical point sensor **1320**, **1321** send sensor signals, embodying the high and low point data, to the controller **129**CNT.

An amount of weight and a position of the weight is determined based on the movement of the wheel assembly **111** in the radial and axial acceleration directions and/or the high and low point data (FIG. **27**, Block **1430**). For example, the controller **129**CNT includes an empirically derived table EDT that correlates amounts of weights and positions of those weights on the wheel assembly **111** to the detected movement of the wheel assembly **111** in the radial and axial acceleration directions and/or the detected high and low point data. There may be an empirically derived table EDT for each different tire **111**T and wheel **111**W combinations such that based on the tire/wheel combination and the detected movement of the wheel assembly **111** in the radial and axial acceleration directions and/or the detected high and low point data the controller **129**CNT searches the empirically derived tables EDT to determine from the corresponding empirically derived table EDT the amount and position of the weights to be affixed to the wheel assembly **111**. In other aspects, the amount and position of the weights to be affixed to the wheel assembly **111** may be determined in any suitable manner such as analytically as a function of the detected movement of the wheel assembly **111** in the radial and axial acceleration directions and/or the detected high and low point data knowing the material properties and sizes of the tire and wheel.

With the amount of weight and the position of the weight determined the weight is applied to the wheel **111**W (FIG. **27**, Block **1440**) in any suitable manner (e.g., with automated equipment or manually), such as described herein.

Referring to FIGS. **28**A and **28**B a tire balancer **129**M**6** is illustrated. The tire balancer **129**M**6** includes a remote motion detection module **1520** and a vibration inducing member **1530**. The remote motion detection module **1520** may be substantially similar to the remote motion detection module **320** described herein and includes a mounting plate **1521** to which motion sensors **1522**A, **1522**B, **1522**C are coupled. The motion sensors **1522**A, **1522**B, **1522**C are substantially similar to motion sensors **320**A, **320**B, **320**C described herein. For example, the motion sensors **1522**A, **1522**B, **1522**C may each include a three-dimensional motion sensor configured to detect accelerations in at least one radial direction R (e.g., one of X and Y) and in the +/−Z direction.

The vibration inducing member **1530** includes a frame **1530**F that includes an end effector mount **129**MM for coupling the vibration inducing member **1530** to the robotic arm **126**. In other aspects, the vibration inducing member **1530** may be stationary/fixed at any suitable location of a tire changing station (see FIGS. **1**B and **35**) that provides for the vibration inducing member **1530** inducing vibration to the wheel assembly **111**. The vibration inducing member **1530** is any suitable actuator that includes a drive **1530**DM and an impactor **1530**R (e.g., hammer, rod, etc.). The drive **1530**DM is configured to effect a striking movement of the impactor **1530**R (one or more of a rotary motion and linear motion) against the wheel **111**W (or the tire **111**T) for inducing vibration of the wheel assembly **111**. The impinger **1530**R is configured to induce vibration in the wheel **111**W without leaving marks on the wheel (e.g., the portion of the impactor **1530**R striking the wheel **111**W includes a non-marking pad that interfaces with the wheel **111**W).

The controller **129**CNT is communicably coupled to the motion sensors **1522**A, **1522**B, **1522**C so that with the wheel **111**W struck by the impactor **1530**R, the motion sensors **1522**A, **1522**B, **1522**C sense vibrations of the wheel **111**W and send signals to the controller **129**CNT embodying those vibrations. Where the tire assembly is balanced the vibrations (e.g., frequency) of the wheel **111**W sensed by the different motion sensors **1522**A, **1522**B, **1522**C may be substantially similar. Where the tire assembly is imbalanced the vibrations (e.g., frequency) of the wheel **111**W sensed by the different motion sensors **1522**A, **1522**B, **1522**C may be different. The controller **129**CNT is configured to analyze

the different frequencies from the different motion sensors **1522**A, **1522**B, **1522**C and determine an amount of weight and location of weight to be applied to the wheel **111**W to effect balancing of the wheel assembly **111** (and e.g., make the vibration frequencies sensed by the different sensors **1522**A, **1522**B, **1522**C substantially the same).

Referring to FIGS. **28**A, **28**B and **16**, in operation the tire balancer **129**M**6** and the wheel assembly **111** are positioned relative to one another (FIG. **29**, Block **1600**). In one aspect, the robotic arm positions the tire balancer **129**M**6** relative to the wheel assembly **111** such as with the vehicle **110** on a lift **170**; while in other aspects, the vehicle **110** is driven to a tire changing station (such as those described herein) to position the wheel assembly **111** relative to the tire balancer **129**M**6**; while in still other aspects, the tire balancer may be a module unit (e.g., cart) that is positioned adjacent the wheel assembly **111**.

The controller **129**CNT operates the drive **1530**DM so that the impactor **1530**R is driven to strike the wheel **111**W (or tire **111**T) (FIG. **29**, Block **1610**) and induce vibration of the wheel assembly **111**. Wheel balance metrics (e.g., vibrational frequencies) are obtained by the controller **129**CNT from the motion sensors **1522**A, **1522**B, **1522**C (FIG. **29**, Block **1620**) and the controller **129**CNT determines an amount of wheel weight and position of the wheel weight **3188** (FIG. **29**, Block **1630**; see also, e.g., FIGS. **44**A and **56**), based on the detected vibrational characteristics of the wheel assembly **111**, to effect balancing of the wheel assembly. The wheel weight **3188** may be applied to the wheel **111**W in any suitable manner such as manually and/or with automation.

Referring to FIGS. **30**A-**30**C, a tire balancer **129**M**7** is illustrated. The tire balancer **129**M**7** includes a frame **310**, a drive roller **300**, a road force roller **305**, and drive motors that are substantially similar to any one or more of tire balancers **129**M**1**, **129**M**2**, **129**M**3**, and **129**M**5**; however, in this aspect one or more sensors for detecting imbalances of the wheel assembly **111** are integrated into the wheel weights **1701**. For example, each wheel weight **1701** include an adhesive backing **1705** configured to adhere the wheel weight **1701** to the wheel **111**W. The wheel weight **1701** also includes an inertial measurement unit **1702** integrally formed therewith so that the wheel weight **1701** itself detects the radial accelerations R (e.g., up and down vibrations or "hop") and both the positive axial accelerations +Z and negative axial accelerations −Z (e.g., sideways motion or "wobble") of the wheel assembly **111**. The inertial measurement unit **1702** includes any suitable sensors for detecting the radial and axial accelerations, where such sensors include but are not limited to accelerometers, gyroscopes, or any other suitable sensor, one or more of which may be a Micro Electro Mechanical System (MEMS) sensor.

The wheel weight **1701** includes a wireless transmitter **1703** configured to communicate with the controller **129**CNT wirelessly over wireless communication protocol/connection WCP. For example, the tire balancer **129**M**7** includes receivers **1720** that are configured to receive radial and axial acceleration data and transmit that data to the controller **129**CNT. The controller **129**CNT is configured to determine, based on the radial and axial acceleration data from the wheel weights **1701** an imbalance of a respective wheel assembly **111** and identify a change in position of the weight(s) **1701** and/or an amount of weight needed to balance the wheel assembly **111**.

The wireless transmitter **1703** may be configured to communicate with the receivers **1720** over a wireless communication protocol/connection WCP that is the same as and has the same frequency as, for example, the TPMS sensors of the automobile on which the wheel assembly **111** is mounted. With the wheel weight **1701** communicating over the TPMS sensor frequency and protocol, the wheel weight **1701** is configured to send radial and axial acceleration data to the automobile computer **110**CNT (e.g., during operation of the automobile on a road or other surface) where the automobile computer **110**CNT is configured to determine, based on the radial and axial acceleration data from the wheel weights **1701** an imbalance of a respective wheel assembly **111** and alert an operator of the vehicle of the imbalance through any suitable user interface **110**U of the automobile **110**. In other aspects, the transmitter **1703** of the wheel weights **1701** is configured to communicate with a smart device **1715** (e.g., phone, tablet, etc.) where any imbalances detected for a respective wheel assembly **111** are communicated to an operator of the vehicle through the smart device **1715**.

While the tire balancer **129**M**7** was described above, as having an end effector mount **129**MM for coupling the tire balancer **129**M**7** to the at least one robotic arm **126**, in other aspects, the tire balancer **129**M**7** may be a stand-alone floor unit **129**M**7**S (see FIG. **30**D) or the tire balancer **129**M**7** may be a component of tire changing system **100**, **100**A (see FIGS. **1**A, **1**B and **35**) where the vehicle **110** is driven into the alignment cell and onto the tire balancer **129**M**5** (which is generally referred to in FIGS. **1** and **35** as tire balancer **129**MS). For example, the tire balancer **129**M**7**S includes a shaft **1777** to which the wheel **111**W/wheel assembly **111** is coupled. A drive motor **1776** rotates the shaft **1777** (and the wheel **111**W/wheel assembly **111**) to effect balancing of the wheel assembly **111** as described herein.

In operation, still referring to FIGS. **30**A-**30**C and also to FIG. **31**, the at least one robotic arm **126** positions the tire balancer **129**M**7** relative to the wheel assembly **111**, with the wheel assembly in situ the vehicle **110**; or the vehicle is driven to position the wheel assembly **111** relative to the tire balancer **129**M**7** (FIG. **31**, Block **1800**). The drive roller **300** and the road force roller **305** (and in some aspects dynamic balance rollers similar to those described herein) are moved radially, by their respective motors (substantially similar to motors **720**, **721** described above), so as to engage (e.g., substantially contact) the tire **111**T (FIG. **31**, Block **1810**). The drive roller **300** is rotated, by the motor DM, so as to rotate the wheel assembly (FIG. **31**, Block **820**) and wheel balance metrics (e.g., one or more of the radial runout and lateral runout) are obtained from the inertial measurement units **1702** of the respective wheel weights **1701** that are applied to the wheel **111**W (FIG. **31**, Block **1830**).

The amount of weight to be coupled to the wheel **111**W and the location of weight to be coupled to the wheel are determined (FIG. **31**, Block **1840**) by the controller **129**CNT in any suitable manner (such as in a manner similar to that described herein). Where the location and weight determination results indicate the wheel assembly is balanced (e.g., the amount of weight and location of the wheel weights **1701** result in a balanced wheel assembly **111**) the balancing procedure ends and the wheel weights **1701** remain on the wheel **111**W (e.g., where in some aspects the wheel weights **1701** communicate with the automobile computer **110**CNT to provide wheel assembly balance information to the user

of the automobile as described herein). In other aspects, the wheel weights **1701** may be removed and replaced with conventional wheel weights **3188** (see, e.g., FIGS. **44**A and **56**) having the same mass and location as wheel weights **1701** removed from the wheel **111**W. Where the location and weight determination results indicate the wheel assembly is not balanced one or more of repositioning of the wheel weights **1701**, increasing an amount of wheel weights **1701**, and decreasing an amount of wheel weights **1701** is effected based on the weight and position determination (FIG. **31**, Block **1840**), in any suitable manner (such as by a human operator or automation). With the wheel weights repositioned and/or the amount of wheel weights changed, Blocks **1820**-**1850** are repeated until the position and weight determination indicates the wheel assembly is balanced.

Referring now to FIGS. **32**A-**32**C and **33**, the high point of radial runout (referred to herein as the high point) **1900** of the tire **111**T and the low point of radial runout (referred to herein as the low point) **1901** may be determined prior to balancing the wheel assembly **111** in the manners described herein. For example, a portion of a tire balancer **129**M**8**, which may be incorporated with any one or more of the tire balancers described herein, is employed for determining (and is configured to determine, with the controller **129**CNT) the high point **1900** and low point **1901** of the tire **111**T and wheel **111**W so that the respective high point **1900** and low point **1901** of the tire **111**T and wheel **111**W are positioned relative to each other when the tire **111**T is mounted to the wheel **111**W in a manner that may decrease/minimize the amount of weight added to the wheel assembly **111** and to effect balancing of the wheel assembly **111**.

To determine the high point **190** of the tire **111**T, the tire **111**T is mounted to a temporary wheel **111**TW (FIG. **33**, Block **2000**) having a known (i.e., controlled/calibrated) diameter. The temporary wheel **111**TW is also balanced so that rotation of the temporary wheel **111**TW, with the tire **111**T mounted thereto, does not influence the determination of the high point **1900** of the tire. The location of the high point of the tire **111**T is determined (FIG. **33**, Block **2010**) as described below. The determination of the high point **1900** location on the tire **111**T may be effected off of the vehicle by any of the tire balancers **129**M described herein (such as where the tire balancers are stand-alone units); while in other aspects, the temporary wheel **111**TW may be mounted to the vehicle **110** and the at least one robotic arm **126** may position the tire balancer **129**M for determining the high point **1900** of the tire in situ the vehicle **110**. The drive roller **300** and road force roller **305** of the tire balancer **129**M engage the tire **111**T, the tire **111**T is spun, and the radial runout is measured using any suitable sensors, such as those described herein. The location of the tire **111**T having the greatest runout (e.g., the greatest distance from a center TWC of the temporary wheel **111**TW) is determined by the controller **129**CNT to be the high point **1900** of the tire. The high point **1900** is marked (FIG. **33**, Block **2020**) on the tire (e.g., with a sticker, marker, or in any other suitable manner) and the tire **111**T is removed from the temporary wheel **111**TW.

The low point **1901** of the wheel **111**W may be determined with the wheel **111**W in situ the vehicle **110** or with the wheel **111**W removed from the vehicle **110**. To determine the low point **1901** of the wheel **111**W, the old tire (if replacing a tire) is removed from the wheel **111**W (FIG. **33**, Block **2030**). Here, a low point determining apparatus **1950** is employed to determine the low point of the wheel **111**W (FIG. **33**, Block **2040**). The low point determining apparatus **1950** may be substantially similar to the tire balancer **129**M. The low point determining apparatus **1950** may be coupled to and carried by the at least one robot arm **126** or the low point determining apparatus **1950** may be a stand-alone unit. The low point determining apparatus **1950** includes a drive roller **300** (driven by drive motor DM) and a secondary roller **300**S (such as the road force roller **305** or idle (non-driven) roller **300**D). The drive roller **300** and secondary roller **300**S are moveably coupled to the frame **310** in any suitable manner so as to be biased against the wheel **111**W with the wheel **111**W and low point determining apparatus **1950** positioned relative to each other for determining the low point of the wheel **111**W. The low point determining apparatus **1920** includes one or more deflection sensors **1970** for determining the deflection of one or more of the drive roller **300** and secondary roller **300**S relative to, for example, the frame **310** with the wheel rotating. The deflection sensor(s) **1970** send signals, to the controller **129**CNT, that embody an amount of deflection of the one or more of the drive roller **300** and secondary roller **300**S, where the controller **129**CNT is configured to determine the low point **1901** (e.g., the point on the wheel **111**W with the smallest distance DLW from a center WWC of the wheel **111**W) of the wheel **111**W based on the deflection data from the deflection sensor(s) **1970**. The low point **1901** of the wheel **111**W may be marked (FIG. **33**, Block **2050**) in any suitable manner, such as with a sticker, marker, etc.

The determination of the low point **1901** and high point **1900** may be determined substantially simultaneously or one before the other. With the high point **1900** and low point **1901** determined the tire **111**T is mounted to the wheel **111**W (FIG. **33**, Block **2060**) in any suitable manner (such as automatically with the tire mount/dismount tool **129**E (optical sensors may be employed by the tool **129**E to align the high and low points) or manually) so that the low point **1901** and high point **1900** are aligned with each other as illustrated in FIG. **32**B. The wheel assembly **111** is balanced (FIG. **33**, Block **2070**) in the manner described herein, where the balancing is effected by any one of the tire balancers **129**M described herein.

Referring to FIGS. **34** and **35**, aspects of the above-described tire balancers **129**M**1**-**129**M**7** (generally illustrated as tire balancers **129**MS, one or more of which may include the portion of the tire balancer **129**M**8**) may be employed with floor mounted roller systems, where two or more wheels of the vehicle **110** are disposed on the roller systems so that two or more of the wheel assemblies **111** of the vehicle **110** are substantially simultaneously balanced under simulated real-world conditions. For example, the tire changing system **100**A (see also tire changing system **100** in FIGS. **1**A and **1**B) includes floor mounted roller assemblies **2200** (one for each wheel assembly **111** of the vehicle **110**). Each roller assembly **2200** includes a drive roller **300** and a road force roller **305** in a manner similar to that described herein. The roller assemblies **2200** corresponding to an axle(s) (e.g., front and/or rear) of the vehicle **110** may be mounted on a slide **2100** so that the distance **2199** between the roller assemblies **2200** corresponding to the different axle(s) of the vehicle **110** may be adjusted according to a wheel base WLBS of the vehicle **110** (FIG. **36**, Block **2300**). The slide **2100** may be coupled to and driven by any suitable motor SLM under control of the controller **129**CNT to effect

adjustment of the distance **2199** depending on the vehicle **110** wheelbase WLBS. The vehicle **110** is driven onto the roller assemblies **2200** (FIG. **36**, Block **2310**) and a remote/wireless sensing device (e.g., one of the remote motion detection module **320** (either employing the passive fiducials **922**A-**922**C or the motion sensors **322**A-**322**C) and the wheel weights **1701**) are affixed to each wheel **111**W (FIG. **36**, Block **2320**). The drive rollers **300** of each roller assembly **2200** drive/spin the respective wheel assembly **111** (FIG. **36**, Block **2330**) to replicate actual/real-world driving conditions (e.g., travel of the vehicle **110** along a roadway) and so that two or more of the wheel assemblies are substantially simultaneously assessed for imbalance. Each of the roller assemblies **2200** includes receivers for receiving sensor data from the remote motion detection modules **320** and/or wheel weights **1701**; or, in other aspects, the sensor data from the remote motion detection modules **320** and/or wheel weights **1701** is sent to and received by the controller **129**CNT. The controller **129**CNT is configured to determine the amount of wheel weight and location of the wheel weight for each wheel assembly **111** (FIG. **36**, Block **2340**) based on the respective sensor data from the respective remote motion detection module **320** in the manner(s) described herein. The wheel weight(s) **3188** (see, e.g., FIGS. **44**A and **56**) or wheel weights **1701** are applied to and/or relocated on the respective wheels **111**W (FIG. **36**, Block **2350**) to effect balancing of each wheel assembly **111** in the manner(s) described herein.

Still referring to FIG. **35**, the tire changing system **100**A includes a tire exchange cabinet **2370** adjacent each roller assembly **2200**. Each tire exchange cabinet includes any suitable tire exchange robot **2220** (such as tire changing bot **120** described herein). The tire exchange cabinet **2370** includes a tire exchange position/location **2380** that is accessible through a door **2381** at which tire exchange position a human operator exchanges old and new tires with the respective tire exchange robot **2220**. For example, the vehicle **110** is driven onto the roller assemblies **2200** (FIG. **36**, Block **2310**). The lift **170** raises the vehicle **110** (FIG. **36**, Block **2360**) and the old tire **111**T is removed from the wheel **111**W by the tire exchange robot **2220** (FIG. **36**, Block **2370**), where the wheel **111**W remains in situ the vehicle **110**. The tire exchange robot **2220** places the old wheel at the tire exchange position **2380**. The human operator opens the door **2381**, removes the old tire from the tire exchange position, places a new tire at the tire exchange position **2380**, and closes the door **2381**. The tire exchange robot **2220** picks the new tire from the tire exchange position **2380** and mounts the new tire to the wheel **111**W (FIG. **36**, Block **2380**). The vehicle **110** is lowered (FIG. **36**, Block **2390**) onto the roller assemblies **2200** and the wheel assemblies **111** are balanced in the manner(s) described herein.

While the tire changing system **100**A was described employing the remote sensing devices, in other aspects, any of the tire balancers described herein may be employed in the tire changing system **100**A. It is also noted that the tire changing system **100**A may facilitate balancing tires of an all-wheel-drive vehicle under simulated real-world driving conditions as all four wheels are driven at the same time.

Referring now to FIG. **37**, the tire balancers described herein (generally referred to as tire balancer **129**M) may include a belt type road force tire driving mechanism **2400**. For example, the pulleys **2410**, **2411** are mounted to the frame **310** in any suitable manner. Pulley **2410** is a drive pulley that is driven in rotation by any suitable drive motor DM. The pulley **2411** is an idler or driven pulley. An endless/conveyor belt **2420** is wrapped around the pulleys **2410** and is driven around the pulleys by the driven rotation of the pulley **2410**. The endless belt **2420** engages the pulleys **2410**, **2411** in any suitable manner, such as with a toothed engagement so that slippage between the endless belt **2420** and the pulleys **2410**, **2411** is minimized or substantially eliminated. Any suitable force sensor **2460** (such as a strain gauge) is coupled to shaft of the pulley **2411** (or the mount between the pulley **2411** and the frame **310**) so that the force sensor **2460** measures, e.g., strain, on the pulley shaft or mount with the belt **2420** deflected under loading of the wheel assembly. Here, the deflection of the belt **2420** (and the tension caused by the deflection) exerts a force FRC on the force sensor **2460**.

The amount of deflection **2499** of the belt **2420** changes as the wheel assembly **111** rotates due to the high and low points of radial runout of the wheel assembly (e.g., highest deflection/force as determined by the force sensor **2460** indicates a wheel assembly high point and a lowest deflection/force as determined by the force sensor **2460** indicates a wheel assembly low point). The controller **129**CNT is configured to determine the high and low points of the wheel assembly **111** based on the sensor signals from the force sensor **2460**. The angular positions of the high and low points relative to the wheel assembly **111** (i.e., where along the perimeter of the wheel assembly **111** the high and low points are located) may be determined by correlating, with the controller **129**CNT, a rotation position of drive roller **2410** (as determined by any suitable encoders/sensors and/or stain gauge data) with the rotational angle of the wheel assembly **111** with the tire **11**T engaged with (e.g., in substantial contact with) the belt **2460**.

Referring also to FIGS. **38**A and **38**B, it is noted that the belt type road force tire driving mechanism **2400** for each of the tire balancers **129**MS (see, e.g., FIGS. **1**A, **1**B, and **35**) may be coupled so as to be driven substantially simultaneously by a common motor CDM. Driving the (e.g., four) tire balancers **129**M with a common drive motor CDM provides for substantial simultaneously balancing the four tire assemblies of an all-wheel-drive vehicle. For example, the drive pulleys **2410** of the tire balancers **129**M corresponding to the front and/or rear wheels of a vehicle are coupled by a drive shaft **2510**, **2511** so that the common drive motor CDM drives the tire balancers **129**M corresponding to both front wheels or both rear wheels. A drive system **2560** (e.g., belt and pulley, chain and sprocket, or other suitable drive system) couples the drive pulleys **2410** of the tire balancers **129**M corresponding to the front wheels of the vehicle with the drive pulleys **2410** of the tire balancers **129**M corresponding to the rear wheels of the vehicle. Here, the drive systems **2560** couples the four drive pulleys **2410** to the common drive motor CDM so that the common drive motor CDM simultaneously drives the belts **2420** of the four tire balancers **129**M at substantially the same rate.

Referring to FIGS. **39**A-**39**C a tire balancer **129**M**9** will be described. The tire balancer **129**M**9** includes a frame **2605**, at least one tension member **2620**, and at least one force gauge **2610**. The frame **2605** has any suitable shape (e.g., a channel shape, a U shape, etc.) and/or include any suitable features (e.g., stanchions, rails, etc.) such that one end of the at least one tension member **2620** is coupled substantially directly to the frame **2605** at or adjacent one end the frame **2605** and the other end of the at least one tension member

is coupled to the frame **2605** by the at least one force gauge **2610** at or adjacent the other end of the frame **2605**.

The at least one tension member **2620** is any suitable tension member configured to engage the tire **111**T. For example, the at least one tension member **2620** may be one or more of a belt, cable, thin strand or wire, chain, etc. The at least one tension member **2620** includes anti-friction properties (e.g., rollers, coatings, surface finish, etc.) that provide for slipping of the tire **111**T across or along the at least one tension member **2620** substantially without spinning of the tire **111**T (e.g., about the wheel hub of the vehicle **110**) generating pulling/pushing forces along a length of the at least one tension member **2620**. While five tension members **2620** are illustrated in FIG. **39**A, in other aspects there may be more or less than five tension members **2620**.

The at least one force gauge **2610** is communicably coupled to the controller **129**CNT (e.g., by a wired or wireless connection/protocol WCP) so as to transmit signals to the controller **129**CNT that embody force detected by the at least one force gauge **2610**. The at least one force gauge **2610** is any suitable force gauge such as a strain gauge, cable tension transducer, or any other suitable load cell configured to detect/measure changes in tension of the at least one tension member **2620**. Here, a force gauge **2610** is provided for each of the tension members **2620**; however in other aspects one force gauge **2610** may be coupled to more than one tension member **2620**.

In one aspect the frame **2605** includes an end effector mount **129**MM configured to couple the tire balancer **129**M**9** to the robotic arm **126**; while in other aspects, the frame **2605** is coupled to a linear slide **2650**, while in still other aspects, the frame **2605** may be stationarily fixed to a floor (e.g., such as of any tire changing station described herein). With the tire balancer **129**M**9** coupled to the robotic arm **126**, the robotic arm **126** positions the tire balancer **129**M**9** relative to the wheel assembly so that the tire seats against the at least one tension member **2620** so as to register any suitable predetermined tension/force on the at least one force gauge **2610** (e.g., preload the at least one tension member **2620** with the wheel assembly **111**). The wheel assembly **111** is rotated/spun relative to the at least one tension member **2620** (such as by any suitable drive roller such as those describe herein, and which drive roller may be mounted to the frame **2605**, or in any suitable manner) so that as the wheel rotates/spins about the wheel hub of the vehicle **110** and relative to the at least one tension member **2620** high and low points of the wheel assembly and/or imbalance of the wheel assembly causes deflection (e.g., a change in tension as detected by the at least one force gauge **2610**) of the at least one tension member **2620**. The at least one force gauge **2610** sends tension detection signals to the controller **129**CNT where the controller is configured to determine a location where on the tire the high points, low points, and imbalance exist. It is noted that the location of the tire the high points, low points, and imbalance exist may be timed with the force gauge **2610** signals via sensors/encoders located on the drive roller **300** (and/or the drive roller drive) such that the controller **129**CNT employs the sensors signals from the drive roller **300** and the force gauge **2610** to determine the location of and amount of imbalance, etc. of the wheel assembly **111**.

The wheel assembly **111** may be rotated relative to the tension members **2620** by one or more of holding the frame **2605** stationary and rotating/spinning the wheel assembly **111** about the wheel hub of the vehicle **110** (e.g., with drive roller **300** or in any suitable manner) in direction **2678** against the tension members **2620** and by moving the frame **2605** in direction **2677** so that the tension members **2620** at least in part cause (e.g., alone or in conjunction with the drive roller **300**) rotation of the wheel assembly **111** in direction **2678**.

Where the frame **2605** is moved to, the robot arm **126** or linear slide **2650** may move the frame **2605** in direction **2677** so that the tension members **2620**, in substantial contact with/preloaded by the tire **111**T, cause the tire to rotate in direction **2678**. The frame **2605** and the at least one tension member **2620** have any suitable length **2666** so that as the frame **2605** is moved in direction **2677** the at least one tension member **2620** has a length sufficient to cause at least one full rotation of the wheel assembly **111** about an axis of rotation (such as the wheel hub of vehicle **110**) of the wheel assembly **111**.

Where the frame **2605** remains stationary, and the wheel assembly **111** is rotated in direction **2678** the at least one tension member **2620** may include any suitable friction reducing/anti-friction properties such as those described above. As a further example, the at least one tension member **2620** may have a hollow core and surface perforations through which lubricant (e.g., water or other friction reducing fluid) is flowed (e.g., pumped) to reduce friction between the at least one tension member **2620** and the tire **111**T. In other aspects, rollers **2698** may be coupled to the at least one tension member **2620** (see FIG. **39**C) where the roller has a non-rotating portion **2697** (e.g., coupled to the at least one tension member **2620**) and a roller portion **2699** rotatably coupled to the non-rotating portion **2697**. The tire **111**T contacts the roller portion **2699** with the wheel assembly **111** engaged with the at least one tension member **2620**. In still other aspects, such as where the at least one tension member **2620** is a chain (see FIG. **39**D), the chain rollers **2691** may have a diameter such that the rollers **2691** protrude above the chain links so that the rollers contact the tire **111**T to reduce friction between the at least one tension member **2620** and the tire **111**T.

Still referring to FIG. **39**B, where the frame **2605** is fixed in place, such as to a floor of a tire changing system (such as those described herein), the vehicle **110** may be driven onto the at least one tension member **2620**. The wheel assembly **111** is rotated relative to the at least one tension member **2620** by the drive roller **300** or in any other suitable manner. Here, the drive roller **300** (and road force roller **305**) may be moved in direction **2636** to contact the tire **111**T such that the tire **111**T remains in contact with the at least one tension member **2620** to maintain the predetermined tension on the at least one force gauge **2610**; while in other aspects the at least one tension member **2620** is positioned relative to vertically stationary drive and road force rollers **300**, **305** such that as the vehicle **110** drives onto the drive and road force rollers **300**, **305** the tire **111**T deflects the at least one tension member **2620** to effect the predetermined tension on the at least one force gauge **2610** with the wheel assembly **111** being supported by the drive and road force rollers **300**, **305**; while in still other aspects, the at least one tension member **2620** provides the road force (e.g., in lieu of the road force roller **305**) such that the wheel assembly **111** (and vehicle **110**) is supported by the at least one tension member **2620** and drive roller **300**. Friction between the tire **111**T and the at least one tension member **2620** may be reduced in the manner described above.

Referring to FIGS. **40**A-**40**C a tire balancer **129**M**10** will be described. The tire balancer **129**M**10** may be referred to as an orbital scanning balancer that electromagnetically or sonically scans the wheel assembly **111** (or a portion thereof, e.g., the tire **111** and/or wheel **111**W) to detect anomalies of/in the wheel assembly **111** (e.g., slipped belting of the tire, foreign objects lodged in the tire, defective tire pressure monitoring system sensors, damaged wheels, etc.). Balancing of the wheel assembly may also be effected with any suitable image analysis programmed into the controller **129**CNT, where the images/video captured by the sonic and/or electromagnetic sensor is analyzed to determine radial and/or lateral runout of the tire assembly **111**.

In a manner similar to that described above, the tire balancer **129**M**10** may be incorporated into either one of tire changing systems **100**, **100**A. For example, the tire balancer **129**M**10** includes a frame **310** that includes the drive roller **300** (or in other aspects, a belt as described with respect to FIGS. **37** and **38**A-**38**B) in a manner similar to that described above. A road force roller **305** may also be provided on the frame to effect road force balancing of the wheel assembly **111** (supplemental to balancing of the wheel assembly **111** with the orbital scanning).

One or more electromagnetic and/or sonic sensors **2710** is coupled to, integral to, or otherwise mounted on the frame **310** in any suitable manner so that the frame and one or more electromagnetic and/or sonic sensors **2710** are carried by the robotic arm **126** via the end effector mount **129**MM; or in other aspects, the one or more electromagnetic and/or sonic sensors **2710** are fixed at predetermined positions within the tire changing system **100**, **100**A; or in still other aspects the one or more electromagnetic and/or sonic sensors **2710** are carried by the robotic arm **126** via the end effector mount **129**MM so as to move relative to a stationary the frame **310** and the wheel assembly **111**. The one or more electromagnetic and/or sonic sensors **2710** include, but are not limited to, one or more of an ultrasonic sensor/transducer, an X-ray scanner, a computerized tomography scanner, three-dimensional millimeter wave imaging scanner, a three-dimensional imager, or any other suitable sensor configured to effect anomaly detection and balancing of the wheel assembly **111**. For example, anomalies may include increased or decreased thickness of tire walls/tread (e.g., compared to other areas of the tire wall/tread), increased or decreased tire belt density, wheel chips/gouges, etc. With the controller **129**CNT being programmed with material properties of the tire **111**T and wheel **111**W, and with the size (e.g., volume) and location of the anomaly determined from the orbital scanning, the controller **129**CNT is configured to determine a mass (e.g., a missing mass/void or an increase in mass) of the anomaly. Based on a missing mass, the controller **129**CNT may indicate placement of a wheel weight **3188** (see, e.g., FIGS. **44**A and **56**) having substantially the same mass as the missing mass to be placed on the wheel **111**W at or adjacent the location of the missing mass. Based on an increased in mass, the controller **129**CNT may indicate placement of a wheel weight **3188** having substantially the same mass as the increased mass to be placed on the wheel **111**W at a location opposite the location of the increased mass. Wobble of the wheel assembly **111** (e.g., in the Z direction) may be determined by the controller **129**CNT based on the three-dimensional distance sensing inherent to the one or more electromagnetic and/or sonic sensors **2710**.

As described above, in some aspects, the frame **310** includes an end effector mount **129**MM that couples the tire balancer **129**M**10** to the robotic arm **126** so that the robotic arm **126** positions the tire balancer **129**M**10** relative to the wheel assembly **111**, with the wheel assembly in situ the vehicle **110**, in a manner similar to that described herein; while in other aspects, the frame **310** of the tire balancer **129**M**10** is stationarily mounted as part of the tire changing system **100** (see FIG. **1**B, where the frame **310** and drive roller **300** of tire balancer **129**M**10** is generally illustrated as tire balancer **129**MS) with the one or more electromagnetic and/or sonic sensors **2710** being carried by the robotic arm **126**; while in still other aspects, both the frame **310** and one or more electromagnetic and/or sonic sensors **2710** are stationarily mounted as part of the tire changing system **100**A (see FIG. **35**).

In operation, the tire balancer **129**M**10** is positioned relative to wheel assembly **111** or vice versa (FIG. **41**, Block **2800**). Positioning the wheel assembly **111** relative to the tire balancer **129**M**10** includes positioning one or more electromagnetic and/or sonic sensors **2710** relative to the wheel assembly **111**, or vice versa, to image the wheel assembly **111** substantially in its entirety (such as where a field of view of the sensor is configured to image the entire wheel assembly **111** or where the one or more electromagnetic and/or sonic sensors **2710** includes a sensor array **2710**RA having a combined field of view for imaging the entire wheel assembly **111**); or positioning the wheel assembly **111** relative to the tire balancer **129**M**10** includes positioning one or more electromagnetic and/or sonic sensors **2710** relative to the wheel assembly **111**, or vice versa, to image at least a portion thereof (which with the tire spun about the wheel hub each portion of the wheel assembly **111** is sequentially imaged by the one or more electromagnetic and/or sonic sensors **2710** to capture a composite image of the wheel assembly **111** in its entirety). In some aspects, for example, the robotic arm **126**, with the tire balancer **129**M**10** coupled thereto, positions the tire balancer **129**M**10** relative to the wheel assembly **111**. In other aspects, the robotic arm **126**, with the one or more electromagnetic and/or sonic sensors **2710** coupled thereto, positions the one or more electromagnetic and/or sonic sensors **2710** relative to the wheel assembly **111**. In other aspects, the vehicle **110** is driven into the tire changing system **100**A to position the wheel assembly **111** relative to the one or more electromagnetic and/or sonic sensors **2710** of the tire balancer **129**M**10**. Where more than one of the one or more electromagnetic and/or sonic sensors **2710** are employed, the electromagnetic and/or sonic sensors **2710** may be positioned relative to the wheel assembly **111** in a manner substantially similar to that illustrated in FIGS. **26**A-**26**C with respect to the sensors **1310**, **1320**, **1321** or in any other suitable sensor array **2710**RA.

The controller **129**CNT effects with the one or more electromagnetic and/or sonic sensor **2710** the scanning of the wheel assembly **111**, the wheel **111**W, and/or the tire **111**T (FIG. **41**, Block **2810**). It is noted that the vehicle **110** is positioned on the lift **170** so that the wheel assembly **111** is unloaded as the one or more electromagnetic and/or sonic sensors **2710** scan the wheel assembly **111** so that wheel loading does not affect orbital scanning and anomaly detection. The controller **129**CNT includes any suitable non-transitory image analysis algorithms so that the controller **129**CNT is configured to detect one or more of the above-noted anomalies through analysis of the scanned images of

the wheel assembly **111**, the wheel **111**W, and/or the tire **111**T. An exemplary scanned image **2770** of the tire **111**T is provided in FIG. **40**B while an exemplary scanned image **2780** of the wheel **111**W is provided in FIG. **40**C. Anomaly detection may be effected with the wheel assembly **111** rotationally fixed.

Where the wheel assembly **111** is rotated to effect scanning of the wheel assembly **111** in its entirety (such as where only a portion of the wheel assembly is in a field of view of the one or more electromagnetic and/or sonic sensors **2710**), the frame **310** includes any suitable lift drive LM (e.g., jack screw, air bag, linear actuator, etc.) that raises and lowers the drive roller **300** to selectively engage and rotate the tire **111**T so that different portions of the wheel assembly **111** are presented in the field of view of one or more electromagnetic and/or sonic sensors **2710** and/or in contact with a sonic sensor/transducer of the one or more electromagnetic and/or sonic sensors **2710**. The drive roller **300** is disengaged from the tire **111**T by the lift drive LM for scanning of the wheel assembly with the one or more electromagnetic and/or sonic sensors **2710**. It is noted that the different images may be stitched together in any suitable manner, such as by rotating the tire by an amount that is less than an area of the sensor field of view (e.g., so that different images include common features used to match/stich the different images with each other). To rotate the wheel assembly **111** the controller **129**CNT actuates the drive motor DM (and the drive roller **300** driven thereby) to effect rotation of the wheel assembly **111** (FIG. **41**, Block **2820**).

As noted above, in some aspects the wheel is rotated to and/or the sensors are moved (such as by the robotic arm **126**) determine anomalies present in the wheel assembly **111** (FIG. **41**, Block **2820**); while in other aspects the anomalies are detected with the wheel rotationally stationary. The controller determines the amount and location of weights to be affixed to the wheel assembly **111** (FIG. **41**, Block **2830**) in the manner described above where a mass of the anomaly or anomalies is/are determined and an amount and location of the wheel weights **3188** (see, e.g., FIGS. **44**A and **56**) is/are selected based on the anomaly mass/location determinations. The wheel weight(s) **3188** are applied to the wheel **111**W (FIG. **41**, Block **2840**) through automation or manually.

As noted above, a supplemental dynamic and/or road force balance of the wheel assembly may be performed to verify the balancing of the wheel assembly obtained with the orbital scanning. For example, in a manner similar to that described above, the wheel assembly **111** is rotated with the wheel weights **3188** (as determined by the orbital scanning) attached where the electromagnetic and/or sonic sensor **2710** scans the rotating wheel assembly **111** to obtain a baseline image/video (noting that the scanning is a three-dimensional scanning that provides for acceleration detections in both the lateral and radial runout directions) corresponding to a baseline runout (radial and/or lateral). Where the baseline runout is out of tolerance the wheel assembly **111** may be scanned again (FIG. **41**, Block **2810**) to verify/modify balance of the wheel assembly **111** and/or the balance of the wheel assembly **111** may be modified by rotating (e.g., by the drive roller **300** engaged or not engaged to road force roller **305**) the wheel assembly for a dynamic balance and/or road force balance in a manner similar to those described herein.

Referring to FIGS. **50**A-**50**C, a tire balancer **129**M**11** will be described. The tire balancer **129**M**11** may be referred to as a probe balancer and includes a touch probe **3710** that includes an end effector mount **129**MM for coupling the touch probe **3710** to the robotic arm **126** or any other suitable actuator configured to move the touch probe **370** relative to the wheel assembly **111** for determining a contour of the wheel assembly **111**. The touch probe **3710** is shaped and sized so that (and the actuator includes a suitable number of degrees of freedom and is sized to effect) the touch probe **3710** may be moved around and/or between the vehicle suspension components **500** (inclusive of brakes, rotors, etc., i.e., with the vehicle **110** lifted off of the ground by the lift **170** and the vehicle suspension components **500** fully relaxed/drooped down) for contacting the wheel **111**W and tire **111** as described herein.

The touch probe **3710** includes an array of tactile pins **3700** where each pin **3700**P in the array of tactile pins **3700** is movably coupled to a housing **3710**F of the touch probe **3710**. Each pin **3700**P is biased by a respective resilient member **3720** so that the pin **3700**P protrudes from the housing **3710**F by a predetermined distance **3721**. The touch probe **3710** includes sensors **3730** that detect an amount of movement of the pins **3700**P (e.g., relative to the predetermined distance or an amount the pin moves into the housing **3410**F), such as with the pins **3700**P pressed against an object. Each pin **3700**P is movable into and out of the housing **3710**F independent of each other pin **3700**P so that with the pins **3700**P pressed against the object a surface contour of the object is determined from sensors **3730** detecting the amount of movement of each pin **3700**P relative to each other pin **3700**P.

In operation, the touch probe **3710** is moved relative to the wheel assembly **111** (which is held stationary) so that the array of tactile pins **3700** of the touch probe **3710** are pressed into contact with the wheel assembly **111**. As each pin **3700**P is moved into the housing **3710**F by the contact between the pins **3700**P and the wheel assembly **111**, the sensors **3730** register/detect an amount of movement of the pins **3700**P and communicate the sensor data embodying the amounts of movement to the controller **129**CNT. The touch probe **3710** is moved to different locations of the wheel assembly **111**, contacting the wheel assembly **111**, so that a surface contour data of at least a portion of the wheel assembly is obtained and communicated to the controller **129**CNT. A distance between the housing **3710**F of touch probe **3710** and the wheel assembly **111** with the pins **3700**P in contact with the wheel assembly may be maintained at any suitable distance (e.g., as determined by any suitable proximity sensor **3740** including but not limited to optical and sonic proximity sensors) so that as the touch probe **3710** is moved to contact different portions of the wheel assembly **111**, the distance the pins **3700**P are moved relative to the housing **3710**F at one portion of the wheel assembly **111** are correlated to the distance the pins **3700**P are moved relative to the housing **3710**F at each other portion of the wheel assembly **111**.

The controller **129**CNT is configured to combine the surface contour data from the sensors **3730** in any suitable manner (e.g., such as by correlating movement of the robotic arm **126** with the sensor data and/or by matching detected surface features where there is overlap between the different portions of the wheel assembly **111** contacted by the touch probe **3710**). The controller **129**CNT, based on the combined surface contour data, is configured to generate a three-

dimensional model **111**VM (see FIG. **42**C) of at least a portion of the wheel assembly **111** for determining one or more of high and low points of the wheel **111**W, tire **111**T and runout of the wheel assembly in the radial R and axial Z directions. The controller **129**CNT includes any suitable image processing programming configured to analyze the three-dimensional model of the wheel assembly **111** to effect determination of the one or more of high and low points of the wheel **111**W, tire **111**T and runout of the wheel assembly in the radial R and axial Z directions.

An amount of weight and a position of the weight may be determined by the controller **129**CNT based on the determination of the one or more of high and low points of the wheel **111**W, tire **111**T and runout of the wheel assembly in the radial R and axial Z directions. For example, the controller **129**CNT includes an empirically derived table EDT that correlates amounts of weights and positions of those weights on the wheel assembly **111** to the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions. There may be an empirically derived table EDT for each different tire **111**T and wheel **111**W combinations such that based on the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions and the tire/wheel combination the controller **129**CNT searches the empirically derived tables EDT to determine from the corresponding empirically derived table EDT the amount and position of the weights to be affixed to the wheel assembly **111**. In other aspects, the amount and position of the weights to be affixed to the wheel assembly **111** may be determined in any suitable manner such as analytically as a function of the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions or a wheel assembly weight distribution (e.g., as determined by the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions knowing the material properties and sizes of the tire and wheel).

Referring to FIGS. **42**A-**42**C one or more of the tire balancers described herein (inclusive of the robotic arm mounted tire balancers, generally **129**M, **129**MS, and the stand alone tire balancers, generally **183**) may include a scanning system that models the wheel assembly **111** in three dimensions so that the high and low points of the wheel assembly **111** (or a portion thereof, e.g., the wheel **111**W and/or tire **111**T) are determined from the three-dimensional model of the wheel assembly **111** (or the portion thereof). The generation of three dimensional model of the wheel assembly **111** is effected with the wheel assembly **111** located in situ (i.e., installed on) the vehicle. For example, a scanner **2910** may be movably mounted to the frame **310** (e.g., via any suitable actuators or robotic arms) so that the scanner **2910** may be automatically driven/moved in one or more directions/degrees of freedom, e.g., under control of the controller **129**CNT, to scan one or more of both lateral sides of the wheel assembly **111** and the tread of the tire **111**T, one lateral side of the wheel assembly **111** and the tread, one later side of the wheel assembly **111**, the tread of the tire **111**T, and both lateral sides of the wheel assembly **111**. While scanner **2910** is illustrated in the FIG. **42**A as being movably mounted to the frame **310**, in other aspects, as described herein, the scanner **2910** may be mounted to the robotic arm **126** (in a manner similar to that described herein with respect to FIGS. **50**A-**50**C) and/or or provided in a scanner array **2910**RA (e.g., with more than one scanner **2910** positioned in a manner similar to that illustrated in FIGS. **26**A-**26**C or in any other suitable arrangement) for substantially simultaneous scanning of the lateral sides and tread of the wheel assembly **111**.

The scanner **2910** is an optical scanner such as a blue light three-dimensional scanner, a structure light scanner, or any other suitable three-dimensional scanner/distance sensor. The scanner **2910** has a field of view FOV**29** that extends over at least a portion of the wheel assembly **111**. In one aspect the field of view FOV**29** is shaped and sized so as to image at least an entire lateral side of the wheel assembly **111** with the wheel assembly remaining rotationally fixed (i.e., the wheel does not rotate); while in other aspects, the field of view FOV**29** is shaped and sized so as to image a portion of the side wall such that with the wheel rotated the scanner **2910** captures images of different portions of the at least the lateral side of the wheel **111** where the different images of the different portions of the lateral side wall are stitched together in any suitable manner (e.g., with any suitable image analysis algorithm of the controller **129**CNT, to form an image of at least the entire lateral side of the wheel **111**. Where a scanner array **2910**RA is provided, each scanner in the scanner array **2910**RA is similar to scanner **2910**. Each scanner in the scanner array **2910**RA includes a respective field of view (which may overlap a field of view of at least one other scanner) where the respective fields of view provide images that are stitched together in a manner similar to that described herein to form the three-dimensional model of the wheel assembly **111**.

To effect stitching of the different images, any suitable targets **2999** are randomly affixed to the wheel assembly **111** and the controller **129**CNT is configured to align the different images to each other employing the detected targets **2999** as markers for aligning the different images with each other. The random placement of the targets **2999** forms, in effect, a unique arrangement of targets that are matched between the different images using the image processing software to form a composite image/model (e.g., the three-dimensional model **111**VM of the wheel assembly **111**). The targets **2999** are affixed to both lateral sides and the tread of the wheel assembly **111** so that as the wheel assembly **2999** is rotated and the scanner **2910** moves relative to the frame from one lateral side of the wheel assembly to the other lateral side of the wheel assembly, the entirety of the wheel assembly is scanned and different images captured by the scanner are stitched together to form the three-dimensional model **111**VM of the wheel assembly **111**. In other aspects, such as where the scanner array **2910**RA is provided, there may be more than one scanner **2910** (e.g., a scanner on each side of the wheel assembly and one scanner adjacent the tread (e.g., in a manner similar to that illustrated in FIGS. **26**A-**26**C) so that different images from the different scanners are stitched together by the controller **129**CNT to form the three-dimensional model **111**VM of the wheel assembly **111**.

It is noted that the wheel assembly **111** may be rotated in any suitable manner to effect scanning of the wheel assembly **111**. For example, the drive roller **300** may be provided to selectively engage the tire **111**T for rotating the wheel

assembly **111**. As described herein, the frame **310** includes the lift drive that moves the drive roller **300** into contact with the tire **111**T (e.g., to rotate the wheel assembly **111**) and moves the drive roller **300** away from the tire **111** (e.g., such as when the wheel assembly is scanned so that the wheel assembly is unloaded during scanning). In other aspects, the scanner **2910** may be coupled to the robotic arm **126** so that the scanner **2910** moves relative to the wheel assembly **111** to effect scanning of the wheel assembly with or without rotation of the wheel assembly **111** (as described herein). With the scanner **2910** moved by the robotic arm **126**, scanning of the wheel assembly **111** may be substantially continuous so that the three dimensional model **111**VM is generated from the substantially continuous scan (e.g., stitching of images may be avoided).

The three-dimensional model **111**VM of the wheel assembly **111** may be displayed on any suitable user interface GUI**29** of the tire changing system **100**, **100**A and the controller **129**CNT may determine, with any suitable image analysis, one or more of high and low points of the wheel **111**W, high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions based on the three-dimensional model **111**VM. In a manner similar to that described herein, the amount of weight and a position of the weight may be determined by the controller **129**CNT based on the determination of the one or more of high and low points of the wheel **111**W, tire **111**T and runout of the wheel assembly in the radial R and axial Z directions. For example, the controller **129**CNT includes an empirically derived table EDT that correlates amounts of weights and positions of those weights on the wheel assembly **111** to the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions. There may be an empirically derived table EDT for each different tire **111**T and wheel **111**W combinations such that based on the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions and the tire/wheel combination the controller **129**CNT searches the empirically derived tables EDT to determine from the corresponding empirically derived table EDT the amount and position of the weights to be affixed to the wheel assembly **111**. In other aspects, the amount and position of the weights to be affixed to the wheel assembly **111** may be determined in any suitable manner such as analytically as a function of the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions or a wheel assembly weight distribution (e.g., as determined by the determined one or more of the high and low points of the wheel **111**W, the high and low points of the tire **111**T, and runout of the wheel assembly in the radial R and axial Z directions knowing the material properties and sizes of the tire and wheel).

Referring to FIGS. **43**A-**43**B one or more of the tire balancers described herein (inclusive of the robotic arm mounted tire balancers, generally **129**M, **129**MS, and the stand alone tire balancers, generally **183**) may include a sonic scanning system **3000** that effects detection of one or more of axial (e.g., along the Z direction) and radial (e.g., along the Y and X directions) anomalies of the wheel assembly **111** (or any of the components thereof). In this example, the tire balancer **183**, **129**M, **129**MS includes one or more ultrasonic sensors **3001**-**3003** (e.g., such as a phased array sensor or any other suitable sonic sensor) coupled to the frame **310**, **183**F in any suitable manner so that a least a portion of the wheel assembly **111** is within a field of view of the one or more ultrasonic sensors **3001**-**3003**. For example, the ultrasonic sensors **3001**-**3003** are positioned on the frame so that sensor **3001** detects a side view of the tire and barrel/drum **111**WB of the wheel **111**W; sensor **3002** detects a side view of the wheel hub **111**WH and spokes/center disc **111**WS; and sensor **3001** detects an end view of the tire **111**T (e.g., the tire tread) and barrel **111**WB. While three ultrasonic sensors **3001**-**3003** are illustrated in FIGS. **43**A-**43**B, in other aspects, there may be more or less than three ultrasonic sensors positioned to detect any suitable portions of the wheel assembly **111**. As may be realized, the wheel assembly **111** may be rotated by the drive roller **300** of tire balancer **129**M, **129**MS or a suitable drive shaft **3099** of tire balancer **183** to effect scanning of the wheel assembly **111** with the sonic scanning system **3000**

The ultrasonic sensors **3001**-**3003** are coupled to the controller **129**CNT in any suitable manner (e.g., a wired connection or a wireless connection). The controller **129**CNT is configured to operate the ultrasonic sensors, in any suitable manner, to obtain three-dimensional images/models and/or two-dimensional images of the wheel assembly **111**. The controller **129**CNT includes any suitable image analysis algorithms that effects detection of anomalies in the wheel assembly **111** from the obtained three-dimensional images and/or two-dimensional images of the wheel assembly **111**. As described herein, anomalies may include increased or decreased thickness of tire walls/tread (e.g., compared to other areas of the tire wall/tread), increased or decreased tire belt density, wheel chips/gouges, etc. With the controller **129**CNT being programmed with material properties of the tire **111**T and wheel **111**W, and with the size (e.g., volume) and location of the anomaly determined from the orbital scanning, the controller **129**CNT is configured to determine a mass (e.g., a missing mass/void or an increase in mass) of the anomaly. Based on a missing mass, the controller **129**CNT may indicate placement of a wheel weight **3188** (see, e.g., FIGS. **44**A and **56**) having substantially the same mass as the missing mass to be placed on the wheel **111**W at or adjacent the location of the missing mass. Based on an increased in mass, the controller **129**CNT may indicate placement of a wheel weight **3188** having substantially the same mass as the increased mass to be placed on the wheel **111**W at a location opposite the location of the increased mass. Wobble of the wheel assembly **111** (e.g., in the Z direction) may be determined by the controller **129**CNT based on the three-dimensional distance sensing inherent to the ultrasonic sensors **3001**-**3003** (and ultrasonic sensor **3004** described below).

In other aspects, an ultrasonic sensor **3004** may be provided that is shaped and sized so as to have a field of view that is large enough to view an entirety of the wheel assembly **111** (e.g., view the entire tire sidewall and face of the wheel). Here, a complete three-dimensional image/model of the wheel assembly **111** may be generated by the controller **129**CNT, whereas three dimensional images/models of the wheel assembly may only include the portions of the wheel assembly included in the respective fields of view of the ultrasonic sensors **3001**-**3003**.

Referring to FIGS. **51**A and **51**B tire balancer **129**M**12** is illustrated. The tire balancer **129**M**12** provides for substantially simultaneous determination of tire imbalance for each wheel assembly **111** of a front-wheel drive, rear-wheel drive, or all-wheel drive vehicle. The tire balancer **129**M**12** includes at least one continuous loop belt **3800** that has a riding surface **3800**S supported by more than one idler roller **3810**. The vehicle **110** is driven onto the riding surface **3800**S such that the vehicle is supported by the continuous loop belt **3800**. The continuous loop belt is illustrated as a single belt in FIG. **43**B on which all four wheel assemblies **111** (e.g., front wheel assemblies **111**F and rear wheel assemblies **111**R) are supported; however, in other aspects, there may be more than one continuous loop belt (such as illustrated in FIGS. **38**A and **38**B). Where more than one continuous loop belt is provided, rotation of each continuous loop belt is coupled to the rotation of each other continuous loop belt by any suitable transmission/drive system (e.g., such as drive system **2560**) so that each continuous loop belt rotates substantially simultaneously with and at the same rate as each other continuous loop belt.

The continuous loop belt **3800** simulates a driving/riding surface on which the vehicle **110** travels where the vehicle moves under its own power. For example, the vehicle **110** is driven onto the continuous loop belt, such as at or adjacent a tire changing system **100**, **100**A. The vehicle **110** is secured to any suitable fixed location(s) of or adjacent the tire changing system **100**, **100**A so that the vehicle **110** is held stationary. For example, anchors **3888** are provided adjacent the continuous loop belt **3800** and the vehicle **110** is tethered to the anchors **3888** in any suitable manner (in a similar manner a vehicle is tethered to an automotive dynamometer) so that as power is applied to one or more of the vehicle wheel assemblies **111**R, **111**F (e.g., by the vehicle motor/engine), the wheels assemblies **111**R, **111**F cause the continuous loop belt **3800** to rotate about the rollers **3810**. As may be realized, the driving of the continuous loop belt **3800** (common to all wheel assemblies **111**R, **111**F of the vehicle **111**) by one or more wheel assemblies **111***r*, **111**F causes non-powered wheels **111**R, **111**F to rotate at the same speed at substantially the same time, or where all wheel assemblies **111**R, **111**F are powered the common continuous loop belt **3800** provides for all-wheel drive vehicle operation. As may also be realized, resistance (e.g., opposing the drive force of the wheel assemblies **111**R, **111**F) may be provided to the continuous loop belt **3800** by one or more of the rollers **3810** to simulate travel of the vehicle along a roadway.

To determine/detect one or more of radial accelerations R of each wheel assembly **111** and axial accelerations Z (relative to the wheel hub/spindle to which the wheel assembly **111** is coupled) of each wheel assembly **111** the remote motion detection module **320** and/or the wheel weights **1701** may be affixed to each wheel assembly **111**R, **111**F in the manner described herein. The vehicle **110** is operated to provide motive force to at least one wheel assembly **111**R, **111**F to effect rotation of all of the wheel assemblies **111**R, **111**F of the vehicle **110** supported by/on the continuous loop belt **3800**. Wheel balance metrics (e.g., one or more of the radial runout and lateral runout) are obtained for each wheel assembly **111**R, **111**F, as described herein, by the controller **129**CNT from the inertial measurement units **1702** of the respective wheel weights **1701** and/or from the sensors of the respective remote detection module **320** applied/coupled to the respective wheel assembly **111**R, **111**F. The amount of weight to be coupled to the respective wheel **111**W and the location of weight to be coupled to the respective wheel are determined by the controller **129**CNT in any suitable manner (such as in a manner similar to that described herein with respect to FIGS. **16**A-**19** and **30**A-**31**).

In other aspects, the riding surface **3800**S may be formed by, e.g., a facility floor, test track, etc. of known ride quality (e.g., known flatness), where the known ride quality is configured such that with the vehicle travelling on and over the riding surface, effects of the riding surface on the wheel assemblies with respect to wheel accelerations in the radial R and axial Z directions is negligible. Here, the vehicle travels along the riding surface with the remote motion detection module **320** and/or the wheel weights **1701** may be affixed to each wheel assembly **111**R, **111**F. Wheel balance metrics (e.g., one or more of the radial runout and lateral runout) are obtained for each wheel assembly **111**R, **111**F, as described herein, by the controller **129**CNT from the inertial measurement units **1702** of the respective wheel weights **1701** and/or from the sensors of the respective remote detection module **320** applied/coupled to the respective wheel assembly **111**R, **111**F. The amount of weight to be coupled to the respective wheel **111**W and the location of weight to be coupled to the respective wheel are determined by the controller **129**CNT in any suitable manner (such as in a manner similar to that described herein with respect to FIGS. **16**A-**19** and **30**A-**31**).

In still other aspects, deflection of the support surface **3800**S between the rollers **3810**, e.g., forward and aft of each wheel assembly **111**R, **111**F supported by the continuous loop belt **3800** may be employed to determine the wheel balance metrics for balancing the wheels assemblies **111**R, **111**F in a manner substantially similar to that described above with respect to FIGS. **37**-**38**B. However, in this aspect the continuous loop belt is driven in rotation under motive force of the vehicle **110** wheel assemblies rather than a drive motor DM driving the rollers (see FIGS. **37**-**38**B).

Referring to FIGS. **55**A and **55**B tire balancer **129**M**15** is illustrated. The tire balancer **129**M**15** provides for substantially simultaneous determination of tire imbalance for each wheel assembly **111** of a front-wheel drive, rear-wheel drive, or all-wheel drive vehicle. The tire balancer **129**M**15** includes passive rollers **4200** and remote motion detection module **320** (as described herein) and/or wheel weights **1701** (as described herein). The passive rollers **4200** includes a passive roller **4200**FR, **4200**FL, **4200**RR, **4200**RL each of which corresponds to and is configured to support a respective wheel assembly **111**FR, **111**FL, **111**RR, **111**RR of the vehicle **110**. The passive rollers **4200** are not driven by a motor so as to cause rotation of the respective wheel assembly **111**, rather it is motive force from the wheel assembly (e.g., via the vehicle motor/engine) that causes rotation of the passive roller **4200**. In some aspects, the passive rollers **4200** may be configured to provide rolling resistance (e.g., against the motive force of the wheel assembly) to the drive wheels of the vehicle **110**.

In a manner similar to that described herein with respect to FIG. **34**, the rollers corresponding to the front and/or rear wheel assemblies of the vehicle **110** may be movable. For example, the passive rollers **4200** corresponding to an axle (s) (e.g., front and/or rear) of the vehicle **110** may be mounted on a slide **2100** so that the distance **4299** between the front passive rollers **4200**FR, **4200**FL (corresponding to

the front wheel assemblies **111**FR, **111**FL) and the rear passive rollers **4200**RR, **420**RLF (corresponding to the rear wheel assemblies **111**RR, **111**RL) may be adjusted (prior to driving the vehicle onto the passive rollers **4200**) according to a wheel base WLBS of the vehicle **110**. The slide **2100** may be coupled to and driven by any suitable motor SLM under control of the controller **129**CNT to effect adjustment of the distance **4299** depending on the vehicle **110** wheel-base WLBS.

The passive rollers **4200**FR, **4200**FL, **4200**RR, **4200**RL may be selectively coupled to each other depending on a drive train configuration (e.g., front-wheel drive, rear-wheel drive, all-wheel drive) of the vehicle **110** so that substantially simultaneous balancing of the driven and non-driven wheel assemblies is effected. For example, the tire balancer **129**M**15** includes any suitable transmissions TRAN**1**-TRAN**5** (e.g., shafts) and clutches/differentials CLU**1**-CLU**3** that selectively couple one passive roller to another passive roller. For example, the front passive rollers **4200**FR, **4200**FL are coupled to each other by, for example, transmissions TRAN**1**, TRAN**2** and a differential CLU**1** (such as a conventional automobile differential) that allows the passive rollers **4200**FR, **4200**FL to rotate at different speeds. The rear passive rollers **4200**RR, **4200**RL are coupled to each other by, for example, transmissions TRAN**3**, TRAN**4** an differential CLU**3** (such as a conventional automobile differential) that allows the passive rollers **4200**RR, **4200**RL to rotate at different speeds. Each differential CLU**1**, CLU**3** is coupled to a respective portion TRAN**5**A, TRAN**5**B of transmission TRAN**5**. The portions TRAN**5**A, TRAN**5**B are selectively coupled to each other by clutch CLU**2**. Here, the passive rollers **4200** may be configured for an all-wheel drive by disengaging clutch CLU**2** so that each wheel assembly **111** drivingly rotates a respective passive roller **4200**. The passive rollers **4200** may be configured for a front or rear wheel drive vehicle by engaging clutch CLU**2** so that, with for example a front-wheel drive vehicle, at least one of the front passive rollers **4200**FR, **4200**FL drives rotation of both rear passive rollers **4200**RR, **4200**RL; and with for example a rear-wheel drive vehicle, both of the front passive rollers **4200**FR, **4200**FL are driven by rotation of at least one rear passive roller **4200**RR, **4200**RL. To effect rotation of both front passive rollers by the at least one rear passive roller, the differential CLU**1** may include a clutch that selectively locks the differential (e.g., a locking differential) so that both the front passive rollers are driven. Similarly, to effect rotation of both rear passive rollers by the at least one front passive roller, the differential CLU**3** may include a clutch that selectively locks the differential so that both the rear passive rollers are driven. The selections of engaging/disengaging the clutch CLU**2** and engaging/disengaging the clutch of the differentials CL**1**, CLU**3** may be made by an operator of the tire changing station, through the controller **129**CNT based on the vehicle **110** drive train. The controller **129**CNT may also be programmed to engage/disengage the clutch CLU**2** and lock/unlock the differentials CLU**1**, CLU**3** to accommodate any suitable all-wheel drive system including, but not limited to, asymmetric or symmetric all-wheel drive.

The passive rollers **4200** simulate a driving/riding surface on which the vehicle **110** travels where the vehicle moves under its own power. For example, as noted above, the passive rollers **4200** are configured as drive on/off rollers/modules that may be integrated into a floor of a tire changing system **100**, **100**A in a manner similar to that illustrated in FIG. **35**. The vehicle **110** is driven onto the passive rollers **4200**, such as at or adjacent a tire changing system **100**, **100**A. The vehicle **110** is secured to any suitable fixed location(s) of or adjacent the tire changing system **100**, **100**A so that the vehicle **110** is held stationary. For example, anchors **3888** are provided adjacent the continuous loop belt **3800** and the vehicle **110** is tethered to the anchors **3888** in any suitable manner (in a similar manner a vehicle is tethered to an automotive dynamometer) so that as power is applied to one or more of the vehicle wheel assemblies **111**FR, **111**FL, **111**RR, **111**RL (e.g., by the vehicle motor/engine), the wheel assemblies **111**FR, **111**FL, **111**RR, **111**RL cause the respective passive roller **4200**FR, **4200**FL, **4200**RR, **4200**RL to rotate.

To determine/detect one or more of radial accelerations R of each wheel assembly **111** and axial accelerations Z (relative to the wheel hub/spindle to which the wheel assembly **111** is coupled) of each wheel assembly **111** the remote motion detection module **320** and/or the wheel weights **1701** may be affixed to each wheel assembly **111**FR, **111**FL, **111**RR, **111**RL in the manner described herein. The vehicle **110** is operated to provide motive force to at least one wheel assembly **111**FR, **111**FL, **111**RR, **111**RL. Wheel balance metrics (e.g., one or more of the radial runout and lateral runout) are obtained for each wheel assembly **111**FR, **111**FL, **111**RR, **111**RL, as described herein, by the controller **129**CNT from the inertial measurement units **1702** of the respective wheel weights **1701** and/or from the sensors of the respective remote detection module **320** applied/coupled to the respective wheel assembly **111**FR, **111**FL, **111**RR, **111**RL. The amount of weight to be coupled to the respective wheel **111**W and the location of weight to be coupled to the respective wheel are determined by the controller **129**CNT in any suitable manner (such as in a manner similar to that described herein with respect to FIGS. **16**A-**19** and **30**A-**31**).

Referring to FIGS. **52**A-**52**C tire balancer **129**M**13** is illustrated. Here, the tire balancer includes a remote motion detection module **320**, a wheel assembly spin unit **3930**, and a vision system **3905**. The remote motion detection module **320** is substantially similar to that described herein with respect to FIG. **22** and includes the passive fiducials **922**A, **922**B, **922**C. The wheel assembly spin unit **3930** is substantially similar to that described above with respect to FIG. **20**A and includes the centering protrusion **760** and the motor **710** for rotating the centering protrusion **760**. Here, the mounting plate **321** of the remote motion detection module **320** includes a central aperture **321**AP configured so that the centering protrusion **760** passes through the central aperture **321**AP to engage the wheel **111**W in the manner described herein. The vision system **3905** includes one or more optical sensors **3910** (e.g., any suitable cameras) coupled to a housing/frame **3930**F of the wheel assembly spin unit **3930**. The housing **3930**F includes an end effector mount **129**MM so that the housing **3930** may be coupled to the robotic arm **126**; while in other aspects the tire balancer **129**M**13** may be stationarily fixed at a tire changing system **100**, **100**A, where the wheel assembly is rotated by a floor mounted roller **300** or the centering protrusion **760** (e.g., where the centering protrusion **760** may be coupled to a linear actuator to move axially for engaging and disengaging the wheel assembly **111**).

In operation of the tire balancer **129**M**13**, the vehicle suspension components **500** are substantially immobilized,

such as by compressing a shock of the suspension components **500** against a suspension restraint **3950** (e.g., jack stand, jack, lift, etc.) that engages, for example, a control arm of the suspension components **500**. The shock is compressed a suitable amount such that movement of the suspension components caused by rotation of the wheel assembly **111** is negligible with respect to balancing of the wheel assembly **111**.

The remote motion detection module **320** is coupled to the wheel assembly **111** in the manner described herein and the centering protrusion **760** is engaged with the wheel **111**W in the manner described herein. The vision system **3905** images the wheel assembly at least the fiducials **922**A-**922**C of the remote motion detection module **320** coupled to the wheel assembly **111** with the wheel assembly **111** held rotationally stationary (i.e., a "still" image—see FIG. **52**B). The vision system **3905** communicates signals from the one or more optical sensors **3910** to the controller **1219**CNT that embody the still image(s) of at least the fiducials **922**A-**922**C. The centering protrusion **760** is driven in rotation by the motor **710** so that the wheel assembly **111**, and the remote motion detection module **320** coupled to the wheel assembly **111**, is/are rotated (in other aspects, the wheel assembly **111** may be rotated in any suitable manner such as with the roller **300**). With the wheel assembly **111** rotating the image system **3905** images at least the fiducials **922**A-**922**C (i.e., a "dynamic" image—see FIG. **52**C). The vision system **3905** communicates signals from the one or more optical sensors **3910** to the controller **1219**CNT that embody the dynamic image(s) of at least the fiducials **922**A-**922**C. The controller **129**CNT is configured to correlate the still image(s) with the dynamic image(s) in any suitable manner to determine one or more of the radial R and axial Z accelerations/runout of the wheel assembly. For example, the fiducials **922**A-**922**C in the still image have a predetermined pattern are placed along a virtual circle VC having a predetermined diameter. The fiducials **922**A-**922**C may also have different shapes and/or colors so that one fiducial is distinguished from another fiducial in the images obtained with the optical sensor(s) **3910**. The controller **129**CNT is configured to compare the locations of the different fiducials **922**A-**922**C (and/or the virtual circle VC on which the fiducials are arranged) as obtained from any suitable number of dynamic images with the locations of the fiducials **922**A-**922**C (and/or the virtual circle VC on which the fiducials are arranged) in the still image(s) to determine radial R accelerations of the wheel assembly. The controller **129**CNT may also be configured to perform any suitable image analysis (e.g., a pixel by pixel analysis), e.g., such as a Doppler shift analysis, to determine whether the fiducials are moving towards or away from the optical sensors **3910** in the Z direction and based on the Doppler shift the controller **129**CNT determines the axial X accelerations of the wheel assembly **111**. In other aspects, the radial R and axial Z accelerations may be determined in any suitable manner from the obtained still and dynamic images.

In a manner similar to that described herein, the controller **129**CNT may determine an amount of wheel weight and a location of the wheel weight **3188** (see, e.g., FIGS. **44**A and **56**) with an empirically derived table EDT stored in a memory of the controller **129**CNT that correlates the amount and position of the wheel weight **3188** with the determined radial R and axial Z accelerations of the wheel assembly **111**.

Referring to FIGS. **53**, **54**A, and **54**B the tire changing stations described herein may be configured to balance a wheel assembly **111** by determining a center of gravity and/or center of mass of the wheel assembly **111** and applying wheel weights **3188** (see, e.g., FIGS. **44**A and **56**) to the wheel assembly so that the center of mass is disposed at a predetermined location of the wheel assembly. The predetermined center of mass may be empirically derived for each tire/wheel combination and stored in a table CMT accessible by the controller **129**CNT and/or a human operator of the tire changing system **100**, **100**A. Referring to FIG. **53**, the tire balancer **129**M**14** is illustrated. The tire balancer **129**M**14** may be substantially similar to that illustrated in FIGS. **50**A-**50**C; however, in this aspect the robotic arm **126** carries at least one laser triangulation sensor **4000** that is configured to measure the center of mass of a rotating body (such as the wheel assembly **111** spun by the centering protrusion in the manner described herein with respect to FIGS. **20**A-**20**D and **52**A). A suitable example of a laser triangulation sensor **4000** is manufactured by Acuity Laser, a division of Schmitt Industries, Inc. of Portland, Oregon USA. The robotic arm **126** (or other suitable actuator positions the at least one laser triangulation sensor **4000** relative to the wheel assembly **111**, the wheel assembly is spun by, for example, centering protrusion **760** or in any other suitable manner such as roller **300**), and the center of mass is measured by the at least one laser triangulation sensor **4000** and controller **129**CNT. The suspension components **500** may be substantially immobilized by the suspension restraint **3950** in the manner described herein with respect to FIG. **52**A. The centering protrusion **760** (or roller **300**) may be mounted to a linear slide so that with the wheel assembly **111** spinning the centering protrusion **760** (or roller **300**) may be disengaged from the wheel assembly **111** to allow the wheel assembly to spin freely or "free wheel" with the at least one laser triangulation sensor **4000** sensing the wheel assembly. The controller **129**CNT is configured to determine the center of mass CM based on the signals/data provided by the at least one laser triangulation sensor **4000**.

The tire balancer **129**M**14** may also include a remote motion detection module **320** substantially similar to that illustrated in FIGS. **16**A-**16**D; however, the mounting plate **321** includes the central aperture **321**AP illustrated in FIGS. **52**A-**52**C to allow engagement of the centering protrusion **760** with the wheel assembly **111**. The remote motion detection module **320** and the at least one laser triangulation sensor **4000** may be used in combination or separately. Here, remote motion detection module **320** is coupled to the wheel assembly **111** (e.g., in the manner described herein), the wheel is spun in the manner described above, and the motion sensors **322**A, **322**B, **322**C detect the radial and axial accelerations of the wheel assembly **111**. The suspension components **500** may be substantially immobilized by the suspension restraint **3950** in the manner described herein with respect to FIG. **52**A. The centering protrusion **760** (or roller **300**) may be mounted to a linear slide so that with the wheel assembly **111** spinning the centering protrusion **760** (or roller **300**) may be disengaged from the wheel assembly **111** to allow the wheel assembly to spin freely or "free wheel" with the at least one laser triangulation sensor **4000** sensing the wheel assembly. In other aspects, the wheel assembly **11** may be impacted, such as in the manner described herein with respect to FIGS. **28**A and **28**B where the motion in the wheel assembly **111** induced by the impact

is employed to determine the center of gravity. The controller **129**CNT is configured to determine the center of gravity CG of the wheel assembly **111** based on the data from the motion sensors **322**A, **322**B, **322**C. A suitable manner in which the center of gravity CG may be determined by the controller **129**CNT can be found in "Calculating the location of the Center-of-Gravity Using an Accelerometer Array" by Kristin Angel, Rochester Institute of Technology, RIT Scholar Works, Thesis, May 29, 2019, the disclosure of which is incorporated herein by reference in its entirety. In other aspects, the center of mass/gravity may be determined in any suitable manner.

The controller **129**CNT may determine the amount of weight to be applied to the wheel assembly **111** and the location of the weight on the wheel assembly **111** based on the determined center of gravity/mass and an expected location of the center of gravity/mass. For example, the controller **129**CNT may include a center of mass/gravity table CMT that includes empirically derived expected locations for the center of mass/gravity for different tire and wheel combinations. The controller **129**CNT may compare the expected locations for the center of mass/gravity with the determined locations for the center of mass/gravity and determine in any suitable manner a mass (e.g., wheel weight **3188**, see, e.g., FIGS. **44**A and **56**) and placement of the mass on the wheel assembly that moves the center of mass/gravity from the determined location to the expected location (e.g., if the determined location and expected locations do not substantially match within a predetermined tolerance). The wheel weight is applied to the wheel assembly **111** at the location prescribed by the controller **129**CNT in any suitable manner, such as those described herein.

Referring to FIGS. **54**A and **54**B, the center of mass/gravity may also be determined with the wheel assembly **111** off of the vehicle. For example, the wheel assembly **111** may be placed on a center of gravity scale **4100** (a suitable example of which is available from Loadstar ° Sensors of Fremont California, USA) or any suitable balance fixture **4101** on which the wheel assembly may be balanced. The center of gravity scale **4100** is configured to automatically determine the center of gravity of the wheel assembly **111** and wheel weights **3188** (see, e.g., FIGS. **44**A and **56**) may be affixed to the wheel assembly (e.g., according to the table CMT) to move the center of gravity to the expected position for the given tire and wheel combination. The balance fixture **4101** is configured to support the wheel assembly **111** at a location corresponding to the expected center of gravity so that the wheel assembly **111** (when unbalanced) tilts relative to the horizontal and/or vertical planes HP, VP. Wheel weights **3188** (see, e.g., FIGS. **44**A and **56**) may be affixed to the wheel assembly **111** so that the wheel assembly **111** is aligned with the horizontal and/or vertical planes HP, VP as illustrated in FIGS. **54**A and **54**B. As may be realized, the center of gravity of the wheel assembly may be assessed with the wheel assembly in the horizontal orientation (see FIG. **54**A) and the vertical orientation (see FIG. **54**B).

Referring to FIG. **59**, the tire balancers described herein may include a wheel weight location sensor **4600** that is configured one or more of detect a location of a wheel weight **3188** affixed to the wheel **111**W and indicate a location of the wheel **111**W to place a wheel weight **3188**. For example, the wheel weight location sensor **4600** includes a sensor arm **4601** that is disposed on the tire balancer so that at least a portion of the sensor arm **4601** is positioned for insertion within the wheel barrel **111**WB, between the suspension components **500** and the wheel barrel **111**WB. The sensor arm **4601** may be movable in direction **4699** so that the portion of the sensor arm **4601** is inserted and removed from wheel barrel **111**WB in any suitable manner, such as with any suitable actuator **4620** controlled by, for example, controller **129**CNT. The sensor arm **4601** includes a laser scanner **4610** that is shaped and sized so as to scan at least the wheel barrel **111**WB and detect the location of any wheel weights **3188** affixed to the wheel **111**W. As may be realized, the sensor arm **4601** (such as where the wheel weight location sensor **4600** is mounted to the wheel shroud **700**) and/or the wheel assembly **111** is rotated to effect scanning of the wheel barrel **111**W. As described herein, the rotational angle of the wheel assembly **111** relative to the laser scanner **4610** may be provided to/determined by the controller **129**CNT with encoders of the drive motors DM, **710** and data signals received from the laser scanner **4610**. Here, the wheel assembly **111** may be rotated to a determined rotational angle (as determined with the detection of a wheel weight **3188** by the laser scanner **4610**) to position the wheel weight **3188** relative to a wheel weight removal tool (as described herein) for removal of the wheel weight. For installation of a wheel weight, such as by an operator, the laser scanner may cast a laser line on the wheel **111**W and the wheel may be rotated to a determined rotational angle such that the laser line marks the installation location of the wheel weight **3188**.

Referring to FIGS. **45** and **46**A-**46**D the tire changing system **100**, **100**A includes wheel weight applicator tool **3300**. The wheel weight applicator tool **3300** is described herein with respect to employment of the wheel weight applicator tool **3300** with tire balancing machine **180**, but in other aspects, the wheel weight applicator tool **3300** may be coupled to the robotic arm **126** (FIG. **1**B) or tire exchanging robot **2220** (FIG. **35**) and employed to apply wheel weights to the wheel **111**W with the wheel **111**W in situ the vehicle **110** in tire changing system **100** and/or tire changing system **100**A.

The wheel weight applicator tool **3300** includes an articulated arm **3301** to which an applicator **3302** is coupled. The articulated arm **3301** may be a part of the tire balancing machine **183**, the robotic arm **126**, or a part of the tire exchange robot **2220**. Where the articulated arm **3301** is the robotic arm **126**, the applicator **3302** includes the end effector mount **129**MM for coupling the applicator **3302** to the robotic arm **126**. The applicator **3302** is flexible (e.g., comprises resiliently coupled segments **3355**) so as to conform to a contour of the wheel barrel **111**WB (see FIG. **46**B). The applicator **3302** is configured to hold at least one wheel weight **3188** in any suitable manner. For example, the applicator **3302** includes a vacuum grip **3333** configured to selectively activate and deactivate suction at each of the segments **3355** for selectively holding and releasing a respective wheel weight **3318**.

The wheel weights **3188** may be adhesive wheel weights such that prior to application of one or more of the wheel weights **3188** to the wheel **111**W by the applicator **3302** the release liner **3188**L is removed in any suitable manner (such as with a brush, suction cup, mechanical gripper, forced air, etc. that peels the adhesive liner **3188**L from the wheel weight **3188**) to expose the adhesive of the wheel weight **3188**.

Here, the position and amount of wheel weight **3188** to be affixed to the wheel assembly **111** is determined as described herein using any of the tire balancers **183**, **129**M, **129**MS described herein. The controller **129**CNT controls the tire balancer and the wheel weight applicator tool **3300** to effect affixing the one or more wheel weights **3188** to the wheel **111**W. For example, the drive roller **300** rotates the wheel assembly **111** so that a predetermined position of the wheel **111**W at which the wheel weight is to be applied is located at, for example, the 6 o'clock position (or at any other suitable position depending on the position of the applicator **3302** relative to the wheel **111**W or vice versa). Rotational positioning of the wheel **111**W may be effected with any suitable sensors, such as those described herein, and/or with any suitable encoders of the drive motor DM of tire balancer shaft **3099**. The release liner **3188**L is removed from one or more of the wheel weights **3188** held by the applicator **3302** and the applicator **3302** positions the one or more wheel weights **3188** relative to the wheel **111**W. The articulate arm **3301** moves the applicator **3302** relative to the wheel **111**W so that the one or more wheel weights **3188** are pressed against the wheel at the predetermined location of the wheel **111**W. The one or more wheel weights **3188** is selectively released by the controller **129**CNT (e.g., by stopping, e.g., the vacuum of a segment(s) **3355** holding the one or more wheel weight **3188**) and the articulate arm **3301** moves the applicator **3302** away from the wheel **111**W leaving the one or more wheel weights **3188** affixed to the wheel **111**W.

In other aspects, referring also to FIG. **47**, the wheel weights may be provided, for application by the application **3302**, from a roll or reel of wheel weights **3188**R. The roll of wheel weights is mounted to the applicator **3302** in any suitable manner and includes any suitable drives for unrolling the wheel weights **3188** for application to the wheel **111**W. Here, the roll **3188**R may be configured such that there is no release liner that needs to be removed from the wheel weights **3188** (e.g., one surface of the wheel weights may function as a release liner in a manner similar to that of a roll of tape); while in other aspects, the release liner may be removed from the wheels weights **3188** in any suitable manner (e.g., forced air, a peeling knife, a driven spool (take up reel) that pulls the release liner off and rolls removed released liner on the spool, etc.) as the wheel weights **3188** are unrolled. The applicator **3302** includes a punch or press **3400** that pushes one or more wheel weights **3188** from the unrolled wheel weights **3188**, off of the applicator **3302** and onto the wheel **111**W for affixing the one or more wheel weights **3188** at the predetermined position of the wheel **111**W.

Referring to FIG. **56**, it is noted that while the wheel weights **3188** are described herein as being applied to the wheel **111**W (e.g., at the wheel barrel **111**WB; see FIG. **46**B), the wheel weights **3188** may be configured as a center mass or ballast **3188**C that is mounted on the wheel assembly axle or hub **4300** in any suitable manner. For example, referring also to FIG. **57**, the center mass **3188**C may be configured as an eccentric plate having any suitable shape (examples of which are illustrated in FIGS. **56** and **57**) that includes a central mounting portion **4350** and an eccentric mass portion **4351**. In the examples illustrated the center mass **3188**C is configured as a plate that is disposed between the wheel **111**W mounting pad and the wheel hub. The central mounting portion **4350** includes apertures **4350**A through which the wheel studs **4310** pass. Tightening of the lug nuts to secure the wheel assembly **111** to the wheel hub also secures the center mass **3188**C to the wheel assembly **111** so to rotate with the wheel assembly **111**. In other aspects the central mass **3188**C may be secured or otherwise affixed to the wheel assembly **111**, wheel hub, and/or drive axle in any suitable manner (e.g., such as clamps, snaps, straps, etc.). The center mass **3188**C may be selected from a number of different center masses **3188**CN each having a different balancing characteristic (e.g., different eccentric mass, different shape so as to position the eccentric mass at a desired location, etc.).

Referring to FIGS. **44**A and **44**B the tire changing system **100**, **100**A includes wheel weight removal tool **3100**. The wheel weight removal tool **3100** includes an end effector mount **129**MM for coupling the wheel weight removal tool **3100** to the robotic arm **126**. In other aspects, the wheel weight removal tool **3100** may be mounted at a fixed location adjacent a respective wheel balancer **129**MS of tire changing system **100**A.

The wheel weight removal tool **3100** includes a frame **3101** to which the end effector mount **129**MM is coupled such as in tire changing system **100**; while in other aspects the frame **3101** effects spatially fixing the location (e.g., mounting to the floor or other stationary structure) of the wheel weight removal tool **3100** such as in the tire changing system **100**A. The wheel weight removal tool **3100** includes an end effector or arm **3102** that is movably mounted to the frame **3101** so as to move in at least two degrees of freedom. For example, two or more drive motors **3110**, **3111** are coupled to the frame and the arm **3102**. The drive motor **3110** moves the arm **3102** in the radial direction R (e.g., with respect to the wheel assembly **111**) and the drive motor **3111** moves the arm **3102** in the axial or Z direction (e.g., with respect to the wheel assembly **111**). The drive motors **3110**, **3111** are coupled to the controller **129**CNT so that the controller **129**CNT effects movement of the arm **3102** with the drive motors **3110**, **3111**.

The wheel weight removal tool **3100** is in communication with the controller **129**CNT so that the controller **129**CNT operates the arm **3102** in conjunction with the drive roller **300** so that the drive roller **300** rotates the wheel assembly **111** to position (e.g., substantially align) the wheel weight **3188** relative to the arm **3102**. For example, where the wheel weight removal tool is positioned substantially at the 6 o'clock position (see FIG. **44**A) relative to the wheel assembly, the controller may operate the drive roller **300** to position a wheel weight **3188** (that is affixed to the wheel **111**W) substantially at the 6 o'clock position. Alignment of the arm **3102** and the wheel weight **3188** may be effected with any suitable position sensor **3150**, such as a vision sensor **3150**V or pressure sensor **3150**P, coupled to controller **129**CNT. The position sensor **3150** may be mounted to the frame **3101** or at any other suitable location so that the arm **3102** and a portion of the wheel **111**W adjacent the arm **3102** is within a field of view of the vision sensor **3150**V or so that contact between the arm **3102** and the wheel **111**W is detected so as to position the arm **3102** relative to the wheel in the radial direction R. The wheel **111**W rotates via the drive roller **300** under control of the controller **129**CNT so that the wheel weight **3188** enters the field of view of the vision sensor **3150**V and is detected by vision sensor **3150**. The controller **129**CNT stops rotation of the wheel **111**W with the wheel weight **3188** in alignment with the arm **3102** based an image analysis of the signals from the position

sensor **3150**. In other aspects pressure sensor **3150**P is configured to detect contact between the arm **3102** and the wheel weight **3188** as the wheel **111**W is rotated. In still other aspects, any suitable capacitive, inductive, etc. sensors may be used to position the wheel weight **3188** relative to the arm **3102**.

With the wheel weight **3188** aligned with the arm **3102**, the controller **129**CNT extends the arm **3102** in the Z direction so that the arm **3102** engages the wheel weight **3188**. The arm **3102** includes a tapered end **3102**E that in one aspect, is inserted (e.g., which may include movement of the arm **3102** in the radial direction R and employment of the position sensor **3150** to position the tapered end **3102**E) between the wheel weight **3188** and wheel **111**W so that the arm **3102** severs/cuts the adhesive between the wheel weight **3188** and the wheel **111**W and pries (via movement of the arm **3102** in one or more of directions R, Z) the wheel weight **3188** from the wheel **111**W; while in other aspects the arm **3102** is driven in the Z direction so that the tapered end **3102**E (constructed of a material harder than the wheel weight material) is driven at least partially into the wheel weight **3188** (typically made of a soft material) so that movement of the arm in one or more directions R, Z peals, pulls, or pushes the wheel weight **3188** off of the wheel **111**W. As may be realized, the wheel weight removal tool **3100** may be positioned (e.g., by the robotic arm **126** or stationarily mounted) at any suitable location (e.g., clocking position such as 12 o'clock, 3 o'clock, etc.) relative to the wheel assembly that effects removal of the wheel weight **3188** as described herein.

The wheel weight removal tool **3100** includes a waste bin **3140** into which the removed wheel weights are inserted. In one aspect the removed wheel weights **3188** may be inserted into the waste bin **3140** by suction (e.g., a vacuum source **3140**V of the wheel weight removal tool **3100**) or in any other suitable manner (such as by compressed air source **3131**, brushes, etc.).

Referring to FIG. **48** the tire balancers describe herein may include a wheel cleaning/wheel weight removal system **5300** that may be carried by the robotic arm **126** (e.g., as a stand-alone end of arm tool or mounted to the frame **310** of a tire balancer carried by the robotic arm **126**) or mounted at a fixed location adjacent a tire exchange location of the tire changing system **100**, **100**A. The wheel cleaning/wheel weight removal system **5300** includes a rotating brush **3560** mounted to an articulate arm **5301** (which as noted above may be in some aspects the robotic arm **126**). The articulated arm **5301** includes a spindle **3561** to which the brush **3560** is rotatably coupled. The spindle **3561** includes a motor **3562** configured to rotate the brush **2650** about a spindle axis SPAX; while in other aspects the motor **2562** may be located at any suitable location (such as within arm **5301**) and coupled to the brush **3560** by any suitable transmission for rotating the brush **2650** about the spindle axis SPAX.

Any suitable fluid conduit **3533** (e.g., flexible hose or tube) may be provided where the fluid conduit **3533** supplies cleaning fluid/solvent to the brush **3560** through the spindle **3561**. For example, the spindle **3561** may be hollow such that the fluid conduit **3533** supplies the cleaning fluid/solvent to the brush through the spindle **3561**. The brush **3560** includes apertures **3560**A (e.g., at the brush core) through which the cleaning fluid/solvent exits the spindle **3561** to wet the bristles of the brush **3560**.

The brush **3560** is configured to at least strip a wheel weight **3188** from the wheel **111**W. For example, the brush **3560** includes bristles having a stiffness or configuration (e.g., hooked bristles) sufficient to grip a wheel weight **3188** affixed to the wheel **111**A and strip or otherwise remove the wheel weight **3188** from the wheel **111**W. In other aspects, the wheel weight **3188** may be removed from the wheel **111**W by a combination of the brush **3560** and the (scraper) arm **3102**. The removed wheel weight **3188** may be directed away from the wheel **111**W by the brush **3560** towards any suitable collection receptacle **3583**.

The articulated arm **5301** is configured for at least two degree of freedom movement (e.g., such as in the Z direction and the R direction) where the articulated arm moves in the Z direction to align the brush **3560** with at least part of the barrel **111**WB of the wheel **111**W, and moves the brush **3560** into contact with the barrel **111**WB of the wheel **111**W. The tire assembly **111** is rotated by, for example, drive roller **300** to move the wheel weights towards and through the brush **3560**. Here, the drive roller **300** is operated by the controller **129**CNT so that the wheel assembly **111** rotates a full rotation to clean the barrel **111**WB and remove any wheel weights **3188**; while in other aspects, any suitable vision sensors may be employed to identify a location of the wheel weight(s) and the drive roller **300** may be operated by the controller **129**CNT to position the wheel weights for removal by the brush **3560**.

The cleaning fluid/solvent may be configured to remove brake dust and other debris from the wheel. In some aspects, the cleaning fluid/solvent may also be configured to soften/dissolve the adhesive holding the wheel weight **3188** to the wheel **111**W to help facilitate removal of the wheel weight **3188** by the brush **3560** and to, with the brush **3560**, clean the adhesive from the wheel **111**W.

Referring to FIG. **49** the tire balancers describe herein may include a wheel weight removal system **3600** that may be carried by the robotic arm **126** (e.g., as a stand-alone end of arm tool or mounted to the frame **310** of a tire balancer carried by the robotic arm **126**) or mounted at a fixed location adjacent a tire exchange location of the tire changing system **100**, **100**A. The wheel weight removal system **3600** includes an articulated arm **3601** that includes an end effector or spatula **3650**. In this example the articulated arm includes arm links that provide at least two degrees of freedom, such as in the Z and R directions so as to position the spatula **3560** substantially against the barrel **111**WB of the wheel **111**W. The drive roller **300**, under control of the controller **129**CNT, rotates the wheel assembly **111** so that the wheel weight rotates past the spatula **3650**. With rotation of the wheel assembly, the spatula **3560** is inserted between the barrel **111**WB and the wheel weight **3188**, severing the adhesive bond between the wheel weight **3188** and the wheel The removed wheel weight **3188** may be directed by the spatula **3650** to any suitable collection receptacle **3583**.

Referring to FIG. **60**, the tire balancers and/or tire changing systems **100**, **100**A described herein may include wheel weight removal tool **4700**. The wheel weight removal tool **4700** includes a frame **4700**F. The frame **4700**F include end effector mount **129**MM for coupling the wheel weight removal tool **4700** to, for example, the robotic arm **126** or any other suitable actuator configured to position the wheel weight removal tool relative to a wheel (the wheel being disposed in situ the vehicle or off the vehicle). The wheel weight removal tool **4700** include at least one grinder **4720**

mounted to the frame **4700**F and at least one wheel lip detection sensor **4730** (e.g., laser scanner, proximity sensor, vision sensor, etc.). The at least one grinder **4720** may be movably coupled to the frame **4700**F for movement in direction **4799** (e.g., by any suitable actuator); while in other aspects, the at least one grinder **4720** is stationarily fixed to the frame **4700**F. Here, with the tire **111**T removed from the wheel **111**W, the robotic arm **126** (or other actuator) scans the wheel to detect a position of the lip **4710** (e.g., in the coordinate system of the robot). The controller **129**CNT, knowing the angular rotational position of the wheel weight (as described herein) rotates the wheel **111**W with the wheel rotator **4760** (generically representative of the wheel rotation means described herein, e.g., rollers, centering protrusions, etc.) and/or the robotic arm **126** moves the wheel weight removal tool **4700** relative to the wheel to position the wheel weight **3188** and the wheel weight removal tool **4700** relative to each other. The at least one grinder **4720** includes a grinder wheel **4720**W that is positioned so that as the grinder **4720** is moved in direction **4799** (either by the actuator coupled to the frame **4700**F or by movement of the robotic arm) the grinding wheel grinds the wheel weight **3188** off of the wheel **111**W substantially without contacting the lip **4710** of the wheel **111**W.

Referring to FIG. **61**, the tire balancers and/or tire changing systems **100**, **100**A described herein may include wheel weight removal tool **4800**. The wheel weight removal tool **4700** includes a gripper **4810** that is coupled to the robotic arm **126** (or other suitable actuator) by end effector mount **129**MM. The robotic arm **126** or any other suitable actuator is configured to position the gripper **4810** relative to a wheel (the wheel being disposed in situ the vehicle or off the vehicle) so as to clamp/grip the wheel weight **3188** for removal (e.g., pulling) of the wheel weight **3188** from the wheel **111**W. The controller **129**CNT, knowing the angular rotational position of the wheel weight (as described herein) rotates the wheel **111**W with the wheel rotator **4760** (generically representative of the wheel rotation means described herein, e.g., rollers, centering protrusions, etc.) and/or the robotic arm **126** moves the gripper **4810** relative to the wheel **111**W to position the wheel weight **3188** and the gripper **4810** relative to each other. In some aspects a vision sensor **4850** may be included in the wheel weight removal tool **4800** for effecting, at least in part, positioning of the gripper **4810** relative to the wheel weight **3188**. The gripper **4810** includes any suitable clamping jaws, fingers, etc. configured to engage and stably hold the wheel weight **3188**. The robotic arm **126** is moved, with the wheel weight gripped by the gripper **4810**, so that the wheel weight **3188** is pulled or otherwise removed from the wheel **111**W.

In accordance with one or more aspects of the present disclosure, a tire changing system is provided. The tire changing system includes a robotic end effector configured to effect rotation of a wheel assembly about a wheel hub with the wheel assembly in situ the vehicle; a remote motion detection module configured to couple with the wheel assembly so as to rotate as a unit with the wheel assembly and detect radial and axial accelerations of the wheel assembly; and a controller in communication with the remote motion detection module, the controller being configured to determine an amount of wheel balance weight, based on the detected radial and axial accelerations, that effects balancing of the wheel assembly.

[0461] As described above and as shown in FIG. **143** of the drawings, in one form, the bot **120**, also referred to hereinafter as a robotic apparatus **1101**, includes a plurality of actuators **126**, each of which holds, or is a component of, a different one of the tools described above and below. In one form, the linear actuators **126** can be actuated independently or simultaneously, allowing for multiple tools to be independently controlled and assist in an operation at once.

[0462] The robotic apparatus **1101** is movable in the same fashion as described above with respect to the movement of the bot **120**. For example, the robotic apparatus **1101** may be moveable along a traverse path (such as traverse path **299** in FIG. **2**A) via wheels **120**W, sliding elements such as rails and/or tracks, that include, but are not limited to, guide rod and sleeve bearings, or any other guide system for effecting linear traverse and/or rotational motion of the carriage **120**C.

[0463] Alternatively, as shown in FIG. **151** of the drawings, the robotic apparatus **1101** may be mounted to a ramp **1105** via fasteners or welding of the frame **1102** to the ramp **1105**. The ramp **1105** is configured such that a vehicle **1600** may drive onto it. The vehicle **1600** may then be positioned over a commercial lift **1700** or other lifting structure for lifting above the ramp **1105** or may sit on the ramp **1105** for subsequent operations, the nature and order of which are similar to the preferred embodiment of the robotic apparatus **1101**. The robotic apparatus **1101** shown in FIG. **151** contains linear actuators **1350** (not shown) which allow it to traverse longitudinally and transversally along the ramp **1105**.

[0464] More specifically, the robotic apparatus **1101** includes a frame **1102** onto which the components, tooling and electronics of the robotic apparatus **1101** are mounted. The tooling that is mounted on the robotic apparatus **1101** may include, for example, the tire bead breaker tool **129**H, also referred to hereinafter as a bead breaker system **2000**, the tire mounting/dismounting tool **129**E, also referred to hereinafter as a bead tool system **82100**, the tire deflation tool **129**, the tire inflation tool **129**L, an inflation tool system **2401**, one or more gripper systems **82200**, the wheel cleaning tool **129**I, also referred to hereinafter as a cleaning tool system **2500**, a lubrication tool system **2600**, a valve stem tool system **2700**, an alignment tool system **2800** and one or more gripper systems **82200**. The collection of tools on the robotic apparatus **1101** is henceforth referred to as "tooling" for description purposes.

[0465] The actuators **126**, which may be linear actuators **1350**, are mounted to the frame **1102** of the robotic apparatus **1101**, preferably using fasteners in mounting holes provided by the manufacturer on the linear actuator **1350**. An exemplary linear actuator **1350** formed in accordance with the present invention, which is shown in FIG. **147** of the drawings, preferably comprises a rotatable ball screw **1352** and a block carriage **1351** that is mechanically engaged with the ball screw **1352**. Although the linear actuator **1350** preferably comprises a ball screw **1352**, it is envisioned to be within the scope of the present invention to use any sufficient mechanism for producing linear motion, such as a screw, lead screw, linear motor, pneumatic or hydraulic cylinder, rack and pinion, work gear, gear drive, or other mechanism. As will be described in greater detail in the forthcoming paragraphs, the tooling is mounted to the block carriage **1351** of the linear actuators to effect linear motion of the tooling along the axial length of the linear actuator **1350**.

[0466] More specifically, the linear actuator **1350** includes a housing having a first axial end, a second axial end situated opposite the first axial end and a pair of oppositely disposed side walls that are spaced apart from one another and extend between the first axial end and the second axial end of the housing. The pair of oppositely disposed side walls defines an open channel within the housing that extends between the first axial end and the second axial end of the housing. Each of the oppositely disposed side walls preferably includes a guide track that is formed on or in an inner surface thereof and extends at least partially along the axial length of the housing.

[0467] The rotatable ball screw **1352** includes a first axial end, a second axial end disposed opposite the first axial end and a threaded outer surface. The rotatable ball screw **1352** is at least partially situated within the open channel in the housing such that the first axial end of the ball screw **1352** is in proximity to the first axial end of the housing and the second axial end of the ball screw **1352** is in proximity to the second axial end of the housing. Preferably, the rotatable ball screw **1352** is retained within housing by linear actuator bearings **1353** that are situated at the first axial end and the second axial end of the housing.

[0468] The block carriage **1351** is formed as a generally rectangular member and includes a top wall, a bottom wall situated opposite the top wall, a first side wall, a second side wall, a third side wall and a fourth side wall, each of the side walls extending between the top wall and the bottom wall, the first side wall being disposed opposite to the third side wall and the second side wall being disposed opposite to the fourth side wall. The second side wall and the fourth side wall of the block carriage **1351** include at least one guide member. The block carriage **1351** is at least partially situated within the open channel in the housing and each guide member is at least partially received within a guide track in a respective one of the oppositely disposed side walls of the housing. The block carriage **1351** further includes a threaded bore that extends along the axial length of the carriage **1351** between the first side wall and the third side wall of the carriage **1351**. The threaded bore has a thread pattern that corresponds to the threaded outer surface of the rotatable ball screw **1352** so that at least a portion of the rotatable ball screw **1352** can be received therein and so that, upon rotation of the rotatable ball screw **1352**, the block carriage **1351** is selectively movable at least partially along the axial length of the rotatable ball screw **1352**, between the first axial end and the second axial end thereof, and, as such, is also selectively movable at least partially between the first axial end and the second axial end of the housing of the linear actuator **1350**.

[0469] As described above, the tooling is mounted to the block carriage **1351**. More specifically, the block carriage **1351** preferably includes one or more threaded connections that are situated on the top wall thereof or that extend at least partially between the top wall and the bottom wall of the carriage into the thickness thereof. The tooling is preferably mounted to the block carriage **1351** by aligning one or more corresponding connections that are situated on the tooling with the threaded connections on the block carriage **1351** and engaging the connections with one another with fasteners (e.g., threaded bolts, screws or connectors, etc.). Accordingly, the tooling may readily be mounted and removed from the linear actuators **1350** of the robotic apparatus **1101**. This enables the tooling of the robotic apparatus **1101** to be easily maintainable and replaceable without disassembling the robotic apparatus **1101** or adjacent tooling. This feature also enables the production of the robotic apparatus **1101** to be modularized in which tooling subassemblies are built and fastened to the robotic apparatus **1101** individually and easily. Additionally, this feature enables easy in-field maintenance in which tooling modules may be removed or replaced from the robotic apparatus **1101** without disassembling other aspects of the system. Furthermore, this feature enables the robotic apparatus **1101** to be easily modified or upgradeable such that, when developed, old tools may be easily removed and new tooling or new versions of existing tooling may be fastened to the robotic apparatus **1101**.

[0470] The linear actuators **1350** are driven by motors **1400**, such as stepper motors, AC motors, DC motors, pneumatic motors or hydraulic motors. More specifically, again making reference to FIG. **147** of the drawings, the motor **1400** may be mounted to the linear actuator, preferably to the first axial end of the housing thereof, and mechanically coupled to the rotatable ball screw **1352**. The motor **1400** may also mount onto the linear actuators **1350** using built-in mounting points based on standard (e.g., NEMA) motor profile face plates. Alternatively, the motor **1400** may be mounted using a mounting bracket to the frame **1102** of the robotic apparatus **1101** and connected to the linear actuator **1350** input via a shaft coupler or other suitable method. The motor **1400** rotates the ball screw **1352** of the linear actuator **1350** to selectively advance or retract the block carriage **1351**, as well as the tooling attached thereto, along the axial length of the linear actuator.

[0471] The linear actuator **1350** preferably further includes a distance sensor **1221**, such as an encoder, linear encoder, or linear potentiometer for gauging travel distance. The distance sensor **1221** is preferably mounted onto the block carriage **1351** of the linear actuator **1350**. The distance sensor **1221** is configured to measure the distance between the carriage **1351** of the linear actuator **1350** and the TWA **1610**. Alternatively, the distance sensor **1221** may be configured to measure the distance between the carriage of the linear actuator **1350** and a point on the frame **1102** of the robotic apparatus **1101**. The distance sensor **1221** may also be mounted onto a fixed point on the frame **1102** of the robotic apparatus **1102** and configured to sense the distance from the fixed point to the carriage **1351** of the linear actuator **1350**. Furthermore, the distance sensor **1221** may be mounted to a portion of the housing of the linear actuator to measure the distance between the block carriage **1351**, as well as the tooling mounted thereto, and the location on the housing where the distance sensor **1221** is mounted.

[0472] The linear actuator **1350** may also include one or more limit sensors, such as a limit switch or a proximity sensor **1211**, for detecting when the block carriage **1351** and/or the tooling mounted thereto has reached the bounds of its travel (e.g., the bounds of the travel of the carriage **1351** and/or tooling mounted thereto along the axial length of the ball screw **1352**). More specifically, the one or more proximity sensors **1211** mounted on the linear actuator **1350** are configured to sense the presence of the carriage **1351** on the linear actuator **1350** as the carriage **1351** passes in front of the proximity sensor **1211**. The proximity sensors **1211** are preferably mounted at opposite ends of the linear actuator **1350** and spaced to sense when the carriage **1351** reaches either end of its travel range.

[0473] The linear actuator **1350** or the tooling attached to the linear actuator **1350** may further include a load cell **1230** for sensing the force applied by the linear actuator **1350**. The particular mounting of the load cell **1230** to either the tooling or the linear actuator **1350** changes depending on the specific tooling attached to the linear actuator **1350**, but the load cell **1230** generally will be mounted such that force from the end effector of the tooling must pass through the load cell **1230** before reaching the ball screw **1352**. Preferably, the load cell **1230** is fastened to one end of the linear actuator **1350** such that thrust from the ball screw **1352** passes through the load cell **1230** before it reaches the linear actuator bearings **1353**.

[0474] As describe above and as shown in the figures, in any usage of the linear actuator **1350**, load cells **1230** may be placed in line with the ball screw **1352** such that the load cell **1230** senses the linear force applied by the ball screw **1352** to the carriage block **1351**. Each load cell generates a signal that may be used for general load sensing of the tooling or equipment mounted to the linear actuator **1350** for the purpose of monitoring equipment for overloads, monitoring operating loads against expected operating loads, or for any other purpose. The signal from the load cell **1350** may be used to sense and control the loads applied by the tooling or equipment mounted on the linear actuator **1350** to a workpiece, such as the TWA **1610**. The signal from the load cell **1350** may also be used to monitor for collisions between tooling, equipment, and workpieces such as the TWA **1610**. The load cells may be in electrical communication with either the controller **160** or with an input/output module **1541** inside an electrical panel **1103** of the robotic apparatus **1101** via connectors **1104**, or both, and may communicate measurement signals thereto.

[0475] The distance sensor **1221** and proximity sensors **1211** are preferably in electrical communication either the controller **160** or with an input/output module **1541** inside an electrical panel **1103** of the robotic apparatus **1101** via connectors **1104**, or both, and may communicate measurement signals thereto.

[0476] In a preferred embodiment, the tools may include at least two linear actuators **1350** for linear motion in two axes, such as axial to the tire wheel assembly **1610** and radial to the TWA **1610**. In alternative embodiments, the tooling may have more axes of motion or less axes of motion, including no axes of motion, in which case generally the robotic apparatus **1101** could itself have axes of motion that provide the necessary degrees of freedom for the tooling to operate.

[0477] As described above, the tooling of the robotic apparatus **1101** may be mounted to the linear actuators **1350**.

[0478] Now making reference to FIGS. **63-65** and **146** of the drawings, the bead breaker system **2000** formed in accordance with the present invention preferably comprises a linear actuator **1350**, a bead breaker structure **2010** and bead breaker disc **2020**. The bead breaker structure **2010** includes a proximal end and a distal end situated opposite the proximal end. The proximal end of the bead breaker structure **2010** is mounted to carriage **1351** of the linear actuator **1350**. The bead breaker disc **2020** is preferably rotatably attached to the distal end of the bead breaker structure **2010**.

[0479] More specifically, the bead breaker structure **2010** preferably includes a bore situated in proximity to the distal end thereof that extends at least partially therethrough. The bead breaker disc **2020** includes a central bore that extends at least partially through the thickness thereof. A fastener or other connector is insertable through the central bore of the bead breaker disc **2020** into the bore in the bead breaker structure to rotatably attach the bead breaker disc **2020** to the bead breaker structure **2010** such that the bead breaker disc **2020** is axially constrained to the bead breaker structure **2010**, but free to rotate about the axis of the bore in the bead breaker structure **2010**. The axis of rotation of the bead breaker disc **2020** can be any angle relative to the axis of motion of the linear actuator **1350**, but preferably could be between 25-45 degrees downwards. The bead breaker disc **2020** may further include a bearing or bushing capable of withstanding radial loads and allowing for smoother rotation about the disc bore.

[0480] As also described above, the bead breaker tool **129**H, which is also embodied herein as the bead breaker system **2000**, is used, in part, to manipulate the TWA **1610** and remove the tire **1611** from the rim **1612**. FIG. **146** of the drawings illustrates a tire rim **1612** and the tire bead **1609**. The bead **1609** is the location at which an inflated tire **1611** contacts the rim **1612** and creates a pressure seal. During the bead breaking process, the bead breaker disc **2020** is pressed axially into the tire **1611** in such a way to push the tire **1611** further into the rim **1612** and away from the bead **1609** and cause the seal to be broken, allowing the tire **1611** to later be stretched over the rim **1612** and removed. This process may require high force, such as 2 kN, to fully unseat the tire **1611** from the bead **1609** due to factors such as friction, adhesion, and corrosion of the tire **1611** to the bead **1609**. Once the connection between bead **1609** and tire **1611** has been broken, the bead breaker disc **2020** is retracted away from the TWA **1610** using the linear actuator **1350**.

[0481] Preferably, the bead breaker disc **2020** is of sufficient strength and rigidity such that when it engages the tire **1611** of the TWA **1610**, that it does not deform substantially and is able to apply enough force to break the bead of the TWA **1610**, such as 2 kN. The linear actuator **1350** is of sufficient strength and rigidity to actuate the bead breaker structure **2010** with enough force to break the bead on the TWA **1610**.

[0482] As can be seen in FIGS. **63** and **64** of the drawings, the bead breaker system **2000** preferably includes a distance sensor **1221**, a position sensor **1222**, one or more load cells **1230** and proximity sensors **1211**. The distance sensor **1221** is configured such that it adequately measures the distance between the TWA **1610** and the contact point that the bead breaker disc **2020** makes with the TWA **1610**. This information can be used to position the bead breaker system **2000** relative to the TWA **1610**.

[0483] The motion profile of an exemplary bead breaking maneuver is shown in FIG. **65** of the drawings. The information provided by the position sensor **1221** on the linear actuator **1350** can be used to determine the distance the bead breaker system **2000** has advanced into the TWA **1610**, which is a measure of the "bead breaking distance". When retracting the bead breaker system **2000** after a bead breaking maneuver, the distance sensor **1221** may be used to determine the "pull-back" of the bead on the TWA **1610**, where the pull-back is defined as the distance the bead rebounds from the bead breaking distance.

[0484] The combination of the measurements of bead breaking distance and pull-back are used to determine whether a bead breaking maneuver has been successful.

Preferably, the success of the maneuver could be that the "final break distance" is equal to the difference between the bead breaking distance and the pull-back, where a successful bead breaking maneuver might have a final break distance between 50-100 mm depending on the tire, as illustrated in the following formula:

final break distance=bead breaking distance−pullback

[0485] Nevertheless, it is also envisioned to be within the scope of the invention to utilize other techniques to determine successful maneuvers and final breaking distance.

[0486] In addition to distance measurements, the load cells **1230** can be used to measure the load on the bead breaker system **2000** to determine when minimum loads or overloads have been reached and to supplement the distance sensor **1221** in measuring when a bead has been successfully broken. In one form, a load cell **1230** is affixed to the bead breaker structure **2010** and positioned between the bead breaker disk **2020** and bead breaker structure **2010** such that the axial load experienced by the bead breaker disk **2020** is transmitted to the load cell **1230**. The load cells **1230** are powered by the electrical cabinet **1103** and communicate with the programmable logic controller **1540**. Alternatively or in combination, the load cells **1230** may be in electrical communication with the controller **160**.

[0487] Now referencing FIGS. **66-68** and **69-71** of the drawings, the bead tool system **82100** formed in accordance with the present invention preferably comprises a linear actuator **1350**, a bead tool structure **2110**, a bead tool linkage **2120**, a bead tool arm **2130** and a bead tool end effector **2170**. The bead tool structure **2110** includes a proximal end **5022** and a distal end **5024** situated opposite the proximal end **5022**. The proximal end **5022** of the bead tool structure **2110** is mounted to the block carriage **1351** of the linear actuator **1350**. The bead tool arm **2130** is preferably hingedly or pivotally joined to the bead tool structure **2110** by the bead tool linkage **2120**, which is interposed therebetween.

[0488] As described above, the bead tool linkage **2120** is interposed between and connects the bead tool structure **2110** and the bead tool arm **2130** and acts as a rotational linkage between the bead tool structure **2110** and the bead tool arm **2130**. More specifically, the bead tool arm **2130** includes a proximal end **5004** and an oppositely disposed distal end **5006**. The bead tool linkage **2120** includes a first end **5008**, a second end **85010** disposed opposite to the first end **5008** and a pair of side walls **5012** that are spaced apart from one another and extend between the first end **5008** and the second end **85010**. The bead tool linkage **2120** further includes a first bore **5014** that extends at least partially between the side walls **5015** in proximity to the second end **85010** of the linkage **2120** and a second bore **5016** that extends at least partially between the side walls **5012** in proximity to the first end **5008** of the linkage **2120**. The second bore **5016** in the bead tool linkage **2120** is preferably aligned with a corresponding bore **5018** formed in bead tool structure **2110** in proximity to the distal end **5024** thereof. The first bore **5014** in the bead tool linkage **2120** is preferably aligned with a corresponding bore **85020** that is formed in the bead tool arm **2130** in proximity to the proximal end **5004** thereof. Pins or fasteners **5026**, **5028** are inserted through the respective aligned bores to join the bead tool structure **2110**, the linkage **2120** and the bead tool arm **2130** to one another.

[0489] The bead tool linkage **2120** preferably further comprises bead tool bearings **2140** that are situated between the side walls **5012** of the linkage **2120** and the bead tool structure **2110**, as well as between the side walls **5012** of the linkage **2120** and the bead tool arm **2130**. More specifically, as can be seen in FIGS. **66** and **67** of the drawings, one set of bearings **2140** is aligned with the second bore **5016** in the bead tool linkage **2120** and the bore **5018** formed in bead tool structure **2110** in proximity to the distal end **5024** thereof, such that the pin or fastener **5028** may be inserted therethrough. A second set of bearings **2140** is aligned with the first bore **5014** in the bead tool linkage **2120** and the bore **85020** formed in the bead tool arm **2130** such that the pin or fastener **5026** may be inserted therethrough. Accordingly, the bead tool structure **2110** and bead tool arm **2130** are freely rotatable about the axis of the bearings **2140**.

[0490] The bead tool system **82100** may further include one or more arm springs **2150** and a link spring **2160**. The arm springs **2150** are configured to hold the bead tool arm **2130** from collapsing due to the force of gravity. The link spring **2160** is configured to hold the bead tool linkage **2120** from collapsing due to the force of gravity. Both the arm springs **2150** and the link spring **2160** are also configured to provide a particular motion profile of the bead tool linkage **2120** in response to the de-beading process. The arm springs **2150** and link spring **2160** are both connected to the bead tool linkage **2120** by pins or fasteners. The link spring **2160** is also connected to the bead tool structure **2110** by pins or fasteners and produces a linear force between the bead tool linkage **2120** and the bead tool structure **2110**. More specifically, as can be seen in FIG. **67** of the drawings, in one form, the link spring **2160** includes a first end **5031** and an oppositely disposed second end **5032**. The first end **5031** of the link spring **2160** is connected to the bead tool structure **2110** and the second end **5032** of the link spring **2160** is connected to the bead tool linkage **2120**.

[0491] The arm springs **2150** contain spring legs which are constrained against pins in the bead tool linkage **2120** and the bead tool arm **2130**, producing a torsional load between them. The arm springs **2150** and link spring **2160** may be compression springs, torsional springs, gas springs, wave springs, Belville springs, or any sufficiently elastic configuration. Furthermore, the arm springs **2150** and link spring **2160** may be made of any sufficiently elastic material but would preferably be made of spring steel. The bead tool system **82100** preferably includes an upper hard stop **2121** and lower hard stop **21202**, which limit the motion of the bead tool linkage **2120** and bead tool arm **2130** by providing a rigid surface that prevents motion of the bead tool linkage **2120** beyond those surfaces. Basically, the upper hard stop **2121** bounds the rotation of the bead tool linkage **2120** clockwise such that the bead tool arm **2130** lifts relative to the bead tool structure **2110**, and vice-versa for the lower hard stop **2122**.

[0492] An alternative form of the bead tool system **82100**, wherein the angle of the bead tool arm **2130** is actively controlled by a motor, is shown in FIG. **68** of the drawings. As can be seen in FIG. **68** of the drawings, a motor **1400** is mounted to the bead tool structure **2110**. The motor **1400** communicates with and is controlled by the electrical panel **1103** and/or the controller **160**. A bead tool coupling **2180** couples the position of the shaft of the motor **1400** to the bead tool ball screw **2181** such that rotation of the motor **1400** shaft causes rotation of the bead tool ball screw **2181**.

A bead tool control link **2182** is mounted on the bead tool ball screw **2181** such that rotation of the bead tool ball screw **2181** causes a linear motion of the bead tool control link **2182** along the axis of the bead tool ball screw **2181**. A pivot pin **2184** passes through a fixed bore in the bead tool structure **2110**. The bead tool arm **2130** contains a bore through which the bead tool pivot pin **2184** passes through, allowing the bead tool arm **2130** to rotate around the axis of the bead tool pivot pin **2184** relative to the bead tool structure **2110**. The bead tool control pin **2183** passes through another bore in the bead tool arm **2130** located rearward of the bead tool pivot pin **2184**. The bead tool pivot pin **2184** passes through the bead tool bearings **2140**. The sides of the bead tool arm **2130** rotate between the bead tool bearings **2140**.

[0493] The bead tool control link **2182** has a fork feature through which the bead tool control pin **2183** passes. The fork feature controls the location of the bead tool control pin **2183** in the axis of the bead tool ball screw **2181** while allowing it to move relate to the bead tool control link **2182** in the other two principal directions. As the bead tool control link **2182** is moved up, it forces the bead tool control pin **2183** to move up as well, causing the bead tool arm **2130** to rotate clockwise on the bead tool pivot pin **2184**, affecting a downwards motion of the tip of the bead tool end effector **2170**. In this way, the angle of the bead tool end effector **2170** may be controlled by the motion of the motor **1400**. Distance sensors **1221** may be used in combination with the known location of the bead tool pivot pin **2184** to calculate the angle of the bead tool arm **2130**. Alternatively, rotary encoders, angle sensors, or any other suitable sensor may be used. The motor **1400**, bead tool ball screw **2181**, and bead tool coupling **2180** may be replaced with a linear actuator **1350**.

[0494] The bead tool end effector **2170** is preferably mechanically coupled to the distal end of the bead tool arm **2130**; however, the bead tool end effector **2170** may also be formed as an integral part of the bead tool arm **2130**. The bead tool end effector **2170** is sufficiently strong and rigid to not deform substantially when contacting the rim or rubber of the TWA **1610**. The linear actuator **1350** is of sufficient strength and rigidity to actuate the bead tool system **82100** with enough force to deform the tire in the TWA **1610**.

[0495] As can be seen in FIG. **69** of the drawings, bead tool end effector **2170** includes an upper hook **2171** and lower hook **2172**. The upper hook **2171** may be used for aligning with the rim of the TWA **1610**. The lower hook **2172** may be used for hooking the edge or bead of the tire in the TWA **1610** and to manipulate the bead outside the face of the rim to facilitate removal of the front bead of the tire from the rim.

[0496] FIG. **70** of the drawings shows another form of the bead tool end effector **2170**. A major drawback of traditional bead tools is the significant amount of sliding friction they create between the tire **1611** and the bead tool end effector **2170**. To remedy this problem, the bead tool end effector **2170** may include bead tool rollers **2173** which are free to rotate relative to the bead tool end effector **2170**. The bead tool rollers **2173** are ideally available as commercial off-the-shelf roller bearings that are fastened to the bead tool end effector **2170** using pins. The bead tool rollers **2173** introduce a rolling element between the tire **1611**, rim **1612**, and the bead tool end effector **2170**, reducing the overall friction of the system. This reduction reduces the drive torque required to rotate the TWA **1610** relative to the bead tool end effector **2170**, reduces the loading on the bead tool end effector **2170**, and aids in bead removal.

[0497] It is also envisioned to be within the scope of the present invention to form the bead tool rollers **2173** as balls, rollers, ball bearings, or roller bearings. In the case of cylindrical rolling elements, pins and pockets in the bead tool end effector **2170** may be used to join the bead tool end effector **2170** to the bead tool rollers **2173**. In the case of spherical rolling elements, pockets, detents, and peens may be used. The bead tool rollers **2173** may also be made of a low friction material or be coated in a low friction material. In an alternative form, the rollers **2173** may be stationary, fixed to the bead tool end effector **2170**, or integrated into the bead tool end effector **2170** as a single part.

[0498] The bead tool system **82100** preferably further includes a distance sensor **1221**, one or more load cells **1230** and one or more proximity sensors **1211**. The distance sensor **1221** is configured to adequately measure the distance between the TWA **1610** and the contact point of the bead tool end effector **2170** with the TWA **1610**. This information can be used to position the bead tool system **1100** in 3D space with respect to the coordinate frame of the TWA **1610**. The point of contact between the bead tool end effector **2170** and the TWA **1610** is formed by the tip of the bead tool end effector **2170** and a circle with a diameter slightly, such as 5 mm, larger than the circle formed by circle where the tire **1611** and rim **1612** meet on the face of the TWA **1610**.

[0499] In addition to distance measurements, the load cells **1230** can be used to measure the load on the robotic bead tool system **82100** to determine when minimum loads or overloads have been reached and to supplement the distance sensor **1221** in measuring success in the various bead removal process steps. Overload/minimum load measurements are done by comparing the current load on the load cell **1230** to pre-set values. Using load cells **1230** to measure successful bead removal is done by comparing the geometry of the load-insertion distance curve to a "control curve" which includes a "bead removal" datum that can be referenced to the measured curve to determine if this point has been reached in the current process.

[0500] An exemplary motion profile for the insertion of the bead tool end effector **2170** during the bead removal operation performed by the bead tool system **82100** is shown in FIG. **71** of the drawings. The information provided by the distance sensor **1221** on the linear actuator **1350** can be used to determine the distance the bead tool system **82100** has advanced into the TWA **1610**, which is a measure of the "tool insertion distance" and can be used to determine when the bead tool end effector **2170** has inserted itself past the bead. This determination is made by comparing the tool insertion distance to the expected bead depth of the TWA **1610** being worked on, when the insertion distance is greater than the expected bead depth, plus some margin.

[0501] When retracting the bead tool system **82100** to initiate pulling the bead of the tire over the rim, the distance sensor **1221** may be used to determine the "overlap" of the bead on the TWA **1610**, where the overlap is defined as the distance past the front of the rim that the bead travels. This is helpful in determining whether the bead has been pulled far enough past the rim to initiate the next step in the bead removal process.

[0502] In the motion profile shown in FIG. **71** of the drawings, the bead tool first presses against the face of the TWA **1610** axially until the bead tool depresses the tire **1611** and forms a gap between the tire **1611** and rim **1612**. The tool then moves in alternating steps of radial motion towards the center of the TWA **1610** and axial motion into the TWA **1610** to widen the gap between tire **1611** and rim **1612**. At the final step of axial travel, the lower hook **2172** passes over the lip of the tire **1611**, which snaps into the hook **2172** and causes it to become latched to the bead tool end effector **2172**. At this point, the bead tool end effector **2172** may be retracted from the TWA **1610** using the linear actuator **1350**, stretching the edge of the tire **1611** over the rim **1612** and beginning the bead removal process.

[0503] Preferably, the bead tool system **82100** is fully autonomous; however, the bead tool system **82100** may also be operated manually or semi-autonomously. For example, the bead tool system **82100** may be operated by hand, via a wired or remote panel on-site, via teleoperation, or by any other means.

[0504] Now referencing FIGS. **81-83** of the drawings, the inflation tool system **2401** formed in accordance with the present invention preferably includes an inflation valve **2413**, an inflation arm **2430**, an airline **2440** having a generally cylindrical side wall that defines an internal bore, a pressure sensor **1280** and a linear actuator **1350**. The inflation arm **2430** includes a first end and a second end situated opposite the proximal end. The first end of the inflation arm **2430** is mounted to the block carriage **1351** of the linear actuator **1350**.

[0505] The airline **2440** includes a first axial end and a second axial end disposed opposite to the first axial end. Preferably, the first axial end of the airline **2440** is connected to a pneumatic air source via a connector, such as an industrial quick connect valve or pneumatic manifold, as is standard in industry. Even more preferably, the airline **2440** is connected to an industrial quick connect fitting on the robotic apparatus **1101**, which may be connected to an existing airline or air compressor in the location of use. The inflation valve **2413** is connected to the second axial end of the airline **2440** and is in fluid communication with the internal bore of the airline **2440**. An inflation valve seal **2421** may be fitted onto or around the inflation valve **2413** to facilitate sealing against surfaces, such as the valve stem **1614** of the TWA **1610**. The inflation valve **2413** is sized to fit over the valve stem of a TWA **1610**. The inflation valve **2413** and airline **2440** are able to withstand a continuous pressure adequate for fast tire inflation, such as 50 PSI-gauge. The inflation valve **2413** and airline **2440** are attached to the inflation arm **2430** in such a way that the airline **2440** doesn't crimp or bend in response to movement in the inflation arm **2430**.

[0506] As described above, the inflation arm **2430** is attached to and moveable by the linear actuator **1350** such that the inflation valve **2413** can be selectively positioned over the valve stem **1614** of the TWA **1610**. As will be described in greater detail in the forthcoming paragraphs, the gripper system **82200** is able to move the tire axially perpendicular to the motion of the inflation arm **2430**. Once the inflation arm **2430** is located axially relative to the TWA **1610** such that the inflation valve **2413** is positioned over the valve stem **1614**, the gripper system **82200** is able to shift the tire up to press the inflation valve **2413** over the valve stem **1614** such that a seal is formed around the valve stem **1614**, allowing for filling of the valve stem **1614** and thus the tire **1611**. After a seal is formed between the valve stem **1614** and the inflation valve **2413**, pressurized air from pneumatic air source is allowed to flow into the seal from a typical control valve (not shown). The pressurized air forms a pressurized environment inside the seal, forcing air into the valve stem **1614** and thus, the tire, thereby inflating it. In another form, the inflation valve **2413** may clamp, align or mate with the valve stem **1614**, rather than sealing over it. In yet another form, as shown in FIG. **83** of the drawings, an annular seal **2450** seals a portion or the entirety of the surface of the tire that the valve stem **1614** protrudes from, whereby the entire space inside the annular seal **2450** may be pressurized to fill the TWA **1610**. The inflation arm **2430** is preferably formed to be sufficiently strong and rigid to withstand the force required to seal the inflation valve **2413** without excessive deflection or yielding.

[0507] The pressure sensor **1280** is preferably connected to the inflation valve **2413** or the airline **2440** and is configured to measure the internal pressure in the tire via the inflation valve **2413** and the airline **2440**. For example, the pressure sensor **1280** may measure the pressure within the internal bore of the airline **2440**, which is in fluid communication with the inflation valve **2413** and valve stem **1614** connected thereto, that is, when the inflation valve **2413** is sealed to the valve stem **1614**. The pressure sensor **1280** is preferably in electrical communication with either the controller **160** or the input/output module **1541** of the robotic apparatus **1101** such that measurements taken by the pressure sensor **1280** can be communicated thereto and processed.

[0508] The inflation tool system **2401** may further include a distance sensor **1221**, which can be used with the inflation arm **2430** to determine the distance from the inflation valve **2413** to the TWA **1610** or valve stem **1614** for the purpose of aiding in sealing the inflation valve **2413**. The inflation tool system **2401** may also include a load cell **1230**, which may be used to measure the load on the inflation valve **2413** to ensure a seal is achieved using force feedback. Preferably, the inflation tool system **2401** is fully autonomous; however, the inflation tool system **2401** may also be operated manually or semi-autonomously. For example, the inflation tool system **2401** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0509] Now referencing FIG. **84** of the drawings, the cleaning tool system **2500** formed in accordance with the present invention comprises a cleaning arm **2513**, a cleaning end effector **2520**, a cleaning drive system **2530** and a linear actuator **1350**. More specifically, the cleaning arm has a first end and an oppositely disposed second end. The first end is mounted to the block carriage **1351** of the linear actuator **1350**. The cleaning drive system **2530** is mounted to a portion of the second end of the cleaning arm **2513**. As will be explained in greater detail in the forthcoming paragraph, the cleaning end effector **2520** is mechanically coupled to the cleaning drive system **2530** via an output shaft and is driven, preferably rotatably driven, by the cleaning drive system **2530**.

[0510] The cleaning drive system **2530** is preferably a rotational drive, such as a direct drive motor, a belt drive system, a gear drive or other type of rotary drive. Nevertheless, the cleaning drive system **2530** may also include any suitable reciprocating drive, such as a cam follower or a rack and pinion. The cleaning drive system **2530** is used to

produce relative motion between the cleaning end effector **2520** and the TWA **1610**. The output shaft of the cleaning drive system **2530** is ideally attached directly to the cleaning end effector **2520** such that motion from the output shaft of the cleaning drive system **2530** directly actuates the cleaning end effector **2520**. The relative motion of the cleaning end effector **2520** to the TWA **1610** produces a cleaning effect on debris and corrosion on the TWA **1610** via a scraping, rubbing, dissolving, adhesion, abrasion, or other action sufficient to remove the debris and corrosion from the surface. Alternatively, the relative motion between the cleaning end effector **2520** and the TWA **1610** may be produced via motion of the cleaning arm **2513**. The cleaning end effector **2520** may be formed as a wire wheel, a sanding wheel, a buffing wheel, a wax applicator, a solvent wheel, a brush or any other end effector that has a structure that is capable of cleaning debris and/or corrosion off the TWA **1610**.

[0511] The cleaning tool system **2500** may further include a distance sensor **1221** for sensing the distance between the cleaning end effector **2520** and the TWA **1610**, and a load cell **1230** for sensing the force the cleaning end effector **2520** is applying to the TWA **1610**. Preferably, the cleaning tool system **2500** is fully autonomous; however, the cleaning tool system **2500** may also be operated manually or semi-autonomously. For example, the cleaning tool system **2500** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0512] Now referencing FIGS. **85** and **86** of the drawings, the lubrication tool system **2600** formed in accordance with the present invention comprises a lubrication arm **2611**, a lubrication end effector **2621** or a lubricant spray head **2630**, a lubrication line **2640** having a generally cylindrical side wall that defines an internal bore and a linear actuator **1350**. The lubrication arm **2611** includes a first end and an oppositely disposed second end. The first end of the lubrication arm **2611** is mounted to the block carriage **1351** of the linear actuator **1350** such that the lubrication arm **2611** is selectively moveable by the linear actuator **1350**.

[0513] The lubrication line **2640** includes a first axial end and a second axial end disposed opposite to the first axial end. Preferably, the first axial end of the lubrication line **2640** is connected to a lubrication source (not shown), such as a reservoir or a lubricant manifold, via a connector, such as an industrial quick connect fitting, which also may be situated on the robotic apparatus **1101**.

[0514] As shown in FIG. **85** of the drawings, the lubrication end effector **2621** is mounted to a portion of the second end of the lubrication arm **2611**. The lubrication end effector **2621** is connected to the second axial end of the lubrication line **2640** and is in fluid communication with the internal bore of the lubrication line **2640**. Again, the lubrication arm **2611** is also mounted to the block carriage **1351** of the linear actuator **1350**. As such, the lubrication end effector **2621** is also selectively movable by the linear actuator **1350**. The lubrication end effector **2621** is preferably formed as a lubricant brush; however, the lubrication end effector **2621** may also be a lubrication wheel, a stick of lubrication or any other commercial lubrication tool or lubricating method. The lubrication end effector **2621** is pushed or placed against the TWA **1610** in the locations in which lubrication is desired. Alternatively, the lubrication end effector **2621** may move relative to the TWA **1610** or vice versa to apply lubrication along a path on the TWA **1610**.

[0515] Alternatively, as shown in FIG. **86** of the drawings, the lubricant spray head **2630** is mounted to a portion of the second end of the lubrication arm **2611**. The lubricant spray head **2630** is connected to the second axial end of the lubrication line **2640** and is in fluid communication with the internal bore of the lubrication line **2640**. Again, the lubrication arm **2611** is also mounted to the block carriage **1351** of the linear actuator **1350**. As such, the lubricant spray head **2630** is also selectively movable by the linear actuator **1350**. The lubricant spray head **2630** is placed in the location on the TWA **1610** in which lubrication is desired and the lubricant spray head **2630** is actuated to apply a spray of lubricant to the location. Alternatively, the lubricant spray head **2630** may move relative to the TWA **1610** or vice versa to spray lubrication along a path on the TWA **1610**.

[0516] The lubrication tool system **2600** may further include a distance sensor **1221** to sense the distance between the lubrication end effector **2621** and the TWA **1610** or the distance between the lubricant spray head **2630** and the TWA **1610**. As described above, the distance sensor may be mounted to the lubrication arm **2611**, the lubrication end effector **2621** or the lubricant spray head **2630**. Alternatively, as also described above, the distance sensor **1221** may be mounted to a portion of the housing of the linear actuator **1350**.

[0517] The lubrication end effector **2621** shown in FIG. **85** of the drawings may also be instrumented with a load cell **1230** to sense the force applied by the lubrication end effector **2621** against the TWA **1610**. Preferably, the lubrication tool system **2600** is fully autonomous; however, the lubrication tool system **2600** may also be operated manually or semi-autonomously. For example, the lubrication tool system **2600** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0518] Now making reference to FIG. **87** of the drawings, the valve tool system **2700** formed in accordance with the present invention comprises a valve tool arm **2711**, a stem driver **2720**, a cap driver **2730**, a stem driver spring **2740**, a cap driver spring **2750**, valve stem rotary drives **2760** and a linear actuator **1350**. The valve tool arm **2711** includes a first end and an oppositely disposed second end. The first end of the valve tool arm **2711** is mounted to the block carriage **1351** of the linear actuator **1350** such that the valve tool arm **2711** is selectively moveable by the linear actuator **1350**. The stem driver **2720**, the cap driver **2730** and the valve stem rotary drives **2760** are preferably mounted to a portion of the second end of the valve tool arm **2711**. Accordingly, the valve tool arm **2711**, as well as the stem driver **2720** and the cap driver **2730** mounted thereto, are selectively movable by the linear actuator **1350** relative to the TWA **1610**.

[0519] The stem driver **2720** has a tip which is contoured to interface with standard valve stems. The stem driver **2720** is backed by stem driver spring **2740** to spring-load it against the valve stem. The stem driver spring **2740** gives the stem driver **2720** play against the valve stem and allows it to unscrew or screw the valve stem by applying even pressure during the linear move associated unscrewing or screwing in the valve stem. The stem driver **2720** is mechanically coupled to one valve stem rotary drive **2760** via an output shaft of the valve stem rotary drive **2760** and is driven, preferably rotatably driven, by the valve stem rotary drive **2760** (i.e., the stem driver **2720** is rotated by the valve stem rotary drive **2760**). The valve stem rotary drive **2760** is

preferably a direct drive motor, but may be powered by a belt drive, a gear drive or other type of rotary drive.

[0520] The cap driver **2730** is designed to grasp the cap of a valve stem at one or more points. The cap driver **2730** is backed by the cap driver spring **2750** to spring-load it against the valve cap. The cap driver spring **2750** gives the cap driver **2730** play against the valve cap and allows it to unscrew or screw the valve cap by applying even pressure during the linear move associated with the unscrewing or screwing in of the valve cap. The cap driver **2730** is mechanically coupled to one valve stem rotary drive **2760** via an output shaft of the valve stem rotary drive **2760** and is driven, preferably rotatably driven, by the valve stem rotary drive **2760** (i.e., the cap driver **2730** is rotated by the valve stem rotary drive **2760**). The valve stem rotary drive **2760** is preferably a direct drive motor, but may be powered by a belt drive, a gear drive or other type of rotary drive.

[0521] Preferably, the valve tool system **2700** is fully autonomous; however, the valve tool system **2700** may also be operated manually or semi-autonomously. For example, the valve tool system **2700** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0522] Now referencing FIGS. **133** and **134** of the drawings, the alignment tool **2800** formed in accordance with the present invention preferably comprises an alignment end effector **2820**, an alignment arm **2810**, an alignment drive system **2830**, alignment tool sensors **2840** and a linear actuator **1350**. The alignment arm **2810** includes a first end and an oppositely disposed second end. The first end of the alignment arm **2810** is mounted to the block carriage **1351** of the linear actuator **1350** such that the alignment arm **2810** is selectively moveable by the linear actuator **1350**. The alignment end effector **2820**, the alignment drive system **2830** and the alignment tool sensors **2840** are preferably mounted to a portion of the second end of the alignment arm **2810**. Accordingly, the alignment arm **2810**, as well as the alignment end effector **2820**, the alignment drive system **2830** and the alignment tool sensors **2840** mounted thereto, are selectively movable by the linear actuator **1350** relative to the TWA **1610**.

[0523] The alignment end effector **2820** is mechanically coupled to alignment drive system **2830** via an output shaft of the alignment drive system **2830** and is driven, preferably rotatably driven, by the alignment drive system **2830** (i.e., alignment end effector **2820** is rotated by the alignment drive system **2830**). The alignment end effector **2820** is configured to interface with an alignment screw **1650** and, when driven by the alignment drive system **2830**, rotate the alignment screw **1650** to adjust the alignment of the TWAs **1610** of the vehicle **1600**. More specifically, as can be seen in FIG. **134** of the drawings, the alignment tool **2800** is engageable with the alignment screw **1650** installed on the vehicle. As described above, the alignment end effector **2820** of the alignment tool **2800** interfaces with the alignment screw **1650** and is selectively rotatable by the alignment drive system **2830**, which causes the alignment screw **1650** that is interfaced with the alignment end effector **2820** to be correspondingly rotated. By rotating the alignment screw **1650**, the alignment of the associated TWA **1610** may be adjusted.

[0524] The alignment tool sensor **2840** is preferably a position sensor that can sense the position of the alignment screw **1650** or TWA **1610**. The alignment tool sensor **2840** and alignment drive system **2830** are powered by and communicate with the electrical panel **1103** of the robotic apparatus **1101** and/or the control unit **160**.

[0525] It is envisioned to be within the scope of the present invention to have the alignment end effector **2820** of the alignment tool **2800** be driven by an off-tool drive system rather than the alignment drive system **2830**. It is also envisioned to be within the scope of the present invention to use multiple linear actuators **1350** to move the components of the alignment tool **2800** relative to the TWA **1610**.

[0526] Preferably, the alignment tool **2800** is fully autonomous; however, the alignment tool **2800** may also be operated manually or semi-autonomously. For example, the alignment tool **2800** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means. As mentioned above, like the other tooling, the alignment tool **2800** may be mounted to the frame **1102** of the robotic apparatus **1101** or may be used independently and selectively mated to the end effector **128** of a particular bot **120**.

[0527] FIGS. **72-80** and **143** of the drawings show several embodiments of a tire gripper system **82200** formed in accordance with the present invention. The tire gripper system **82200** is used to manipulate the TWA **1610**. For example, the gripper system **82200** may be used to stabilize the TWA **1610** and to effect rotation of the TWA **1610** to perform a particular tire servicing procedure. In one form, the tire gripper system **82200** includes a plurality of grippers **2270**, one or more of which is driven by a gripper drive system **2260** to effect rotation of the TWA **1610**. In another form, the tire gripper system includes a rotatable turntable **2360** onto which a plurality of grippers **2270** are mounted. In yet another form, the tire gripper system includes a face gripper **2300** that is engageable with the hub of the TWA **1610** and is driven by a gripper drive system **2260** to effect rotation of the TWA **1610**.

[0528] As described above, in accordance with one form of the present invention, the tire gripper system **82200** includes one or more grippers **2270**, at least one of which is driven by a gripper drive system **2260** to effect rotation of the TWA **1610**. More specifically, as can be seen in FIGS. **72-74** of the drawings, in one form, the gripper **2270** is mountable to a drive assembly **5050** comprising a gripper base **2210**, a gripper pin **82220**, a gripper flange **2250**, a gripper drive system **2260**, a gripper bearing **2230** and a gripper pulley **2240**. In one form, the gripper **2270** includes a first end **5034** and a second end **5036** disposed opposite to the first end **5034**. The second end **5036** of the gripper **2270** is engageable with the gripper pulley **2240**. The gripper pulley **2240** is generally formed as a cylindrical member having a first end **5038** and an oppositely disposed second end **5039**. The first end **5038** of the gripper pulley **2240** includes a recessed slot **5042** that extends axially inwardly therefrom. The slot **5042** has a shape that generally conforms to the shape of the second end **5036** of the gripper **2270** so that the second end **5036** of the gripper **2270** may be at least partially received therein. Preferably the slot **5042** and the second end of the **5036** of the gripper **2270** have a rectangular cross-sectional shape; however, the slot **5042** and the second end of the **5036** of the gripper **2270** may be formed with other cross-sectional shapes, such as hexagonal, spline shaped or round Alternatively, a rectangular shaped "peg" may be machined onto the second end **5036** of the gripper **2270**, which may be received in the slot **5042** in the pulley **2240**.

[0529] The gripper pulley **2240** further includes a bore **5044** that is situated at the first end **5038** thereof and extends radially inwardly through the thickness of the pulley **2240** into the slot **5042**. The gripper flange **2250** is formed as a generally cylindrical member having a centrally located bore **5046** that extends through the thickness thereof. The bore **5046** has a shape that generally conforms to the shape of the second end **5036** of the gripper **2270** so that the second end **5036** of the gripper **2270** may be at least partially inserted therethrough.

[0530] As can be seen in FIG. **74** of the drawings, the second end **5036** of the gripper **2270** is aligned with each of the bore **5046** in the gripper flange **2250** and the slot **5042** in the first end **5038** of the gripper pulley **2240**, and is inserted through the bore **5046** in the gripper flange **2250** and into the slot **5042** in the first end **5038** of the gripper pulley **2240**. The gripper pin **82220** is inserted through the bore **5044** in the gripper pulley **2240** and engages the second end **5036** of the gripper **2270** that is situated in the slot **5042**, thereby joining the gripper **2270**, gripper flange **2250** and gripper pulley **2240** together and retaining the second end **5036** of the gripper **2270** in the slot **5042**. Nevertheless, it is also envisioned to be within the scope of the present invention to utilize other structures and techniques to retain the gripper **2270** in the gripper pulley **2240** and/or join the gripper **2270** to the gripper pulley **2240**, such as a retaining ring, a shaft collar, a peen, an adhesive, a knurl, press-fit, shrink fitting, a magnet or an electromagnet.

[0531] The gripper pulley **2240** is mounted, joined, fastened or otherwise affixed to the gripper bearing **2230**, preferably with fasteners. Similarly, the gripper bearing **2230** is mounted, joined, fastened or otherwise affixed to the gripper base **2210** with fasteners. In one form, as shown in FIG. **74** of the drawings, the gripper drive system **2260** drives the gripper pulley **2240** directly. More specifically, the shaft **5048** of the gripper drive system **2260** may be directly connected to the gripper base **2210**. Nevertheless, in other forms, a belt (not shown) may be used to drive the gripper pulley **2240** so that the gripper drive system **2260** can be offset from the drive assembly **5050**, in particular, from the gripper pulley **2240** of the drive assembly **5050**. Furthermore, a gear drive, a hydraulic motor, a pneumatic motor or any other system that produces rotation may be used to rotational drive the gripper **2270**. Even furthermore, multiple grippers **2270** may be controlled, moved and driven by the same gripper drive system **2260**, gripper pulley **2240**, and other components.

[0532] The gripper flange **2250** serves as a backstop for the TWA **1610**. More specifically, during some tire servicing operations, once the tire **1611** is removed from the rim **1612**, the tire **1611** can become flexible due to the lack of tension on it. This lack of tension can cause the grippers **2270** to have difficulty retaining the tire **1611** axially. The gripper flange **2250** provides a backstop which stops the tire **1611** from advancing axially past that point, allowing for more reliable locating and manipulation of the tire **1611**.

[0533] As can be seen in FIGS. **73** and **143** of the drawings, the gripper **2270** and drive assembly **5050** are mounted to a gripper mounting plate **2211**. More specifically, the gripper mounting plate **2211** includes a proximal end **5052** and an oppositely disposed distal end **5054**. Preferably, the drive assembly **5050** is mounted to the gripper mounting plate **2211** in proximity to the distal end **5054** thereof and the proximal end **5052** of the gripper mounting plate **2211** is mounted to the block carriage **1351** of a linear actuator **1350**. Accordingly, linear movement of the carriage block **1351** results in movement of the gripper mounting plate **2211** and thus, the drive assembly **5050** and gripper **2270** attached thereto.

[0534] The gripper system **82200** may also include load cells **1230**, which are installed thereon, in particular, on one or more of the components of the linear actuator **1350**, the gripper **2270**, the drive assembly **5050** or the mounting plate **2211**, to measure the compressive force of the gripper **2270** on the TWA **1610** and facilitate proper compression and torque transfer. The gripper system **82200** may further include distance sensors **1221**, which are installed thereon, in particular, on one or more of the components of the linear actuator **1350**, the gripper **2270**, the drive assembly **5050** or the mounting plate **2211**, to measure the distance of the grippers **2270** to the TWA **1610** and/or the distance from the gripper system **82200** to other aspects or components of the robotic automotive service system **1100** formed in accordance with the present invention.

[0535] As can be seen in FIG. **143** of the drawings, the robotic apparatus **1101** may include three grippers **2270**, each of which is driven by a respective gripper drive system **2260**. More specifically, as described above, each of the linear actuators **1350** that are coupled to the drive assembly **5050** of a respective rotationally driven gripper **2270** is mounted to the frame **1102** of the robotic apparatus **1101**. The linear actuators **1350** are configured on the gripper system **82200**, which is mounted to the frame **1102** of the robotic apparatus **1101**, to provide linear movement in the radial direction of the TWA **1610**. The gripper **2270** is designed to contact the TWA **1610** such that rotation of the gripper **2270** causes the TWA **1610** be correspondingly rotated. The motion of the linear actuator **1350** allows the gripper system **82200** to drive the gripper **2270** into closer or farther contact with the TWA **1610**.

[0536] As can be seen in FIG. **143** of the drawings, the robotic apparatus **1101** may include one or more grippers **2270**, at least one of which is driven by a gripper drive system **2260** to effect rotational movement of the gripper **2270** and rotate the TWA **1610**. Preferably, the robotic apparatus **1101** includes three grippers **2270**, each of which is rotationally driven by a respective gripper drive system **2260** that is mechanically coupled thereto. In addition to driving rotation of the TWA **1610**, the gripper system **82200** can be used to manipulate the TWA **1610** position and orientation. Again, with reference to FIG. **143** of the drawings, some non-exclusionary examples of manipulation are as follows:

[0537] (1) By tilting the gripper system **82200** forward or backwards, the TWA **1610** may also be tilted. Alternatively, this motion allows the grippers **2270** of the gripper system **82200** to approach the TWA **1610** off-angle.

[0538] (2) By moving all the grippers **2270** of the gripper system **82200** in one direction an equal amount, the TWA **1610** position can be manipulated the same amount. For instance, moving all the grippers **2270** of the gripper system **82200** to the right 100 mm in the image would shift the center of the TWA **1610** to the right 100 mm.

[0539] (3) By moving the gripper **2270** of the gripper system **82200** asymmetrically, the TWA **1610** position can be adjusted relative to the center point between all the grippers **2270** of the gripper system **82200**. For example,

moving the upper gripper inwards and the lower grippers outwards would move the center of the TWA **1610** downwards.

[0540] (4) Moving the center of the TWA **1610** relative to the center point between all the grippers **2270** of the gripper system **82200** allows for non-concentric rotation of the TWA **1610** relative to that point.

[0541] As also described above, in accordance with another form of the present invention, the tire gripper system **82200** includes a rotatable turntable **2360** to which a plurality of grippers **2270** are connected. More specifically, as can be seen in FIG. **79** of the drawings, a plurality of grippers **2270**, which are preferably stationary and non-rotational (i.e., the grippers **2270** are fixed from rotating along their own longitudinal axes), are affixed to a first gripper base **2210**A and a second gripper base **2210**B. Each of the first gripper base **2210**A and the second gripper base **2210**B is engaged with one or more elongated tracks situated on the turntable **2360** and is reciprocatingly movable thereon. A first linear actuator **1350**A and a second linear actuator **1350**B, each of which is preferably a pneumatic linear actuator that includes a cylindrical housing and a rod that is selectively extendable therefrom and retractable therein upon the application of pneumatic force from a pneumatic air source (not shown), are mounted to the turntable **2360**. The rods of the linear actuators **1350**A, **1350**B are mechanically coupled to a respective one of the first and second gripper bases **2210**A, **2210**B. The linear actuators **1350**A, **1350**B drive the gripper bases **2210**A, **2210**B, as well as the grippers **2270** attached thereto, inwardly and outwardly relative to one another along the tracks to grip and release the TWA **1610**. The movement of the linear actuators cause the grippers **2270** to be pressed into the tire **1611**, ideally causing some deformation of the tire **1611** around the gripper **2270**. As long as the grippers **2270** are held against the tire **1611** of the TWA **1610** and not retracted therefrom, they produce a positive drive contact patch on the TWA **1610**, allowing the gripper turntable **2360** to rotate the TWA **1610**.

[0542] As can be seen in FIG. **80** of the drawings, preferably, the grippers **2270** are spaced apart from one another on the first and second gripper bases **2210**A, **2210**B such that, when the TWA **1610** is gripped by the gripper system **82200**, the grippers **2270** are situated on opposite sides of the diameter **5002** of the tire **1611**, the diameter **5002** of the tire **1611** being the longest chord between any two points on the circumference of the tire **1611**. The distance **5001** between any two grippers **2270** is preferably less than the diameter **5002** of the tire **1611**.

[0543] As the TWA **1610** is rotated by the gripper turntable **2360**, a force which acts in a direction opposite to the direction of rotation of the gripper turntable **2360** (a "reverse force" is generated by various objects and components. For example, if the TWA **1610** is on the vehicle, the transmission of the vehicle generates a force that acts in a direction that is opposite to direction of rotation of the gripper turntable **2360** and TWA **1611** gripped thereby. Similarly, various tooling that is engaged with portions of the TWA **1610** creates a similar "reverse force". As the TWA **1610** is rotated by the gripper turntable **2360**, due to the positioning of the grippers **2270** on opposite sides of the diameter **5002** of the tire **1611**, at least some of the grippers **2270** (e.g., half of the grippers **2270** if four grippers **2270** mounted to the turntable **2360**) act against the reverse force and are further driven against the tire **1611** in a direction of increasing chord length of the tire **1611** (i.e., towards the diameter **5002** of the tire **1611**). This increases the grip of the grippers **2270** against the tire **1611** as the gripper turntable **2360** rotates the TWA **1610**. In comparison, the grip of the grippers **2270** against the tire **1611** generally decreases as the distance **5001** between any two grippers **2270** increases towards the diameter **5002** of the tire (e.g., the grippers **2270** are situated closer to the diameter **5002** of the tire **1611**).

[0544] Some tire servicing procedures and tooling require the TWA **1610** be rotated at least one full turn (i.e., a complete revolution of 360 degrees). While it is possible for the gripper turntable **2360** to rotate the TWA **1610** in a full rotation (i.e., 360 degrees or greater) to accomplish a particular tire servicing procedure, to reduce the size of the travel path of the grippers **2270**, for example, on the robotic apparatus, the rotation action may follow a pattern by which the grippers **2270** grip the TWA **1610**, the gripper turntable **2360** rotates the TWA **1610** for a partial rotation, such as 10 degrees, the grippers **2270** release the TWA **1610**, the gripper turntable **2360** rotates in an opposite direction back to its starting position. This pattern may be repeated until the TWA **1610** has been rotated by the amount required for the particular tire servicing procedure.

[0545] Preferably, the gripper turntable **2360** is mounted to a bearing (not shown) which is in turn mounted to the frame **1102** of the robotic apparatus **1101** such that it may rotate about the centerline of the bearing. A motor **1400** is mechanically coupled to the turntable **2360** to effect rotation thereof.

[0546] As also described above, in accordance with yet another form of the present invention, the tire gripper system **82200** includes a face gripper **2300** that is engageable with the hub of the TWA **1610** and is driven by a gripper drive system **2260** to effect rotation of the TWA **1610**. More specifically, as can be seen in FIG. **76** of the drawings, the face gripper **2300** preferably includes a face gripper pin housing **2340** having a first end **5058**, an oppositely disposed second end **5061**, a generally cylindrical side wall **5056** that extends between the first end **5058** and the second end **5061**. The first end of the face gripper pin housing **2340** is preferably open. A face gripper back plate **2310** extends between the side wall **5056** in proximity to the second end **5061** of the face gripper pin housing **2340** and at least partially closes the second end **5061** of the face gripper pin housing **2340**. In an alternative embodiment, rather than being formed as an integral part of the face gripper pin housing **2340**, the back plate **2310** may be mounted to the pin housing **2340** using fasteners. A pulley **2240** is preferably mounted to the back plate **2310** using fasteners. The pulley **2240** is mechanically coupled to a gripper drive system **2260** and rotatably driven thereby to effect rotational movement of the face gripper **2300**. The cylindrical side wall **5056** and the face gripper back plate **2310** define a cavity **5062** in which a plurality of face gripper pins **2320** and a plurality of face gripper pin springs **2330** are situated.

[0547] More specifically, the face gripper pins **2320** and face gripper pin springs **2330** are packed inside the cavity **5062** of the pin housing **2340**. The number of face gripper pins **2320** and face gripper pin springs **2330** may be variable, but in general, should be as large as possible while still allowing for free movement of the components within the

cavity **5062**. The face gripper back plate **2310** closes the back of the face gripper pin housing **2340** (i.e., the second end **5061**).

[0548] The face gripper pins **2320** are attached to the face gripper pin springs **2330** in such a way that the face gripper pin springs **2330** tend to push or bias the face gripper pins **2320** axially, at least partially out of the first end **5058** of the pin housing **2340**. The face gripper pin springs **2330** are attached at the back to the face gripper pin housing **2340**. The attachment between the face gripper pins **2320** and face gripper pin springs **2330** and pin housing **2340** is such that the face gripper pins **2320** cannot pull away from the face gripper pin springs **2330**, which cannot pull away from the pin housing **2340**, such that the face gripper pins **2320** cannot be pushed completely out of the pin housing **2340**.

[0549] Each face gripper pin **2320** and its corresponding face gripper pin spring **2330** can move axially and independently from other face gripper pins **2320** and their respective pin spring **2330**. As one or more face gripper pins **2320** advance into an object, such as the lug nuts **1613** of the TWA **1610**, they are depressed (i.e., pushed inwardly towards the back of the housing **2340**), while the face gripper pins **2320** that have not contacted an object stay in position axially. In this way, the packed face gripper pins **2320** roughly conform to the shape of the tire component that the face gripper **2300** is being advanced into and/or against. The resolution that the face gripper pins **2320** can conform to is related to the number and size of the face gripper pins **2320**. When depressed, the face gripper pins **2320** experience a restoring force by the face gripper pin springs **2330** which tends to push the face gripper pins **2320** out and towards the object and/or component depressing them, such that when the object is removed or the face gripper system **2300** is retracted, the face gripper pin springs **2330** restore the face gripper pins **2320** to their original position, in which they at least partially extend axially from the first end **5058** of the pin housing **2340**.

[0550] As can be seen in FIG. **77** of the drawings, the face gripper **2300** interfaces with the TWA **1610** by gripping the TWA **1610** by the lug positions of the rim. More specifically, the face gripper **2300** is actuated axially such that the face gripper pins **2320** push against the face of the rim. As face gripper **2300** is actuated farther, the face gripper pins **2320** that are not lined up with the lug positions are compressed into the face gripper pin springs **2330**, while the face gripper pins **2320** that are aligned with the lug positions are able to continue moving axially into the lug positions and engaged therewith.

[0551] Once the face gripper pins **2320** are engaged with the lug positions, the gripper drive system **2260** can rotate the face gripper pin housing **2340**, which pushes the face gripper pins **2320** radially into the walls of the lug positions, applying torque to the TWA **1610** and aiding in the rotation of the TWA **1610**.

[0552] In an alternate embodiment of the face gripper **2300**, the face gripper pins **2320** may drive torque into the TWA **1610** by engaging any space, face, edge, point or suitable feature on a component of the TWA **1610** or vehicle, such as the rim spokes.

[0553] In another alternate embodiment of the face gripper **2300**, the face gripper pins **2320** may instead be a compliant component which may deform axially as needed to line up with the driven surface, face, edge or point. The face gripper pins **2320** may also be any component or shape suitable for driving torque, such as spherical balls or square keys. The face gripper pins **2320** may also be replaced with a hydraulic or pneumatic system capable of engaging with the driven surface, face, edge or point.

[0554] In yet another form, the tire gripper system **82200** may include a lug nut gripper **2350**, as shown in FIG. **78** of the drawings, that is mechanically coupled to and rotatable by a gripper drive system **2260**. The lug-nut gripper **2350** interfaces with the lug nuts **1613** or the cavity in the rim **1612** of the TWA **1610** that the lug nuts **1613** generally resides in, such that when the lug-nut gripper **2350** is rotated via the gripper drive system **2260**, the TWA **1610** is rotated as well. The lug nut gripper **2350** may be mounted to the frame **1102** of the robotic apparatus **1101** or may be selectively engageable with the end effector **128** of a particular bot **120**.

[0555] The gripper **2270** may comprise structure and/or surface coatings that optimize attributes, such as friction, torque transfer, aesthetics, or mass or to reduce damage to the TWA **1610**. More specifically, one difficulty of gripping the TWA **1610** via the tire **1611** is that, after deflation, the tire **1611** becomes relatively flexible in the radial direction (towards the center of the tire **1611**). As such, it can be difficult to produce enough force in the radial direction on the tire **1611** to provide sufficient torque for rotating the tire **1611** or TWA **1610** via friction alone, as exemplified by the following equation:

$$\text{Torque} = \text{Normal Force} * \text{Friction Coefficient} * \text{tire radius}$$

[0556] One solution is to increase the friction coefficient between the gripper **2270** and the TWA **1610** (particularly between the gripper **2270** and the tire **1611** of the TWA **1610**) to decrease the normal force required to produce high torque. Various exemplary grippers **2270** that may be used to remedy or overcome the above-mentioned obstacle are shown in FIG. **75** of the drawings. For example, the gripper **2270** may be formed as bare metal gripper, a rubber-coated gripper **2272**, a tungsten carbide (or similar) coated gripper **2273**, a coated gripper **2274** (e.g., the gripper is coated with adhesive or sandpaper, etc.), a toothed gripper **2275**, a lobed Geneva gripper **2276**, a cam-style gripper **2277**, a track belt gripper **2278**.

[0557] The lobed Geneva gripper **2276** drives torque into the tire **1611** by using the deformation of the tire **1611** to produce a positive drive contact point between the lobed Geneva gripper **2276** and the tire **1611**. Every rotation of the lobed Geneva gripper **2276** advances the tire **1611** not through pure friction, but through this positive contact. The cam-style gripper **2277** drives torque into the tire **1611** by using the deformation of the tire **1611** to produce a positive drive contact point between the cam-style gripper **2277** and the tire **1611**. Every rotation of the cam-style gripper **2277** advances the tire **1611** not through pure friction, but through this positive contact. The toothed gripper **2275** drives torque into the tire **1611** by using the deformation of the tire **1611** to produce a positive drive contact point between the toothed gripper **2275** and the tire **1611**. Every rotation of the toothed gripper **2275** advances the tire **1611** not through pure friction, but through this positive contact. Additionally, the teeth of the toothed gripper **2275** tend to produce and grip many small "micro-deformations" in the tire **1611** to produce additional positive contact and tend to use the tread of the tire **1611** to produce positive contact.

[0558] Preferably, the tire gripper system **82200** is fully autonomous; however, the tire gripper system **82200** may also be operated manually or semi-autonomously. For example, the tire gripper system **82200** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0559] A robotic automotive service system **1100** formed in accordance with the present invention is generally shown in FIGS. **62**, **132** and **135** of the drawings. The robotic automotive service system **1100** includes one or more robotic apparatus **1101** that may be used to perform tire servicing procedures/operations. In a preferred embodiment, the robotic automotive service system **1100** contains at least two robotic apparatus **1101**, one each for the driver and passenger side of the vehicle **1600**. As described above, the robotic apparatus **1101** contains a frame **1102** which houses components, tooling, and electronics of the robotic apparatus **1101**.

[0560] The robotic automotive service system **1100** further includes one or more electrical panels **1103** for housing electronics such as a computer **1500**, a data acquisition system **1510**, embedded circuit boards **1523**, a processor **1530**, a programmable logic controller **1540**, a motor controller **1410**, an input/output module **1541** and safety module **1542**; however, it is also envisioned to be within the scope of the present invention to have the electrical panel be formed as a component of the robotic apparatus **1101**.

[0561] A preferred form of the electrical panel **1103** is shown in FIG. **145** of the drawings. The electrical panel **1103** is preferably mounted to the robotic apparatus **1101** such that it translates with the robotic apparatus **1101**; however, the electrical panel **1103** may also be stationary and mounted at a particular location. The electrical panel **1103** contains input and output connectors **1104** for connecting the electronics it houses to various systems and components of the robotic apparatus, which include: communications and power connectors from motor controllers **1410** to motors **1400**; communications and power connectors from the data acquisition system **1510** to the balancing system **3000**; communications and power connectors from the input/output module **1541** to sensors **1200** such as the proximity sensor **1211**, distance sensors **1221**, one or more load cells **1230**, a multi-axis accelerometer **1250**, pressure sensor **1280**; other sensors **1200** used on the robotic apparatus **1101**; communications and power connectors from the vision system **1300** to the programmable logic controller **1540** or computer **1500**; communications and power connectors from the programmable logic controller **1540** to the computer **1500**; and communications and power connectors from the operator interface **1910**, the customer interface **1900** and the operator controls **5210** to the computer **1500**. Motors **1400**, sensors **1200** such as proximity sensors **1211** and distance sensors **1221**, and the vision system **1300** are powered via connectors **1104** from the electrical panel **1103**.

[0562] The robotic apparatus **1101** of the robotic automotive service system **1100** may include a series of tooling, such as a bead breaker system **2000**, a bead tool system **82100**, a series of gripper systems **2200**, an inflation tool system **2401**, a cleaning tool system **2500**, a lubrication tool system **2600**, a valve stem tool system **2700** and an alignment tool system **2800**, each of which was described in above. The collection of tools on the robotic apparatus **1101** is henceforth referred to as "tooling" for description purposes. As mentioned above, a plurality of tools or "tooling" may be mounted to the frame **1102** of the robotic apparatus **1101** or the specific tooling may be selectively mounted to the end effector **128** of one or more bots **120**.

[0563] The robotic automotive service system **1100** is preferably capable of and configured to be fully autonomous so as to perform various tire servicing procedures/operations without human intervention; however, the robotic automotive service system **1100** may also be operated manually or semi-autonomously. In the fully-autonomous embodiment, the robotic automotive service system **1100** obtains information about the required service information a via the customer interface **1900** and operator interface **1910**. The system **1100** obtains information about the vehicle **1600** and environment via onboard sensors **1200** and a vision system **1300**, the signals of which are fed back to the electrical panel **1103** where they are distributed to the programmable logic controller **1540**, data acquisition system **1510**, and control computer **1500**. The computer **1500** synthesizes the service information, vehicle information, and environment information into actionable movements and actions for the robotic apparatus **1101** to perform to fulfill the required service conditions. Fully-autonomous refers to the ability of the robotic automotive service system **1100** to complete the service steps, including obtaining any relevant information throughout the process, without human intervention once it has received the initial inputs from the operator.

[0564] In a preferred embodiment of the invention, in fully-autonomous mode, each individual tool on the robotic apparatus **1101** is also fully autonomous.

[0565] Semi-autonomous operation refers to the ability of the robotic automotive service system **1100** to complete the service steps with intermittent input from an operator. In semi-autonomous operation, individual tools on the robotic apparatus **1101** may be fully autonomous, semi-autonomous, manual, or a mix of any and each.

[0566] Manual operation refers to the ability of the robotic automotive service system **1100** to complete the service steps while being controlled by an operator. In manual operation, one or more of the tools on the robotic apparatus **1101** are controlled manually by an operator.

[0567] Service information obtained by the system **1100** may include the type of service being performed (e.g., tire change, passenger rear tire), the make, model, and year of the vehicle, the type of tire being removed and installed, and other relevant information. Vehicle information obtained by the system **1100** may include vehicle position and orientation on the lift, condition and size of the tire to be changed, and overall vehicle condition. Throughout the process, additional information may include the position of the system and tooling relative to the vehicle. Environmental information obtained by the system **1100** may include verifying that no humans are within the work area, that the appropriate tire **1611** has been loaded into the system for replacement, and that there are no obstructions preventing the system **1100** from fulfilling its service.

[0568] The robotic automotive service system **1100** may be operated by hand, via a wired or remote panel on-site, via teleoperation, or by any other means. When operated by hand, one or more axes on the robotic apparatus **1101** of the robotic automotive service system **1100** are physically actuated by an operator via hand or a hand or handheld power tool. When operated via wired communication, the robotic automotive service system **1100** may communicate and be controlled via a wired connection to the electrical panel

1103, a computer **1500**, or other control device accessible by an operator. When controlled via wired connection, any appropriate communication protocol may be used, such as CANOpen, SPI, or I2C. When operated via wireless communication, the robotic automotive service system **1100** may include a wireless gateway and be able to communicate and be controlled via a wireless connection to a wireless gateway to the electrical panel **1103**, a computer **1500**, or other control device accessible by an operator. Such wireless communication may use Bluetooth standard IEEE 802.15.1, WiFi standard IEEE 802.11, or other appropriate wireless protocols.

[0569] The robotic automotive service system **1100** formed in accordance with the present invention may further include and utilize a lift, a lift system **5000** or a lift plate system **5100**, a tire handling system **9000**, a camera positioning system **5200**, a balancing system **3000**, an accelerometer **1240**, **1250** or other sensor, a gantry balancing system **3200**, a roller system **83300**, a suspension support structure system **83400**, a vision system **1300**, a system dynamics modeling system **3600** and the wheel balancing methods and algorithms described herein, each of which will be described in greater detail in the forthcoming paragraphs, and each of which may also be used separately from and independently of the robotic automotive service system **1100** and the other components thereof.

[0570] Making reference to FIG. **128** of the drawings, the lift system **5000**, which is also referenced above as a lift **170**, preferably comprises a lift structure **5010**, a lift actuator **5020**, lift arms **5030**, arm actuators **5040**, lift pads **5051**, lift sensors **5060** and a vision system **1300**. The lift structure includes a base **5064**, which is preferably situated on the ground, an arm plate **5066** and a lifting mechanism **5068**. The lifting mechanism **5068** is interposed between and mechanically coupled to the base **5064** and the arm plate **5066**. The lifting mechanism **5068** includes a lift actuator **5020** that is mechanically coupled to a portion thereof. The lift actuator **5020**, which is preferably formed as a linear actuator and is selectively moveable between at least a first position and a second position, the first position corresponding to a retracted position in which the rod **5070** of the lift actuator is retracted within a cylinder housing **5072** of the lift actuator, and the second position corresponding to an extended position in which the rod of the lift actuator is extended from the cylinder housing of the lift actuator. The lift actuator **5020** may be selectively moved from the first position to the second position to raise the arm plate **5066** outwardly relative to the base **5064**. Similarly, the lift actuator **5020** may be selectively moved from the second position to the first position to lower the arm plate **5066** inwardly relative to the base **5064**.

[0571] Preferably each lift arm **5030** is mechanically coupled to a respective arm actuator **5040**. Each arm actuator **5040** is mounted to the arm plate **5066**. The arm actuators **5040** are preferably linear actuators that are selectively moveable between at least a first position and a second position such that they can move the arm lift arms **5030** towards and away from each. The lift arms **5030** preferably have a sufficient range of movement that enables them to reach the lift points on a variety of vehicles **1600**, such as a bounding box of 2.3 m by 6.1 m. The lift sensors **5060** and the lift pads **5051** are preferably mounted to the lift arms **5030**. The lift sensors **5060** may be load cells **1230**, distance sensors **1221** and/or proximity sensors **1211**, which can detect the force of lifting, distance lifted, and trigger the limits of motion, respectively. In the case of lifting force, the lift sensors are load cells **1230** which are placed in-line with the lift arms **5030** and sense the force applied by the lift arms **5030**. In an alternative embodiment, the load cells **1230** may be placed in line with the lift pads **5051** to sense the force applied by the lift pads **5051**.

[0572] Preferably, the lift structure **5010** and lift pads **5051** are strong enough to lift a vehicle **1600**. The lift pads **5051** may be formed of a material, such as urethane, that will not damage or scratch the vehicle when the lift pads **5051** come in contact with it. As mentioned above, while the lift actuator **5020** and the arm actuators **5040** are preferably linear actuators, such actuators may also be made of motors, ball screws, pneumatic cylinders, hydraulic cylinders, lead screws, rack and pinions, pulley drives, gear drives or any other suitable actuator technology.

[0573] In a preferred embodiment, the lift actuator **5020** and arm actuators **5040** contain sensors for detecting the actuation force, actuation distance, and limits of actuation such as load cells **1230**, distance sensors **1221**, and proximity sensors **1211**, respectively. Load cells **1230** may be placed in line with the actuator arms **5030** or lift pads **5051**. Distance sensors **1221** may be placed on the base **5064** of the lift structure **5010** and sense the distance from that point to the bottom of the lift arms **5030** or vice versa. Proximity sensors **1211** may be placed at the limits of motion on the lift actuator **5020**. Preferably, the vision system **1300** can see the underside of the vehicle **1600** and detect viable lift points thereon. The vision system **1300** preferably has a suitable range of focus to see the underside of the vehicle **1600** when not lifted and when lifted, such as from 25 mm to 230 mm. The processor **1530** is capable of reading and interpreting the data acquired by the lift sensors **5060** and vision system **1300**.

[0574] In operation, the lift system **5000** can scan the underside of the vehicle **1600** before lifting. The vision system **1300** can be used to find suitable lift points on the vehicle. Suitable lift points can be chosen based on manufacturer-recommended lift points, structural analysis based on the vision system **1300** input and processor calculations, machine learning, teaching by the operator, manual positioning by the operator, or by any other means. Once suitable lift points are chosen, the arm actuators **5040** can actuate to position the lift arms **5030** such that the lift pads **5051** are directly underneath the lift points. Once the lift pads **5051** are appropriately positioned, the lift actuator **5020** can actuate to apply force to the lift points via the lift pads **5051** and begin lifting the vehicle **1600**.

[0575] During lifting, the lift sensors **5060** can monitor the lift system **5000** for force, speed, and distance to ensure that the lifting process is safe. This includes keeping the load below the safe limit, the distance between the safe movement limits, and the speed and acceleration within safe limits of the lift system **5000**. These limits can be set by the operator, shop, or manufacturer, and can be set absolutely or based on the vehicle **1600** being lifted.

[0576] Preferably, the lift system **5000** is fully autonomous; however, the lift system **5000** may also be operated manually or semi-autonomously. For example, the lift system **5000** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0577] Making reference to FIG. **129** of the drawings, a lift plate system **5100** may include many of the components

of the lift system **5000** described above, which may be adapted to be used with an existing, non-autonomous, commercial lift **1700**. More specifically, the lift plate system **5100** preferably comprises a commercial lift **1700**, a control adapter **5120**, lift arms **5030**, arm actuators **5040**, lift pads **5051**, lift sensors **5060**, a vision system **1300** and a processor **1530**.

[0578] The lift plate structure **5110** is preferably formed as a rigid metal plate that spans the lift points of a commercial lift **1700**. The lift plate structure **5110** is ideally mounted rigidly and securely to an appropriate location on the commercial lift **1700**. In the case of a commercial lift **1700** with a wide top structure such as a scissor lift, the lift plate structure **5110** may be mounted directly onto the wide top structure.

[0579] Preferably each lift arm **5030** is mechanically coupled to a respective arm actuator **5040**. Each arm actuator **5040** is mounted to lift plate structure **5110**. The arm actuators **5040** are preferably formed as electric motors that are connected to guided ball screws; however, the arm actuators **5040** may alternatively be formed as pneumatic cylinders, hydraulic cylinders, lead screws, rack and pinions, pulley drives, gear drives or any other suitable actuator technology. Preferably, arm actuators **5040** are selectively moveable between at least a first position and a second position such that they can move the arm lift arms **5030** towards and away from each. Generally, the lift arms **5030** are mounted onto the lift plate structure **5110** via the arm actuators **5040** such that the actuating the arm actuators **5040** allow the lift arms **5030** to traverse the width and length of the lift plate structure **5110** for positioning the lift pads **5051** underneath the vehicle **1600**. The lift arms **5030** preferably have a sufficient range of movement that enables them to reach the lift points on a variety of vehicles **1600**, such as a bounding box of 2.3 m by 6.1 m. The lift sensors **5060** and the lift pads **5051** are preferably mounted to the lift arms **5030**. The lift sensors **5060** may be load cells **1230**, distance sensors **1221** and/or proximity sensors **1211**, which can detect the force of lifting, distance lifted, and trigger the limits of motion, respectively.

[0580] In the case of lifting force, the lift sensors are load cells **1230** which are placed in-line with the lift arms **5030** and sense the force applied by the lift arms **5030**. In an alternative embodiment, the load cells **1230** may be placed in line with the lift pads **5051** to sense the force applied by the lift pads **5051**.

[0581] Preferably, the lift plate structure **5110** and lift pads **5051** are strong enough to lift a vehicle **1600**, which may weigh up to 15,000 lbs. The lift pads **5051** may be formed of a material, such as urethane, that will not damage or scratch the vehicle when the lift pads **5051** come in contact with it.

[0582] Preferably, the arm actuators **5040** contain sensors for detecting the actuation force, actuation distance, and limits of actuation such as load cells **1230**, distance sensors **1221**, and proximity sensors **1211** respectively. Load cells **1230** may be placed in line with the actuator arms **5030** or lift pads **5051**. Preferably, the vision system **1300** can see the underside of the vehicle **1600** and detect viable lift points thereon. The vision system **1300** preferably has a suitable range of focus to see the underside of the vehicle **1600** when not lifted and when lifted, such as from 25 mm to 230 mm. The processor **1530** is capable of reading and interpreting the data acquired by the lift sensors **5060** and vision system **1300**.

[0583] With suitable commercial lifts **1700**, the control adapter **5120** is designed to interface with the controls of the commercial lift **1700** to control the actuation of the commercial lift **1700**. Due to the variety in commercial lift controls, the control adapter **5120** may not always be compatible with the commercial lift **1700**, in which case the native actuation controls for the commercial lift **1700** must be used.

[0584] Once the lift pads **5051** are appropriately positioned, the control adapter **5120** can command the commercial lift **1700** to actuate, applying force to the lift points via the lift pads **5051** and begin lifting the vehicle **1600**. Alternatively, where the control adapter **5120** is not compatible with the commercial lift **1700**, manual control of the lift actuation must be performed.

[0585] In operation, the lift system **5100** can scan the underside of the vehicle **1600** before lifting. The vision system **1300** can be used to find suitable lift points on the vehicle. Suitable lift points can be chosen based on manufacturer-recommended lift points, structural analysis based on the vision system **1300** input and processor calculations, machine learning, teaching by the operator, manual positioning by the operator, or by any other means. Once suitable lift points are chosen, the arm actuators **5040** can actuate to position the lift arms **5030** such that the lift pads **5051** are directly underneath the lift points.

[0586] During lifting, lift sensors **5060**, which may include load cells **1230**, distance sensors **1221**, and proximity sensors **1211** can monitor the autonomous lift plate **5100** for force, speed, and distance to ensure that the lifting process is safe. This includes keeping the load below the safe limit, the distance between the safe movement limits, and the speed and acceleration within safe limits of the lift system **5100**. These limits can be set by the operator, shop, or manufacturer, and can be set absolutely or based on the vehicle **1600** being lifted.

[0587] Preferably, the lift system **5100** is fully autonomous; however, the lift system **5100** may also be operated manually by the operator. In this case, the benefits of the autonomous lift plate **5100** over traditional systems are that it is more ergonomic, faster to position the lift pads **5051**, and safer, as the operator isn't required to be underneath the vehicle **1600** at any time.

[0588] Now making reference to FIG. **141** of the drawings, in one form, the tire handling system **9000** preferably comprises a tire handling stand **9010**, a mounting flange **9015**, one or more tire handling arms **9030** and one or more tire handling grippers **9020**. More specifically, the tire handling stand **9010** includes a proximal end **9011** and an oppositely disposed distal end **9013**. A mounting flange **9015** is preferably rotatably mounted to the distal end **9013** of the tire handling stand **9010**. The one or more tire handling arms **9030** are mounted to the mounting flange **9015** and extend outwardly therefrom. Each of the tire handling grippers **9020** is mounted to a free end **9017** of a respective one of the tire handling arms **9030** such that they move with the tire handling arm **9030** as the mounting flange **9015** is rotated. The tire handling system **9000** may further comprise a rotational drive, such as a motor **1400** (not shown), which may be mechanically coupled to the mounting flange **9015** to drive the rotatably drive the mounting

flange **9015** and the arms **9030** and grippers **9020** connected thereto. The motor **1400** may be mounted to the stand **9010**. The tire handling arm **9030** may also be translated linearly by a linear drive, such as a linear actuator **1350** (not shown), which is mounted on the tire stand **9010**. For example, the linear actuator may be interposed between the handling arm **9030** and the mounting flange **9015**.

[0589] The actuators of the tire handling arm **9030** and the motor **1400** may be actuated and controlled so that tire handling grippers **9020** may present a tire to the robotic apparatus **1101** in a way that allows for transfer of the tire from the tire handling system **9000** to robotic apparatus **1101**. In a preferred form, both the robotic apparatus **1101** and tire handling system **9000** communicate with and are powered by the electrical panel **1103** via connectors **1104**. The computer **1500** or PLC **1540** is able to compute the relative positions of the robotic apparatus **1101** and tire handling system **9000** using the known geometry of the systems and sensor feedback such as from distance sensors **1221** mounted on the robotic apparatus **1101**. The tire handling arms **9030** and the motor **1400** may be actuated as previously described to present the tire **1611** to the center point between the various gripper systems **2200** on the robotic apparatus **1101** such that the gripper systems **2200** may be actuated to grip the tire **1611** and remove it from the tire handling gripper **9020**. The reverse is true—the tire handling arms **9030** may be actuated as previously described to present an empty tire handling gripper **9020** to the robotic apparatus **1101** such that the gripper systems **2200** of the robotic apparatus **1101** are able to be actuated to release a tire **1611** while aligned with the empty tire handling gripper **9020** such that the tire **1611** is captured or constrained by the tire handling gripper **9020**. After either unloading or loading a tire **1611** from the tire handling system **9000** onto the robotic apparatus **1101**, the tire handling arms **9030** may be actuated such that they do not obstruct normal operation of the robotic apparatus **1101**.

[0590] The tire handling system **9000** is preferably designed to interface with the robotic automotive service system **1100** or the robotic apparatus **1101** thereof. In the preferred embodiment, the tire handling system **9000** is mounted to the robotic apparatus **1101**. In this regard, the stand **9010** of the tire handling system **9000** is mounted onto the frame **1102** of the robotic apparatus **1101** via welding or fasteners, and is therefore constrained such that when the robotic apparatus **1101** and thus, frame **1102** moves, the tire handling stand **9010** moves with it. In an alternative embodiment of the tire handling system **9000**, the tire handling stand **9010** is designed to be mounted to the floor. In yet another alternative embodiment of the tire handling system **9000**, the tire handling stand **9010** is designed to be mounted overhead of the robotic apparatus **1101** on the frame **1102**.

[0591] In one form, the tire handling grippers **9020** are round and designed to grip the tire on the outside diameter at one or more locations. One or more of the gripper systems **2200** also be mounted to the mounting flange **9015** or tire handling arms **9030** in the manner describe above with respect to the operation of the gripper systems **2200**. In other forms, the tire handling grippers **9020** may grip the tire on the inside diameter using a gripper system **82200** or similar which actuates radially outward from the center point of the tire **1611** such that when the tire handling grippers **9020** contact the inside diameter of the tire **1611** they produce tension that keeps the tire **1611** constrained.

[0592] In alternative embodiments, the tire handling grippers **9020** grip the face of the tire, or at any other point sufficient to grip the tire using a gripper system **82200** or similar, as previously described. In alternative embodiments, the tire handling grippers **9020** may be elliptical, hook shaped, flat, or any other shape or build for adequately handling a tire. In other alternate embodiments, the tire handling arm **9030** may be a single bar, a robotic arm, a series of linear actuators, or any other component or assembly sufficient to mount and/or manipulate the tire handling grippers **9020**.

[0593] An alternate embodiment of the tire handling system **9000**, in which the tire handling arm **9030** is a single bar mounted on a tire handling stand **9010** designed to be mounted upright on the frame of the robotic apparatus **1101**, is shown in FIG. **149** of the drawings. As can be seen in FIG. **149** of the drawings, the tire **1611** is suspended on one tire handling gripper **9020**. A second, unencumbered tire handling gripper **9020** is ready to accept a new or old tire from the robotic apparatus **1101**. In an alternate embodiment of the invention shown in FIG. **149**, the tire handling stand **9010** may be mounted overhead of the robotic apparatus **1101** from the ceiling, an enclosure, or an external mounting frame. In yet another alternate embodiment of the invention shown in FIG. **149**, the tire handling stand **9010** may be free-standing or bolted into the floor or other stable surface in a location accessible by the robotic apparatus **1101**.

[0594] Now making reference to FIG. **88** of the drawings, a balancing system **3000** formed in accordance with one aspect of the present invention preferably comprises at least one sensor **1200**, a sensor mount **3040**, a data acquisition device (DAQ) **1510** and a position sensor **1222**. Embedded circuitry, a computer, an oscilloscope, or any device sufficient to capture a signal from the sensor **1200** may also be used instead of the DAQ **1510**.

[0595] The position sensor **1222** may be an encoder, laser tachometer or other sensor capable of sensing the angular position of an object either directly or indirectly. Preferably, as shown in FIG. **88** of the drawings, the position sensor **1222** tracks the angular position of the TWA **1610** as it rotates about its axis of rotation. The angular position is determined by assigning "0-degree angle" to a datum line on the TWA **1610** (not a physical line, mathematical construct only) and then measuring the angular position of that datum line relative to a fixed line, such as a horizontal line.

[0596] The sensor **1200** may be installed on a sensor mount **3040**, which is then installed on the vehicle **1600**. Alternatively, as shown in FIG. **89** of the drawings, the sensor **1200** may be installed directly on the vehicle **1600** without the addition of a sensor mount **3040**. For example, the sensor **1200** may be formed as an integrated assembly of sensor **1200** and sensor mount **3040**. The sensor **1200** may also consist of a sensor mount **3040** which contains sensors or sensor circuitry to the effect of integrating a sensor **1200** and sensor mount **3040** into a single component. Furthermore, the sensor **1200** and sensor mount **3040** may be manufactured as a single unit.

[0597] Generally, the sensor **1200** is installed on the vehicle **1600** and connected to the DAQ **1510**, which serves to acquire and log signals from the sensor **1200** during operation of the system. During operation, the TWA **1610** and associated rotational assembly, which includes any components on the vehicle **1600** which rotate as the TWA **1610** rotates, such as the vehicle rotor, wheel bearings, and

hub assembly, is rotated. Imbalance manifests in the system in one or more modes: mass imbalance, non-concentricity imbalance, driveline imbalance, or another mode. The sensor **1200** detects such imbalance signals and transmit them to the DAQ **1510**, from which post processing or further transmission of the data can occur.

[0598] FIGS. **88** and **89** of the drawings show an on-car balancing system. The balancing system **3000** formed in accordance with one aspect of the present invention is in the ability to detect imbalance while the TWA **1610** is on the vehicle **1600**. Balancing the TWA **1610** alone using off-vehicle balancing systems compensates only for mass imbalance of the rotational components. Once the TWA **1610** is placed back on the vehicle **1600**, other modes of imbalance (driveline, non-concentricity) can occur, resulting in additional imbalance in the system.

[0599] FIG. **90** of the drawings illustrates a typical imbalance in the TWA **1610** with a set of principal axes shown. Imbalance in the X-Z plane perpendicular to the rotational axis of the TWA **1610** is often called "static imbalance" and results in "wheel hop" where the imbalance force attempts to lift the TWA **1610** off the surface of the road along the Z-Axis. Imbalance out-of-plane of the X-Z plane is often called "dynamic imbalance" and results in "wheel wobble", where the imbalance forces result in a moment reaction that attempts to twist the TWA **1610** about the X-axis. Preferably, the axes of sensitivity of a given sensor **1200** are aligned in the direction of static and dynamic imbalance, which generally results in a larger imbalance signal which can aid in the mitigation of the imbalance.

[0600] Preferably, the balancing system **3000** is fully autonomous; however, the balancing system **3000** may also be operated manually or semi-autonomously. For example, the balancing system **3000** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0601] The balancing system **3000** may be a component of the robotic automotive service system **1100** formed in accordance with the present invention, as well as used independently therefrom. Furthermore, the balancing system **3000** may be utilized in combination with one or more of the other systems, apparatus and algorithms described herein, such as the roller system **83300** and robotic apparatus **1101**.

[0602] A system dynamics modeling system **3600** formed in accordance with one aspect of the present invention is shown in FIG. **142** of the drawings. The system dynamics modeling system **3600** may be used with the balancing system **3000**, as well as the other systems, apparatus and algorithms described herein, to aid in balancing. The system dynamics modeling system **3600** preferably comprises an impulse generator **3610**, a distance sensor **1221**, such as a linear variable differential transformer, a single-axis accelerometer **1240** and a load cell **1230**. Other sensor packages may be used in the system dynamics modeling system **3600**.

[0603] The impulse generator **3610** may be a solenoid, motor, hammer, pendulum or any other device which can generate a relatively fast impulse against the vehicle **1600**. For example, the impulse generator **3610** may be formed as a solenoid which strikes the vehicle suspension **3630** for 100 milliseconds. The impulse generator **3610** is powered by the electrical panel **1103** and is preferably controlled by the PLC **1540**.

[0604] In one form, the system dynamics modeling system **3600** is mounted to the suspension support structure system **83400**, as shown in FIG. **142** of the drawings; however, the system dynamics modeling system **3600** may also be mounted components of the other systems and apparatus described herein. The single-axis accelerometer **1240** is preferably mounted such that it measures the acceleration of the suspension **1630** in response to the impulse produced by the impulse generator **3610**. The distance sensor **1221** is mounted such that it measures the movement of the suspension **1630** in response to the impulse produced by the impulse generator **3610**. Preferably, the distance sensor **1221** is mounted to either the floor or the suspension support structure system **83400** underneath the suspension **1630** and facing upwards such that the distance sensor **1221** measures the distance from the face of the distance sensor **1221** to the suspension **1630**. In a preferred embodiment, the load cell **1230** is mounted such that it measures the load produced by the impulse generator **3610**.

[0605] After the impulse is generated and measured, and the response of the vehicle **1600** is measured, an estimated or actual model of the dynamics of the vehicle **1600** may be produced. This model may be generated using modal analysis, system identification, machine learning, or any other suitable method. Preferably, the impulse response is used to generate the system model. In alternative embodiments, the step response, ramp response, other physics phenomenon, or a combination of several, may be used. The response data may be acquired by a sensor **1200**, such as a multi-axis accelerometer **1250**, load cell **1230**, distance sensor **1221**, or a combination of multiple sensors.

[0606] In an impulse response frequency model, a known force is applied for a known short time (as short as possible) to the system, and the response (usually displacement or acceleration) is detected and recorded. Frequency analysis of the response illustrates the parameters of the system. These parameters can be used in physics models such as the standard "2^{nd}-order spring mass damper" model or in novel physics models. This method is similar for other response tests such as a step response (constant step input). Frequency response analysis is the method by which frequencies of the mechanical response of the system to the input (in this case impulse force) are plotted against the strength of that response.

[0607] Parameters of the system model can be varied and depend on the resolution required, complexity of the system, and many other factors. Furthermore, it is typical of system models to evolve as they are used and as new or more data is acquired. The preferred system parameters are a mass "m" of the suspension **1630** and other moving parts affected by imbalance, the spring constants "k_{1-n}" of any detectable springs in the system (manufactured springs or elastic members), and dampening coefficients "c_{1-n}" of any detectable dampeners in the system (manufactured dampeners, elastic, or viscous members).

[0608] Once the model of the dynamics of the vehicle **1600** is generated, the model may be used to aid in balancing a TWA **1610**, for predictive maintenance on the vehicle **1600**, or for any other purpose. A model represents a simplified version of the system dynamics. For exemplary purposes, the model may aid balancing by comparing the measured imbalance signal by the balancing system **3000** and comparing it to simulated results in the system model, the potential imbalance magnitude and location may be back calculated. The system dynamics modeling system **3600** may be used to generate a catalog of dynamic models of

various vehicles **3600** for later use (such as in a look-up table). The system dynamics modeling system **3600** may also be used real-time on a larger system. Generally, the output mathematical model of the system identification process will be in either a state-space or transfer function representation, as exemplified below:

$$\text{Transfer Function: } \frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)}$$

$$\text{State-Space Model: } \dot{x} = Ax + Buy = Cx + Du$$

[0609] An exemplary frequency response curve generated by the system dynamics modeling system **3600** is shown in FIG. **144** of the drawings. Modal analysis can be used to determine the dynamics of the system for use with balancing systems or for any other purpose.

[0610] Preferably, the system dynamics modeling system **3600** is fully autonomous; however, the system dynamics modeling system **3600** may also be operated manually or semi-autonomously. For example, the system dynamics modeling system **3600** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0611] The system dynamics modeling system **3600** may be a component of the robotic automotive service system **1100** formed in accordance with the present invention, as well as used independently therefrom. Furthermore, the system dynamics modeling system **3600** may be utilized in combination with one or more of the other systems, apparatus and algorithms described herein, such as the roller system **83300** and robotic apparatus **1101**.

[0612] Now making reference to FIG. **111** of the drawings, a vision-based balancing system **3500** formed in accordance with one aspect of the present invention preferably comprises vision system **1300**. The vision system **1300** includes one or more vision-base sensors, such as an analog camera, structured light, LiDAR, or an IR sensor or array.

[0613] The vision system **1300** is roughly aligned with the face of the TWA **1610**. As the TWA **1610** is rotated, for example, by the roller system **83300** or the robotic apparatus **1101**, the vision system **1300** detects any change in position or orientation of the center of rotation, which corresponds to an imbalance. In the preferred embodiment of the present invention, an analog camera is utilized and the change in position described above is detected by analyzing the camera feed to detect the centerline of the TWA **1610** relative to the vision system over time. Similarly, the change in orientation is detected by analyzing the camera feed to detect the inner and outer diameters of the TWA **1610** and calculating their shift over time, which, if the vision system **1300** is stationary would represent a shift in orientation, the value of which can be calculated using rudimentary geometry and trigonometric functions. Nevertheless, similar methods may be used when the other sensors referenced above are utilized by the vision system **1300**. For example, a LiDAR sensor can be used to detect the center position as previously described. LiDAR can measure depth directly and thus detect a change in orientation by directly measuring the relative distance from the top to bottom and left to right edges of the tire, at which point rudimentary trigonometric functions may be used to calculate the orientation. A processor or controller calculates the magnitude and orientation of the imbalance detected by the vision system **1300** and determines the proper actions to be taken for balancing (e.g., the magnitude and locations of the wheel weights to be added).

[0614] The accuracy of the vision system **1300** can be supplemented using fiducials **3510** on the vehicle **1600** or TWA **1610**, as shown in FIG. **112** of the drawings. The fiducials **3510** provide a known reference captured by the vision system **1300** and can be used to calculate distances, orientation, and other features within the image or point cloud captured by the vision system **1300** for use in calibration or measurement.

[0615] An alternative embodiment of the vision-based balancing system **3500** formed in accordance with the present invention is shown in FIG. **113** of the drawings. As can be seen in FIG. **113** of the drawings, the vision-based balancing system **3500** may further include a hollow cone **3520** that is placed on or coupled to the TWA **1610** and beads **3530**. The hollow cone **3520** preferably has a circular or triangular profile; however, the cone **3520** may also have other geometric profiles. The cone **3520** may further include ribs, divets or other features that allow for the beads **3530** to rest in during operation.

[0616] The beads **3530**, which have a known mass, are placed in the cone **3520**. As the TWA **1610** is spinning, the beads **3530** have a tendency, due to friction, normal force, inertia, and other principles of physics, to come to rest at the location in the cone **3520** which would tend to balance the TWA **1610**. During operation (e.g., spinning) the vision system **1300** takes a scan of the distribution of the beads **3530** inside the cone **3520**. Doing so allows for the calculation of the total mass distribution of the beads **3530** and thus, the calculation of the location and magnitude of the resultant mass necessary to balance the TWA **1610**, which by definition also allows for the calculation of the location and magnitude of the initial imbalance in the TWA **1610**.

[0617] More specifically, the vision system **1300** of the vision-based balancing system **3500** scans the cone **3520** and, the vision-based balancing system **3500**, using a computer **1500** or processor **1530**, differentiates empty parts of the cone **3520** to those with beads **3530** in it. The vision system can similarly detect the location of the beads **3530** in three dimensions. Again, the beads **3530** are all of a known mass. Using mathematical processes such as, for example, vectoral addition, the resultant mass and location of the beads **3530** may be calculated. This resultant mass is the representation of the mass and locations of all the beads **3530** at a single point in space. This resultant mass represents the magnitude of the mass and the inverse of the location of the resultant imbalance mass in the TWA **1610** and rotating assembly **1620**.

[0618] Now making reference to FIG. **91** of the drawings, a sensor **1200** formed in accordance with one form of the present invention comprises a multi-axis accelerometer **1250** having three axes. The multi-axis accelerometer **1250** is preferably configured such that all three axes are distinct and orthogonal. Furthermore, the multi-axis accelerometer **1250** preferably has a sensitivity capable of detecting imbalance signals representative of a small mass imbalance (such as 3.5 grams), an effective range which allows it to detect imbalance signals representative of small to large mass imbalances (such as 3.5 grams to 225 grams), and a sampling frequency which allows it to detect signals which manifest relatively quickly (such as 9000 Hz). The multi-

axis accelerometer **1250** may be electrically connected to the DAQ **1510** via a wired connection or wireless connection.

[0619] As can be seen in FIG. **98** of the drawings, the sensor **1200** comprising the multi-axis accelerometer **1250** may be mounted directly on the TWA **1610** of the vehicle with by any sufficiently strong mounting means, such as magnets or adhesive. As shown in FIG. **98** of the drawings, where the multi-axis accelerometer **1250** is mounted directly on the TWA **1610**, the preferred orientation of the multi-axis accelerometer **1250** is such that its principle axes are aligned with the principle axes of the TWA **1610**. In another form, the axes of the multi-axis accelerometer **1250** may be aligned with the axes of imbalance in the TWA **1610**, as shown in FIG. **54** of the drawings. As the TWA **1610** is rotated, any generated imbalance signals would be detected by the multi-axis accelerometer **1250** in greater strength when these axes are aligned.

[0620] In another form of the present invention, the sensor **1200** may comprise one or more single-axis accelerometers **1240**, but preferably comprises at least two single-axis accelerometers **1240**. An exemplary sensor **1200** that comprises three single-axis accelerometers is shown in FIG. **140** of the drawings. More specifically, as can be seen in FIG. **140** of the drawings, which shows a preferred orientation for the sensor mount **3040** and single-axis accelerometers **1240**, the three single-axis accelerometers **1240** are oriented orthogonal to each other on the sensor mount **3040** and the sensor mount **3040** is oriented such that one single-axis accelerometer's **1240** axis is parallel with the rotational axis of the TWA **1610** and one single-axis accelerometer's **1240** axis is parallel to the plane of the wall of the TWA **1610** and in the direction, most closely aligned with gravitational acceleration. The third single-axis accelerometer's **1240** axis is aligned orthogonal to the previous two axes. FIG. **95** of the drawings shows the sensor **1200** with three single-axis accelerometers described above mounted to the suspension **1630** of a vehicle **1600** via a sensor mount **3040** having magnets **3041** attached thereto (due to the orientation of the sensor **1200** and sensor mount **3040** on the suspension **1630**, one of the three single-axis accelerometers is hidden from view).

[0621] As shown in FIG. **96** of the drawings, the sensor **1200** may further comprise an inertial measurement unit (IMU) **1260**. The IMU contains multiple linear accelerometers and a gyroscope capable of measuring changes in orientation via angular acceleration. Accordingly, the IMU **1260** may replace or supplement other accelerometer(s), such as the single-axis accelerometers **1240** and the axis accelerometer **1250**, and a magnetometer **1270** on the sensor **1200**. For example, as shown in FIG. **96** of the drawings, the accelerometers **1240**, **1250** may be replaced with the inertial measurement unit IMU **1260**. The IMU **1260** aids in the orienting of the sensor mount **3040** or sensor **1200**. The IMU **1260** gyroscope may be used to identify or aid in the orientation of the sensor mount **3040** or sensor **1200**. The IMU **1260** can also be used to quantify and compensate mathematically for changes in the orientation of the sensor mount **3040** or sensor **1200** during operation by detecting angular velocity associated with a change in orientation.

[0622] As shown in FIG. **97** of the drawings, the sensor **1200** may further comprise a magnetometer **1270**. The magnetometer **1270** aids in the orienting of the sensor mount **3040** and/or the sensor **1200**. The magnetometer **1270** can also be used to quantify and compensate mathematically for changes in the orientation of the sensor mount **3040** or sensors **1200** during operation by detecting changes in magnetometer **1270** orientation associated with a change in orientation of the sensor mount **3040**. The magnetometer **1270** axis is affected by magnetic fields (i.e., magnetic north or any interfering fields strong-enough to deflect it). By aligning two readings, the magnetometer **1270** axis orientation with the magnetometer **1270** parallel to one axis of the TWA **1610**, and the magnetometer **1270** axis orientation with the sensor mount **3040** installed, the sensor **1200** axes may be aligned with the axes of the TWA **1610** for a preferred installation. The magnetometer **1270** may used in combination with one or more accelerometers **1240**, **1250** and/or IMUS **1260** on the sensor **1200**.

[0623] As can be seen in FIG. **92** of the drawings, the sensor **1200** may further comprise a sensor mount **3040** onto which the single-axis accelerometer(s) **1240**, the multi-axis accelerometer(s) **1250**, the IMU **1260** and or the magnetometer **1270** may be affixed. The sensor mount **3040** includes at least one magnet **3041** which enables it to be affixed to magnetic components of a vehicle **1600**, such as the suspension **1630**, as shown in FIG. **54** of the drawings. Alternatively, or in combination, the sensor mount **3040** may be mounted to a vehicle **1600**, a component of the vehicle or another structure using adhesive, straps, ties, electromagnets, screws, pins, clamps, clips, or other means.

[0624] The sensor mount **3040** may be formed in a variety of different geometries or shapes, depending on the mounting application. More specifically, as can be seen in FIG. **93** of the drawings, the sensor mount **3040** may be formed with a tapered hook-like geometry which allows it to be hooked onto the suspension **1630** and thereby mounted without any additional mounting features. Once hooked, the sensor mount **3040** may be pushed against the suspension in such a way to engage the taper in the hook, affixing the sensor mount **3040** to the suspension **1630** with friction. The mounting pad may be removed by reversing this process.

[0625] Other geometries and methods similar to those shown in FIG. **93** of the drawings exist which allow the sensor mount **3040** to be affixed to the vehicle **1600** without additional mounting features, such as a detent or lever which can affix the sensor mount **3040** to the suspension. The described embodiment should not be taken to be an exclusive means of doing so. Similarly, other geometries and methods like those in FIG. **93** of the drawings exist which allow the sensor mount **3040** to be removed to the vehicle **1600** with or without features, such as a detent or lever that can be depressed to remove the sensor mount **3040**. The described embodiment should not be taken to be an exclusive means of doing so.

[0626] The multi-axis accelerometer **1250** may be powered and communicate with the DAQ **1510** wirelessly or with wires, as generally shown in FIG. **98** of the drawings. Similarly, each of the single-axis accelerometer **1240**, the IMU **1260** and the magnetometer **1270** may be powered and communicate with the DAQ **1510** wirelessly or with wires. Each of the single-axis accelerometer **1240**, the multi-axis accelerometer **1250**, the IMU **1260** and the magnetometer **1270** may be powered via on-board energy storage. Data from each of the single-axis accelerometer **1240**, the multi-axis accelerometer **1250**, the IMU **1260** and the magnetometer **1270** may be acquired and logged into on-board memory and accessed and analyzed after sensing is complete.

[0627] Alternatively, as shown in FIG. **99** of the drawings, a slip ring **3050** may be used to provide power and connectivity between the multi-axis accelerometer **1250** on the rotating assembly and non-rotating components such as the DAQ **1510**. Each of the single-axis accelerometer **1240**, the IMU **1260** and the magnetometer **1270** may also be provided power and connectivity in a similar fashion. Other methods exist for providing this power and connectivity, such as over-the-air power and connectivity.

[0628] Alternative of the embodiment of the inventions of FIGS. **98** and **98** of the drawings is shown in FIG. **100** of the drawings. As can be seen in FIG. **100** of the drawings, the multi-axis accelerometer **1250** is mounted to the TWA **1610** via a sensor mount **3040**. The sensor mount **3040** may provide support for mounting only or for mounting and orienting. Each of the single-axis accelerometer **1240**, the IMU **1260** and the magnetometer **1270** may be mounted in a similar fashion.

[0629] As can be seen in FIG. **101** of the drawings, the multi-axis accelerometer **1250** may mounted to the TWA **1610** via a rim clip **3060**. The rim clip **3060** may be universal or may be profiled to math different wheel profiles. The rim clip **3060** may be removable or permanent. Each of the single-axis accelerometer **1240**, the IMU **1260** and the magnetometer **1270** may be mounted in a similar fashion.

[0630] As can be seen in FIG. **102** of the drawings, the multi-axis accelerometer **1250** may be installed or manufactured in tire pressure monitoring system (TPMS) assembly **3103** of the TWA **1610**. Additionally, the multi-axis accelerometer **1250** can be powered from a battery, capacitor, or other energy storage device. Furthermore, the multi-axis accelerometer **1250** can be self-powered or powered from the motion of the vehicle. Even furthermore, the multi-axis accelerometer **1250** can be solar powered, or powered by other non-contact means. Each of the single-axis accelerometer **1240**, the IMU **1260** and the magnetometer **1270** may be installed or manufactured, and powered, in a similar fashion.

[0631] As can be seen in FIG. **103** of the drawings, an instrumented TPMS assembly **3103** may include a multi-axis accelerometer **1250** with associated amplification, conditioning, logging, and communication functions on an embedded circuit board **1523**.

[0632] There are various embodiments of the sensor **1200** mounted on the vehicle with or without a mounting component (mounting pad, rim clip, etc.). The orientation of the sensors **1200** and the components thereof relative to the TWA **1610** can be important to adequate sensing of the vibration signal during the balancing process. The orientation of the sensors and the components thereof can be achieved by locking the orientation of the sensors relative to the mounting component and then orienting the mounting component itself relative to the TWA **1610**. The orientation of the sensors may also be achieved by attaching the mounting component to the vehicle and then adjusting the orientation of the sensors relative to the mounting component.

[0633] Now making reference to FIG. **104** of the drawings, a gantry system **3200** formed in accordance with the present invention comprises gantry mounting arms **3210**, gantry guide rods **3220**, one or more sensors **1200** and a gantry carriage **3230**. As will be described in greater detail in the forthcoming paragraphs, the gantry system **3200** is mounted to the TWA **1610** and utilized to detect vehicular imbalances caused by the TWA **1610** and other rotational components of the vehicle and to determine the balancing weight magnitude and position required to balance the TWA **1610**. The gantry system **3200** is mountable to the TWA **1610** and may operate with the TWA **1610** both on and off the vehicle. As mentioned above, the gantry system **3200** may operated as a component of the robotic automotive service system **1100** formed in accordance with the present invention, as well as used independently therefrom. Furthermore, the gantry system **3200** may be utilized in combination with one or more of the other systems, apparatus and algorithms described herein, such as the roller system **83300** and robotic apparatus **1101**.

[0634] As can be seen in FIGS. **104**, **105** and **148** of the drawings, the gantry mounting arms **3210** are disposed opposite from one another and interconnected by the gantry guide rods **3220**. Each gantry mounting arm **3210** preferably includes a mount **3211** that extends inwardly therefrom towards the TWA **1610**. The mount **3211** is mechanically coupled to a portion of the TWA **1610** to rigidly clamp the gantry system **3200** to the TWA **1610**. Preferably, the mount **3211** is formed as a hook-like member which clamps on the edge of the rim **1612**. The gantry carriage **3230** includes a plurality of bores **3233** formed through the longitudinal length thereof through which the guide rods **3220** extend such that the gantry carriage **3230** is reciprocatingly slidable on the guide rods **3220**. One or more sensors **1200**, such as a multi-axis accelerometer **1250**, is mounted to the carriage **3230**. The sensor **1200** may also be a single-axis accelerometer **1240**, load cell **1230**, IMU **1260**, magnetometer **1270**, distance sensor **1221**, a position sensor **1222** or any other sensor that is capable of measuring imbalance. The sensor **1200** may also be mounted on a plane adjacent to the TWA **1610** and be aligned to react to imbalances in the system.

[0635] The gantry carriage **3230** may be passive, as shown in FIG. **104** of the drawings, wherein its position and orientation shift in response to loads and moments. The gantry carriage **3230** may also be active, as shown in FIG. **105** of the drawings, in which its position and orientation are controlled by one or more linear actuators **1350** directly. For example, as shown in FIG. **105** of the drawings, one or more linear actuators **1350** may be interposed between the gantry mounting arms **3210** and mechanically coupled to the carriage **3230** and may selectively reciprocatingly move the carriage **3230** along the axial length of the guide rods **3220** bidirectionally. The gantry carriage **3230** may be a combination of active and passive, where active control may be per axis and/or can be turned on or off.

[0636] With a passive gantry carriage **3230**, such as the gantry carriage shown in FIG. **104** of the drawings, as the TWA **1610** is spinning, imbalance will result in the gantry carriage **3230** adjusting relative to the location and magnitude of the imbalance. By measuring the acceleration on the gantry carriage **3230** via the attached multi-axis accelerometer **1250** and/or the position of the gantry carriage **3230**, the imbalance may be sensed and calculated.

[0637] With an active gantry carriage **3230**, such as the gantry carriage **3230** shown in FIG. **54** of the drawings, as the TWA **1610** is spinning, an imbalance moment and/or load will be induced and can be sensed via the attached multi-axis accelerometer **1250** and/or the position of the gantry carriage **3230**. By actively adjusting the position/orientation of the gantry carriage **3230**, it is possible to

minimize the sensed imbalance. This results in a direct measurement of the balancing weight magnitude and position required to balance the TWA **1610** once the gantry system **3200** is removed.

[0638] The gantry system **3200** may also be formed with additional gantry carriages **3230**, guide rods **3220** and other components to expand the system to more axes of movement. This expansion could feasibly enable balancing in multiple axes using the same methodology and invention as described here. An exemplary two-axis gantry system **3200** is shown in FIG. **148** of the drawings. As can be seen in FIG. **148** of the drawings, the sensor (e.g., the multi-axis accelerometer **1250**) is removed from a first gantry carriage **3230**. Additional gantry mounting arms **3210** and gantry guide rods **3220** are mounted onto the first gantry carriage **3230**. A second gantry carriage with a sensor **1200** (e.g., a multi-axis accelerometer **1250**) mounted on it is placed on the second set of guide rods. The first set of guide rods **3220** (i.e., the set that is closer to the TWA **1610**) allow the multi-axis accelerometer **1250** to translate in one direction. The second set of guide rods **3220** allow the multi-axis accelerometer **1250** to translate in a second direction. This same principle can be applied to additional directions of motion. The two-axis gantry system **3200** shown in FIG. **148** of the drawings may also include a linear actuator **1350** and be actively adjusted using a linear actuator **1350** in a similar manner to the active carriage **3230** shown in FIG. **105** of the drawings.

[0639] Now making reference to FIG. **106** of the drawings, a roller system **83300** formed in accordance with the present invention comprises a roller system base **3340**, a roller system frame **3320** and one or more rollers **3310**. The one or more rollers are mounted between roller system bearings **3330** on the frame **3320**, which allows for free rotation about the longitudinal axis of the instrumented roller system rollers **3310**, and are at least partially contained within frame **3320**. The roller system frame **3320** is mounted on the roller system base **3340**. The mounting scheme is such that the roller system frame **3320** can move up and down on the instrumented roller system base **3340**, but is prevented from rotating relative to the instrumented roller system base **3340** via the roller system guide rods **3350**. Preferably, one roller **3310** is rotated by a motor **1400** that is mechanically coupled thereto.

[0640] One or more load cells **1230** may be mounted on the roller system base **3340** such that the roller system frame **3320** sits on the load cells **3230** in normal operation. The roller system frame **3320** is not rigidly fixed to the load cells **1230** or the instrumented roller system base **3340**. As the roller system frame **3320** is able to freely move up and down relative to the roller system base **3340**, the load cell **1230** becomes the only downward restraint on the roller system frame, causing all force in that direction to pass through and be measured by the load cell **1230**.

[0641] The roller system rollers **3310** contact with the tire **1611** of the TWA **1610**. Friction between the roller system rollers **3310** and the tire **1611** causes the TWA **1610** to rotate when the roller system roller **3310** is rotated by the motor **1400**. The position of the roller system is such that there exists a "pre-load" between the roller system rollers **3310** and the tire **1611** when idle. This preload is a compression of the instrumented roller system **83300** into the tire **1611** such that at rest, the load cells **1230** have a load on them. This ensures that the tire **1611** stays in contact with the roller system rollers **3310** and that the load cells **1230** have a non-zero load on them at all times during operation.

[0642] Rotating the TWA **1610** with the instrumented roller system rollers **3310** slowly will induce a signal in the load cell **1230** indicative of the variation in pre-load on the system due to a combination of stiffness variations and eccentricity of the TWA **1610**. Rotating the TWA **1610** with the instrumented roller system rollers **3310** quickly will induce a signal in the load cells **1230** indicative of the variation in pre-load and the imbalance in the rotating assembly **1620**. By subtracting the pre-load signal previously collected from the load cells **1230**, the imbalance signal can be isolated.

[0643] In one form of the instrumented roller system **83300**, the rollers apply a preload to the tire that represents the road force during balancing. This preload is applied in the same way as the normal balancing preload is applied as described above, where the roller system rollers **3310** are pressed into the tire **1611** with some load to apply a preload before balancing. In road force balancing, a load is applied to the tire **1611** that represents the load applied by the road to the tire **1611**. This preload can be used during balancing to better represent the balance during the use-case.

[0644] In another form of the instrumented roller system **83300**, the rolling action of the roller system rollers **3310** against the TWA **1610** is driven by the spokes of the TWA **1610**, lug nut related features of the TWA **1610**, or by any other useful feature for rotating the TWA **1610**. This is accomplished by utilizing a face gripper system **2300** or lug-nut gripper **2350** as described previously, to rotate the TWA **1610**. The gripper used would be driven off the motor **1400** already mounted on the instrumented roller system **83300**. In other embodiments of the instrumented roller system **83300**, the load cells in the roller system are replaced with other sensor types.

[0645] It has been found that on-car balancing of the rotational assembly is complicated by the fact that the rotational assembly is dynamically coupled to the suspension **1630** and structure of the vehicle **1600**. One such coupling that presents a particular challenge is the suspension hard stop which acts as a limit to how far the suspension springs can extend. The suspension hard stop dampens imbalance vibrations during the balancing procedure by absorbing some of the vibratory energy from the suspension **1630**. It has also been found that if the suspension **1630** was lifted off the suspension hard stop during the balancing process, it could increase the strength of an imbalance signal and result in a more successful balancing process.

[0646] More specifically, the suspension hard stop preloads the suspension **1630** and provides a lower bound upon which the suspension **1630** rests when the load of the vehicle **1600** is removed from the suspension **1630**. As such, when the vehicle **1600** is on a lift, the weight of the vehicle **1600** is lifted off the suspension **1630** such that the suspension **1630** is allowed to "relax" and decompress. The hard stop limits how far the suspension **1630** can decompress. This causes the suspension **1630** to rest on the hard stop. The hard stop can affect the vibration of the suspension **1630** during on-vehicle wheel balancing if the suspension **1630** is allowed to rest on the hard stop during the process.

[0647] As can be seen in FIG. **108** of the drawings, in accordance with another aspect of the present invention, a suspension support structure system **83400** preferably comprises a support system base **83410**, which includes a lower

portion **3411** and an oppositely disposed upper portion **3413**, and a support arm **3420**, which is mechanically coupled to the support system base **83410**, in particular, to the upper portion **3413** thereof. The upper portion **3413** of the base **83410** preferably includes a guide rod support plate **3415**. One or more support guide rods **3430**, each having a first end **3425** and an oppositely disposed second end **3427** are interposed between the support plate **3415** and the support arm **3420**. More specifically, the first ends **3425** of the guide rods are mounted the guide rod support plate **3415** and extend upwardly and outwardly from a top surface **3417** thereof towards the support arm **3420**. A support spring **3440** is disposed around each of the support guide rods **3430**.

[0648] The support arm **3420** preferably includes a top surface **3419**, an oppositely disposed bottom surface **83421** and one or more bores **3423** that extend at least partially through therebetween. The second ends **3427** of the guide rods **3430** are received within the bores **3423** in the support arm **3420** and are reciprocatingly moveable therein. Nevertheless, it is also envisioned to be within the scope of the present invention to have the second ends **3427** of the guide rods **3430** mounted to the bottom surface **83421** of the support arm **3420** and be received within bores formed in the support plate **3415**.

[0649] The support arm **3420** is constrained to the support system base **83410** along the plane parallel to the ground by the support guide rods **3430** but is free to move up and down on support guide rods **3430**. The support springs **3440** tend to push or bias the support arm **3420** upwards along the support guide rods **3430** and into the suspension **1630** of a vehicle or other object.

[0650] One or more support adjustable feet **3450** are mounted to the lower portion **3411** of the base **83410** and can be used to raise the support system base **83410**, further compressing support springs **3440** while pushing the support arm **3420** against the suspension **1630**. For example, the support adjustable foot **3450** may include a generally cylindrical base member **3429** and a threaded rod **3431** that extends upwardly therefrom and is received within a correspondingly threaded bore **3433** formed in the lower portion **3411** of the base **83410**. Accordingly, the cylindrical base member **3429** may be selectively rotated to increase or decrease the height of the base **83410**.

[0651] In the configuration of the suspension support structure system **83400** shown in FIG. **108** of the drawings, the sensor **1200** may also be placed on a moving part of the support structure such as the support arm **3420**. Preferably, the sensor **1200** may be a multi-axis accelerometer **1250** which responds to the vibratory acceleration of the suspension **1630** in response to the imbalance induced by rotating the TWA **1610** and the rotational assembly.

[0652] An exemplary block diagram of the state of the suspension **1630** while the sprung suspension support structure **3400** is engaged, such as via the support arm **3420**, is shown in FIG. **109** of the drawings. The suspension support structure system **83400** may be used singularly, in pairs (e.g., front corners, rear corners, driver's side corners, or passenger side corners), or in any other multiple that makes sense (e.g., all four corners).

[0653] It has also been found that, in the case where on-car balancing of the rotational assembly is being accomplished using a sensor that responds to a static signal (i.e., a signal not solely based on the motion of the sensor), a suspension support structure with spring-capability may not provide the most signal strength. For instance, when using a rigid load cell to measure the imbalance signal, very low signal strength will be achieved when the system is able to vibrate. This is because the force of the vibrations will not selectively follow a path through the load cell, but rather distribute among other preferred paths through the vehicle that restrict motion. As such, if a rigid load cell is to be used to measure the imbalance signal, it may be preferred to restrict the motion of the system through the load cell such that the force generated by the imbalance vibrations passes through the load cell, generating a stronger signal.

[0654] A rigid embodiment of the suspension support structure system **83400** described above is shown in FIG. **110** of the drawings. More specifically, in the case where on-car balancing of the rotational assembly is being accomplished using a sensor that responds to a static signal (i.e., a signal not solely based on the motion of the sensor), a suspension support structure with spring-capability may not provide the most signal strength. For instance, when using a rigid load cell to measure the imbalance signal, very low signal strength will be achieved when the system is able to vibrate. This is because the force of the vibrations will not selectively follow a path through the load cell, but rather distribute among other preferred paths through the vehicle that restrict motion. As such, if a rigid load cell is to be used to measure the imbalance signal, it may be preferred to restrict the motion of the system through the load cell such that the force generated by the imbalance vibrations passes through the load cell, generating a stronger signal.

[0655] As can be seen in FIG. **110** of the drawings, the rigid embodiment of the suspension support structure system **83400** further includes a sensor, such as a load cell **1230**, that is affixed to the guide rod support plate **3415** of the base **83410** and is situated underneath the support arm **3420**. A loading screw **3460** is threaded through the support arm **3420** and positioned relative to the sensor **1230** in such a way that it couples the support arm **3420** to the sensor **1230** and can be adjusted to contact the component of the sensor **1230** appropriate for sensing. The loading screw **3460** may be locked into place using jam nut **3470**.

[0656] As described above, the support springs **3440** tend to push or bias the support arm **3420** upwards along the support guide rods **3430** and against the suspension **1630**. The support adjustable feet **3450** can be used to raise the support system base **83410**, further compressing support springs **3440** while pushing the support arm **3420** against the suspension **1630**. Any imbalance during rotation of the TWA **1610** and/or rotational assembly can manifest in the suspension **1630**. Since the hard stop is no longer a pseudo-rigid structure it absorbs less of the vibratory energy of the imbalance. The sensor, which may be a load cell **1230**, responds to the vibratory loads of the suspension **1630** in response to the imbalance induced by rotating the TWA **1610** and the rotational assembly.

[0657] FIG. **150** of the drawings illustrates an alternate embodiment of the suspension support structure system **83400** shown in FIG. **110** of the drawings. In this embodiment, a support clamping plate **3421**A is oriented above the support arm **3420** such that the vehicle suspension **1630** is located between the support clamping plate **3421**A and the support arm **3420**. As can be seen in FIG. **150** of the drawings, clamping screws **3422** which, when rotated, can advance or retract the support clamping plate **3421**A in relation to the support arm **3420**. By advancing the support

clamping plate **3421**A towards the support arm **3420** while a suspension **1630** is between them, the suspension **1630** becomes rigidly captured between the support clamping plate **3421**A and the support arm **3420**. This action serves to isolate the arm of the suspension **1630** from the springs of the suspension. During the balancing process, assuming the suspension support structure system **83400** is rigid such that the arm of the suspension **1630** is unable to vibrate past the point at which it is clamped in the suspension support structure system **83400**, clamping the arm of the suspension **1630** as such causes all vibratory energy in the arm of the suspension **1630** to dissipate via the suspension support structure system **83400** through the support clamping plate **3421**A and the support arm **3420**. The load cell **1630** produces signals from this vibratory energy which, as previously described, can be used to balance the TWA **1610**.

[0658] As can be seen in FIG. **110** of the drawings, vibratory energy from the imbalance can be transmitted through the support arm **3420**, through the loading screw **3460** and into and through the sensor **1230**. A signal is generated by the sensor **1230** in response to the vibratory energy of the imbalance passing through it. That signal is passed to the data acquisition system **1510** and then analyzed by the computer **1500**.

[0659] Now making reference to FIG. **130** of the drawings, in a basic form, the camera positioning system (CPS) **5200** preferably comprises a vision system **1300** and a processor **1530**. The vision system **1300** is in electrical communication with the processor **1530**. The processor **1530** is capable of reading and interpreting the data acquired by the vision system **1300**. In a preferred form, a CPS **5200** system may be mounted to every lift point on the commercial lift **1700**. Each CPS **5200** on the lift **1700** can be controlled by operator controls **5210**. The vision system **1300** is preferably oriented and positioned such that the center of the field of view (FOV) of the vision system **1300** is lined up with the center of the lift pads **5051**.

[0660] In another form, the CPS **5200** may further comprise an arm actuator **5040** for moving the arms on the commercial lift **1700**. The arm actuator **5040** mounts to the arms or lift points of a commercial lift **1700**. The vision system **1300** mounts near the lift pads **5051** of the commercial lift **1700**, facing in the lifting direction. In a preferred embodiment of the invention shown, arm actuators **040** can move the arms of the commercial lift **1700**.

[0661] In an alternate embodiment, the operator controls **5210** contain controls to allow the operator to actuate the lift pads **5051** and lift arms **5030**. An exemplary display on the operator controls **5210** is shown in FIG. **131** of the drawings. As can be seen in FIG. **131** of the drawings, the display on the operator controls **5210**, which contains a display that shows the output of the vision system **1300**, preferably as a live image. The operator controls **5210** display may also display a reticle **5220**, crosshairs, or other aiming device intended to aid the operator in understanding where the center of the lift pads **5051** is. As shown in FIG. **131** of the drawings, the vision system **1300** is lined up with the suspension of the vehicle and the reticle **5220** is overlaid below the suspension spring, illustrating that the lift arm is lined up with that point.

[0662] The operator uses the operator controls **5210** and output of the vision system **1300** to actuate the lift arms **5030** and lift pads **5051** of the commercial lift **1700** to proper lift points on the vehicle **1600**. Once the lift arms **5030** and lift pads **5051** are in the proper location, the operator may use the controls on the commercial lift **1700** or the control adapter **5120** (if compatible and installed) to actuate the commercial lift **1700** up and into the vehicle **1600**, causing it to lift.

[0663] In an alternate embodiment of the invention, the lift arms **5030** are not actuated or not controllable by the operator controls **5210**. In this case, the operator may still use the operator controls **5210** display and vision system **1300** to visualize the lift points under the vehicle **1600**, while the lift arms **5030** and lift pads **5051** are moved into position by another method, such as a manual move or other system. In such alternate embodiment, the operator is not required to look underneath the vehicle **1600** when positioning lift points, saving time, and increasing task ergonomics and safety.

[0664] A method for on-car wheel balancing in accordance with one aspect of the present invention is illustrated in FIG. **114** of the drawings. The method determines balancing weight magnitudes and locations which will offset the imbalance of the TWA **1610** and balance the wheel to below an acceptable threshold. For example, a list of balancing weight magnitudes and locations which will offset the imbalance of the TWA **1610** and balance the wheel to below an acceptable threshold may be generated. The acceptable (or "acceptance") threshold is a bound or set of bounds of sensor data and/or balancing weight mass which indicates that the level of imbalance in the system is below the level that the user states is an acceptable balance. Once a system is below the acceptance threshold, the system is said to be "balanced" or "balanced enough" or "balanced to within tolerance". The method can also generate an imbalance vector, a TWA **1610** displacement reading, or any other suitable output to assist in the balancing process.

[0665] The method for on-car wheel balancing generally includes the following steps:

[0666] 1. Mount the TWA **1610** to the vehicle. This is done in the typical fashion according to the owner's manual of the vehicle.

[0667] 2. Apply sensors and connect DAQ: the sensors could include any of the sensors or sensor systems previously described including a mounted multi-axis accelerometer **1250**, a suspension support structure system **83400** with a load cell **1230**, an instrumented roller system **83300** with a load cell **1230**, vision system **1300**, or any other on-vehicle balancing system.

[0668] 3. Spin up the TWA **1610** to the test speed. The test speed may vary depending on the condition and size of the TWA **1610** and vehicle **1600**, but will generally be between 4 Hz and 20 Hz of rotational speed. Spin-up can be done with a gripper system **82200**, commercial tire spinner **4010**, or other system.

[0669] 4. In the case of a constant speed test, the TWA **1610** is kept at a constant speed for the following step. In the case of a spin-down test, the rotational drive input is removed from the TWA **1610**, which is allowed to begin de-accelerating (spinning down).

[0670] 5. The sensor signal is logged. The time for logging depends on the type of test run and other test conditions as previously described, but is generally between 1 s-60 s in length.

[0671] 6. The sensor data is post processed. This may include filtering of the data, arrangement of the data, reformatting, and other "cleanup steps" before further analysis.

[0672] 7. The post-processed sensor data is fed into the balancing algorithm. This algorithm will further process the data depending on the type of algorithm being used.

[0673] 8. Determining the weight magnitudes and locations of tire weights to be added to the TWA **1610** to balance the rotational assembly, which includes the TWA **1610**, using a balancing algorithm. These equate to the mass of the weights that, when placed at the prescribed locations on the TWA **1610**, will reduce the imbalance sensor data to an acceptable level.

[0674] 9. Outputting the determined weight magnitudes and locations of the tire weights, preferably, in a list of balancing weight magnitudes and locations.

[0675] 10. Determining if the weight magnitudes and locations of the tire weights in the list of balancing weight magnitudes and locations are below acceptable levels. In the preferred method shown, this involves determining whether the resultant magnitude of the weights to be placed is below the acceptance threshold. In an alternative embodiment, this could involve determining whether the expected sensor signal during a future test after placing the recommended weights would be below the acceptance threshold. In an alternative embodiment, this involves repeating the spin test, re-sampling and analyzing sensor data to determine if it is below the acceptance threshold.

[0676] 11. If the weight magnitudes and locations of the tire weights in the list of balancing weight magnitudes and locations are below acceptable levels, then the balancing process ends. If not, in the preferred method shown, the recommended weights are be placed and steps 1-10 are. In an alternative method, the weights could be placed and sensor signal re-analyzed before making a determination (minimum one balancing spin and one verification spin).

[0677] An alternative acceptance criteria for the balancing described above is whether the amplitude add/or intensity of the sensor data or the post processed sensor data is within an acceptable level or outside of an acceptable level.

[0678] An exemplary tire-balancing sensor system is shown in FIG. **107** of the drawings. As can be seen in FIG. **107** of the drawings, the instrumented roller system **83300** is in contact with the TWA **1610**. A commercial tire spinner **4010** is used to spin the TWA **1610** up to the testing angular velocity; however, the TWA **1610** can also be spun with the gripper system **82200**, the roller system **83300** or the robotic apparatus **1101**.

[0679] In a constant speed test, the commercial tire spinner **4010** is kept in contact with the TWA **1610** throughout testing to keep it at a constant angular velocity. In a spin-down test, the commercial tire spinner **4010** might be removed from contact with the TWA **1610** to let it spin-down due to friction during data collection. The spin-down test allows balance data to be collected on the system without interference from the commercial tire spinner **4010**. In doing so, a more accurate balance can be achieved.

[0680] To perform a spin-down test, the commercial tire spinner **4010** is applied to the TWA **1610** and rotated until the TWA **1610** reaches the test angular velocity. The commercial tire spinner **4010** is then removed, and the TWA **1610** begins to de-accelerate (spin-down) due to friction. Data is collected during this time, while the commercial tire spinner **4010** is not in contact with the TWA **1610** and is therefore not affecting the data.

[0681] With respect to FIG. **107** of the drawings, in the context of balancing procedure, the instrumented roller system **83300** is an exemplary tire-balancing sensor system. Other such sensor systems may be used to replace or supplement the instrumented roller system **83300**.

[0682] The curves of a typical case of spin-down versus continuous speed testing are shown in FIG. **116** of the drawings. In the spin-down case, the component that spins the TWA **1610**, such as the commercial tire spinner **4010** shown in FIG. **107** of the drawings, the roller system **83300**, the robotic apparatus **1101** or the gripper system **82200**, is removed from contact with the TWA **1610** after the TWA **1610** is brought up to the testing angular velocity such as 10 Hz (test angular velocity may change depending on vehicle **1600** and TWA **1610** size, type, and conditions), at which point friction in the rotating assembly will cause a negative angular acceleration in the TWA **1610** and eventually cause it to cease rotating. This differs from continuous speed testing in which the angular velocity of the TWA **1610** is kept constant, such as through constant contact with the commercial tire spinner **4010**.

[0683] The method shown in FIG. **114** of the drawings illustrates that the on-car wheel balancing process may be performed using a constant-speed test or a spin-down test. In a constant speed test, the TWA **1610** is driven continuously to maintain a constant speed. In a spin-down test, the driving rotational element is removed from the TWA **1610** and the TWA **1610** is allowed to de-accelerate.

[0684] FIG. **116** also illustrates a typical relationship between rotational frequency and time of the TWA **1610** during a constant speed vs. spin-down test. The benefits of a constant speed test are that the data collected by the sensor **1200** represents imbalance at a constant speed. Analyzing the imbalance as such can potentially accent the relevant signals and provide an easier, faster, and/or more complete balancing recommendation. The benefits of a spin-down test are that the TWA **1610** is not influenced by the tire spinner **4010** or other spinning device, or any factors outside of the dynamics of the vehicle **1600**, which can provide a more accurate balancing recommendation.

[0685] The invention described herein is such that, for any algorithm, sensor type, or other balancing method, a pure constant speed test, pure spin-down test, or combination of the two may be used.

[0686] In all balancing methods described herein, the goal is to achieve the minimum imbalance. The gradient descent method for wheel balancing described in detail below does so in two ways: iteratively and using a fit.

[0687] FIG. **115** of the drawings illustrates an example gradient descent curve for wheel balancing, in which test weights of varying magnitude are placed at various positions on the TWA **1610** for the purposes of finding a local minimum of imbalance.

[0688] In the iterative gradient descent method, the goal is to converge the measured imbalance below some acceptance threshold (e.g., 0.25 oz of total imbalance). The input signal is sent to the data acquisition system **1510** and analyzed by a processor **1530** using the iterative gradient descent

method, which outputs a set of balance weight magnitudes and locations that may lower the measured imbalance in the signal. The system may output these values to an automated system such as the robotic automotive service system **1100**, or the system may output them to an operator.

[0689] Using this output, the recommended weights can be placed, and the process repeated until the measured imbalance drops below the acceptance threshold. An example of the method for recommending weights of the present invention is described below.

[0690] For the purposes of this example, the imbalance on the TWA **1610** is assumed to be at 0-degrees.

[0691] 1. The system has previously determined that the proper balancing weight location is at 180-degrees.

[0692] 2. Referencing FIG. **115** of the drawings, looking at the iterations from left to right, the magnitudes attempted might be 0, 5, 6, 7, 8, 9, 9.5, 9.6, 9.7, 9.8, 10, 10.4, 11, 12, 13, 15 grams, with 9.7 grams being the optimal magnitude.

[0693] 3. If the system were to try 8, 9.7, and 11 grams in order, the shape of the curve would form a "bowl". That is, the measured imbalance would drop from 8 to 9.5 and then increase from 9.5 to 11 grams, indicating that the "minimum" is somewhere between 8 grams and 11 grams.

[0694] 4. The system then attempts 9, 9.6, and 10 grams. Again, a bowl shape is formed, indicating that the minimum is between 9 and 10 grams. Also, the measured imbalance is greater at 9.5 grams than 9.6 grams (results from step 3 and 4), indicating that the minimum is actually somewhere between 9.6 grams and 10 grams.

[0695] 5. Repeating this process will eventually yield the optimal balance of 9.7 grams.

[0696] If an iteration results in an increase in measured imbalance, either the magnitude or location of the recommended weights has advanced past the correct balancing value. Of course, there is an infinite variability in magnitude that may be attempted, so some acceptable resolution (e.g. balanced to 0.2 grams) is needed to limit the criteria for balancing.

[0697] The same process described above works for balancing weight location. FIG. **117** of the drawings illustrates an iterative gradient descent sequence in which the algorithm is run, and balance weights are applied iteratively until an acceptable imbalance has been reached, the steps of which include:

[0698] 1. Sensing data is acquired during a previously-described balance data collection process in FIG. **114**.

[0699] 2. The data is post-processed and analyzed by an algorithm as previously described in FIG. **114**.

[0700] 3. If the output is below the acceptable threshold, the gradient descent process is complete.

[0701] 4. If the output is above the acceptable imbalance threshold, then the gradient descent process repeats. The method of iterating is described above.

[0702] FIG. **118** of the drawings illustrates an alternative iterative gradient descent sequence in which the algorithm runs iteratively without the application of successive balancing weights. In this embodiment, the algorithm adjusts its model based on the input signal and/or its own output to estimate the effect of placing the recommended balance weights before iterating until an acceptable imbalance has been reached, at which point the balance weights are placed on the vehicle.

[0703] FIG. **119** of the drawings illustrates a fit-based gradient descent sequence in which the measured imbalance is compared by the algorithm to a parametrized curve. In the fit-based gradient descent algorithm, the concept of minimizing the imbalance signal is the same as in the iterative version. The main difference is that in the fit-based method, the algorithm builds a parameterized, estimated curve of the input signal versus the actual imbalance. Parameters for this curve could include an estimated suspension stiffness, TWA **1610** stiffness, bearing friction, and more. The input signal is compared to this curve by the algorithm, which then outputs a set of balancing weight magnitudes and locations which it estimates will minimize the actual imbalance reading on this curve. The system may output these values to an automated system such as the robotic automotive service system **1100**, or the system may output them to an operator. Using various methods, the curve parameters may be adjusted to provide more accurate outputs of the algorithm. Examples of curve parameter adjustments include system identification, curve fitting (to previously generated curves), or simulation. Alternatively, an operator may manually adjust the curve parameters during operation.

[0704] FIG. **120** of the drawings illustrates a sample curve-fit for the fit-based gradient descent algorithm.

[0705] Discussing FIGS. **119** and **120** in context of on-vehicle wheel balancing, the fit curves may be built using previous iterative balancing methods to form a curve of best fit between the iterations. Alternatively, the fit curves may be built using another algorithm such as system identification or machine learning. Alternatively, the fit curves may be built using physics models based on estimations or the actual system dynamics using known values (e.g., suspension stiffness, dampener curves, etc.)

[0706] Fit curves represent idealized, modeled, or known imbalance-to-signal curves. They may be generated using mathematical models or simulations. They may also be generated through iterative balancing processes using many iterations and typical curve-fitting processes in the prior art (e.g., linear regression, polynomial fit)

[0707] An example of using curve-fitting with a curve generated by a prior gradient descent is provided below:

[0708] 1. A 2005 Toyota Rav4 comes to a shop for balancing. An operator performs an iterative gradient descent as previously described.

[0709] 2. A second 2005 Toyota Rav4 comes into the shop. This vehicle may have different dynamics than the first one (different condition, mileage, aftermarket work, etc.)

[0710] 3. The balancing system attempts a first iteration for balancing the TWAs of this second Rav4. The point generated by this iteration can be placed on the completed gradient descent curve of the first rav4. Using that completed curve, the system can then estimate what balance weight magnitudes and locations would cause the next iteration point to land on the minimum value of the first, completed curve.

[0711] 4. After performing this second iteration, the point may not land at the minimum value of the first, completed curve, but it may be below the acceptance threshold and thus considered "balanced. Even if that is not the case, it is possible that that second guess, which

was more "educated" than a blind iteration, can accelerate the balancing process compared to the process without access to the first, completed curve. The system may repeat steps 3, 4 to more quickly balance the TWAs **1610**.

[0712] FIG. **121** of the drawings illustrates a system identification (SID) process. SID is the process of constructing a dynamical model from observed data. There are multiple approaches, but in each the user will select the order of the system and potentially also the structure. In the context of on-vehicle wheel balancing, the steps of one embodiment of SID can be described as follows: The sensor **1200** is placed in an appropriate location on the vehicle **1600**. Balance-related data is collected by the sensor **1200** using the constant speed or spin-down process described previously. The collected data is sent to and processed for consumption by a system estimator program on the computer **1500**. The user or system selects a model structure (ARX, ARMAX, Box-Jenkins, etc.) and order based on additional information. The model structure refers to the structure of the equation used to build the model of the system. The order of the model refers to the largest order polynomial in the model. The data set is split into a modeling portion and a validation portion. The modeling portion is then run through the system estimator. Once the estimation is complete, the validation portion of the collected data is run through the resultant model for validation purposes. If the validation is successful, the model may be used for balancing. Successful validation is determined by how well the output of the identified model predicts the validation data. A successful model will closely predict the validation data.

[0713] The model structure selection and model order selection steps of the process may be performed by the system user. In an alternative embodiment, a secondary algorithm may make these selections based on information such as the type of vehicle being balanced, age of the vehicle, type of rims on the TWA **1610**, and other such parameters. In yet another alternative embodiment, the selections may be pre-populated in a list which accounts for these parameters (i.e., if a 2007-2015 pick-up truck with a weight over 1000 kg is being balanced, choose selection 7 from the list).

[0714] A method of using SID for the on-car wheel balancing process is depicted in FIG. **122** of the drawings. As described previously, one of the main challenges with balancing the TWA **1610** on the vehicle **1600** is that unknown vehicle dynamics are at play in the system, making it difficult to produce a mathematical balancing model from the core physics. These unknown dynamics include the unknown spring constant, mass, and dampening coefficient of the suspension, the vehicle lift, and any other components of the vehicle that vibrate or move in response to the wheel imbalance. SID bridges that gap by estimating the model parameters of the vehicle dynamics, producing an approximate model for the system by which the imbalance signal can be processed. The application of SID therefore represents a potentially critical improvement in on-vehicle wheel balancing.

[0715] Further referencing FIG. **122** of the drawings, assuming that the SID model has been completed and validated using the steps previously outlined. FIG. **122** of the drawings outlines a method for using such a model for final on-vehicle balancing. Balance data is collected and post-processed before being fed into the SID model previously produced. The SID model can use this data for calculating the imbalance in the system and recommend balancing weight magnitudes and locations. If the resultant imbalance is below an acceptance threshold, the balancing procedure is done. Otherwise, the balancing weights are applied, and the process is repeated until the resultant imbalance is below the acceptance threshold.

[0716] Further referencing FIG. **122** of the drawings, if the resultant imbalance is below the acceptance threshold, the algorithm may use the input signal, its own output, or both to re-model its parameters or other values and re-run, effectively iterating on the sequence without requiring the physical placement of the recommended balancing weights. The output of the SID model may be fed into a secondary algorithm, such as a physics model for additional processing before outputting balancing weight magnitudes and locations.

[0717] FIG. **123** of the drawings illustrates an example of a machine learning (ML) system architecture for on-vehicle wheel balancing. For this process, meta data is first loaded into the model that contains "ground truth" assertions of a particular model. This metadata is collected by the operator and includes the actual geometry of the TWA **1610**, test spin speed, any test weights applied to the system, and other test data. An example of a ground truth in wheel balancing might be the magnitude and location of a balancing weight the operator has applied to the TWA **1610**. Metadata and "ground truth" data is used for training the ML system.

[0718] In the example of a machine learning (ML) system architecture for on-vehicle wheel balancing shown in FIG. **123** of the drawings, a sensor **1200** is attached to the vehicle **1600**. During the balancing procedure, this sensor **1200** collects data related to the balance of the system. This data is used for feature generation. An example of a relevant feature in the data set could be an amplitude spike at a regular frequency which might indicate an imbalance. Feature generation involves the ML model "looking" mathematically through the training data and choosing features of the data that best differentiate the different variables in the test. In balancing, these variables are usually imbalance magnitudes and locations, and the feature selection would select parts of the data set that illustrate different reactions of the sensor due to varying magnitudes and locations. An example of a relevant feature would be if the peak of the curve of sensor amplitude over frequency at 8 hz showed a distinct pattern that was dependent on the magnitude of imbalance weight, such as a linear relationship where sensor amplitude was 2 units at 5 grams of imbalance and 4 units at 10 grams of imbalance. The ML system would be able to choose the sensor amplitude at 8 hz as a relevant feature for determining imbalance magnitude. The ML model can "guess" at and iterate on relevant features in the data set. This would involve choosing a set of features, building an ML model, and testing that model against validation data. If the validation is unsuccessful, the ML model iterates on a new set of features and retries. This process continues until the model is validated.

[0719] In the example of a machine learning (ML) system architecture for on-vehicle wheel balancing shown in FIG. **123** of the drawings, the features and ground truth data are labeled with the overall data stream. Ground truth data and other meta data is labeled by the operator. Features are labeled by the model once selected. The entire data stream

is then split into three parts: training data, validation data, and test data. An operator may perform the data split, but in general the computer **1500** will perform this operation and train and validate the model over many iterations of splits to reduce the chance of outliers skewing the model. In wheel balancing, this would correspond to imbalance signal data used to train the ML model, different imbalance signal data used to validate that the model can accurately analyze data outside the training set, and a further set of imbalance signal data to verify that the in-use model can recommend the correct balance weight magnitudes and locations for a test system, respectively. In the preferred embodiment, the test data especially (but potentially all data) is taken from a calibrated system where the user can verify that the model outputs are as expected based on the system calibration. An example of this would be to first train the model using a calibrated TWA **1610** with known imbalance masses and locations. If the calibrated TWA **1610** had a known imbalance mass of 20 grams at 90-degrees, the expected output of the ML model would predict that same imbalance (to within some tolerance specified by a model calibration procedure).

[0720] In the example of a machine learning (ML) system architecture for on-vehicle wheel balancing shown in FIG. **123** of the drawings, the production ML model represents an estimated relationship between features and the ground truth. In the wheel-balancing case, this is a relationship between the imbalance signal and the actual imbalance magnitude and location.

[0721] The steps described in FIG. **123** of the drawings are as follows:

[0722] 1. Collect raw data and meta data from testing the system the ML model will be trained on. In the case of on-vehicle balancing, this would mean collecting imbalance signals from a balancing system **2000** using a TWA **1610** with a known imbalance and varying that imbalance magnitude and location across many tests. The metadata is the data describing that data (e.g., imbalance mass, imbalance location, TWA geometry, vehicle type).

[0723] 2. The ML model will generate features as previously described.

[0724] 3. All the test data streams will be labeled and sorted by the ML system according to the metadata and generated features.

[0725] 4. The labeled data is split into training data, validation data, and test data by the ML system, such as into an 85%, 10%, 5% respectively. The data split is commonly iterated on many times and the ML model parameters averaged across the splits to reduce the effect of outliers. These iterations involve taking a different 85%, 10%, and 5% of the data for training, testing, and validating respectively in each iteration.

[0726] 5. The training data is used to tune parameters of the ML model to predict the imbalance. To do so, the ML model compares features in each training data stream to the meta data and ground truth. It then adds weight and coefficients to mathematical parameters (the structure of which depends on the specific ML structure chosen) which form an equation that uses the feature values as inputs to predict the output, which is the imbalance on the system.

[0727] 6. To validate, the newly trained ML model attempts to predict the output of the validation data sets, which it has never "seen" before and has not trained on.

[0728] 7. If the training output is good, the mode is inserted into the final verification step.

[0729] 8. In this verification step, the trained and validated model is checked against the test data to determine how accurately the model can predict this new data.

[0730] 9. If successful, the model goes into the production system, where it takes in raw data and outputs estimates of the system imbalance.

[0731] FIG. **124** of the drawings illustrates an exemplary process of wheel balancing using an ML algorithm after the development of a wheel-balancing based ML model using the process shown in FIG. **123** of the drawings. An imbalance signal is acquired from a vehicle **1600** to be balanced, and the signal is post processed by the processor **1530**. In the preferred model, the post-processing includes a Fourier transform and a low-pass Butterworth filter of a frequency of at least the TWA **1610** rotating frequency. The data is then fed into the ML model, which outputs balancing weight magnitudes and locations. If the output falls below an acceptance threshold, the balance is sufficient. The acceptance threshold has been previously described and is the upper threshold of imbalance considered "acceptable" by the system. If the resultant imbalance is below the acceptance threshold, the algorithm may use the input signal, its own output, or both to re-model its parameters or other values and re-run, effectively iterating on the sequence without requiring the physical placement of the recommended balancing weights. The output of the ML model may be fed into a secondary algorithm such as a physics model for additional processing before outputting balancing weight magnitudes and locations.

[0732] FIG. **125** of the drawings illustrates a method for recovering additional training data for the ML model through customer testing. This allows for continued development and refinement of the ML model while the system is deployed. A key step in this system is the classification model, which is a specialized model that can evaluate whether the system is below the "acceptance" threshold. It is not optimized for determining the absolute value of imbalance or determining the proper balancing procedure, and is specialized for determining whether a system's imbalance is "acceptable".

[0733] The steps to this "classification" method are as follows:

[0734] 1. Collect and train the machine learning model as previously described.

[0735] 2. Collect evaluation data and train a "classification model" following a similar procedure to the ML training.

[0736] 3. Deploy ML and classification model to a production environment.

[0737] 4. Using the ML model, balance TWAs **1610**. During this process, the ML model does not have to be perfect and able to balance any TWA **1610**. Rather, it just has to be able to improve the balance with each iteration.

[0738] 5. After running the ML model, perform "mission logic" which is simply the logic for instructing the customer system on where to place balance weights on the TWA **1610** along with other operational steps.

[0739] 6. After customer installation of the balance weights, the classification model is used to determine if

the system is at "acceptable" levels of imbalance. If false, the system repeats steps 4-6. If true:

[0740] 7. The balance iteration details and ML features are exported to a customer data pool. The data includes the value of the ML features used in balancing, the magnitude and location of each iteration of balance weights, and the output of the classification model after each iteration.

[0741] 8. The customer data pool is split into training and evaluation data. This data is added to the existing training and evaluation data and is used to train the ML and classification models.

[0742] As the customer data pool grows, the ML and classification models will improve (it is typical of mathematical models to improve with larger data sets). Periodically, new versions of the ML and classification models may be released to the customer system to improve the production process.

[0743] In one or more of the embodiments of present invention, data from the process may be post-processed before inputting into the balancing algorithm, such as using moving average filters, band-pass filters, or Fourier Transforms. Alternatively, the algorithm may be fed raw (not post-processed) data.

[0744] Additionally, in one or more of the embodiments of the present invention, multiple algorithms may be combined in parallel, series or a combination of both. For example, an iterative gradient descent may be used to generate the initial training data for a machine learning algorithm. A system identification and ML algorithm may be used to generate system parameters in parallel to improve the likelihood of good feature generation. An ML model may be generated and used to reduce the number of iterations required in a curve-fit gradient descent.

[0745] Furthermore, in one or more of the embodiments of the present invention, the output of the algorithm may be post-processed.

[0746] Even furthermore, in one or more of the embodiments of the present invention, the algorithm may be run multiple times on the same data or on each output to iterate on a solution, check the consistency of a solution, for training, or for any other purpose.

[0747] Additionally, in one or more of the embodiments of the present invention, a system dynamics modeling system **3600** or similar system dynamics estimation, measuring, or calculation system may be used to supplement the algorithms and methods discussed.

[0748] As described above, vehicle dynamics present a challenge to on-vehicle wheel balancing that can be overcome through proper design of sensing methods and analysis algorithms. When acquiring a signal from sensors placed to detect imbalance, it is inherent that some aspect of that signal will be related to the vehicle dynamics since the rotating imbalanced mass is attached to the rest of the vehicle.

[0749] FIG. **126** of the drawings shows an exemplary diagram of the contents of a typical signal acquired during the wheel balancing process. A portion of the signal is representative of the rotational assembly imbalance, the "imbalance signal". Another portion is the "vehicle dynamics signal" and is affected by a myriad of different parameters that influence the physics of the vehicle response to various inputs. FIG. **126** of the drawings is for illustrative purposes only. Additional physical parameters exist in the vehicle dynamics and imbalance signals, and in the acquired signal itself (i.e., electrical noise). Furthermore, the acquired signal is not usually so neatly disambiguated into its parts—there is some coupling between the vehicle dynamics and the associated imbalance signal and vice versa. The embodiment shown in FIG. **126** of the drawings is exemplary, but non-exhaustive or exclusive.

[0750] The same methods used to extract useful imbalance data from the acquired signal (SID, ML) can be used to identify other phenomena in the same signal. For exemplary purposes only, a mass imbalance in the TWA **1610** would generally be present in the acquired signal at a frequency equal to that of the wheel speed (e.g., if the wheel was spinning 4 times per second, the imbalance signal would be present at 4 Hz). If the wheel bearing on the rotational assembly of that wheel was wearing out, it might present a vibratory signal, or "chatter", at a higher frequency, such as 20 Hz. These two features, a recurring signal at 4 Hz and one at 20 Hz, can be disambiguated using the algorithmic analysis previously discussed.

[0751] FIG. **127** of the drawings illustrates the above example by showing the fast-Fourier transform (FFT) of an acquired signal. The amplitude spike at 4 Hz represents the imbalance, while the one at 20 Hz represents the wheel bearing chatter. This same disambiguation can be achieved through other algorithmic means and analyzed using the wheel-balancing algorithms discussed above. A conclusion that could be made from the disambiguated signal in FIG. **127** of the drawings is that, in addition to having an imbalance in the rotational assembly, the wheel bearing is likely wearing and requires changing as part of a predictive maintenance plan.

[0752] The example in FIG. **127** of the drawings is non-exhaustive. As described in FIG. **126** of the drawings, there are many aspects of the vehicle dynamics that will influence the acquired signal. In accordance with one aspect of the present invention, analyzing the acquired signal through a framework of SID, ML, and other algorithms allows for the disambiguation of aspects of the vehicle dynamics related to maintenance parts. A non-exhaustive list includes:

[0753] Wheel bearing chatter—Bearings need to be changed.

[0754] Loss/Gain in dampening coefficient—Dampener needs changing or tuning.

[0755] Loss in stiffness—Suspension springs are losing their elasticity; Suspension springs need to be changed.

[0756] Increase in signal decay; Higher friction in the system—Rotors need to be serviced, suspension elements need service, wheel bearings need to be serviced.

[0757] As is apparent, predictive maintenance items may be determined using on-vehicle signal acquisition while animating some aspect of the vehicle. The animation method may be rotating the TWA **1610** either in a continuous speed or spin-down manner; however, rotation can be driven by contact with the rotating assembly **1620** with or without a TWA **1610** present.

[0758] Another method of animating the vehicle for use in predictive maintenance is by providing an impulse input (such as a sharp hit with a hammer) to a part of the vehicle **1600** such as the TWA **1610** or the suspension **1630**. The response in the acquired signal of this impact (impulse-response testing) can be fed into modified versions of the algorithms previously discussed for the purposes of predictive maintenance.

[0759] Another method of animating the vehicle for use in predictive maintenance is by pseudo-linear actuation of the suspension by a linear actuator or jackstand like device. Such a device has already been previously described.

[0760] The above methods of animating the vehicle for use in predictive maintenance are non-exhaustive.

[0761] Another aspect of the present invention is the use of a database lookup function for predictive maintenance. An autonomous on-vehicle wheel balancing system collects a myriad of data (the acquired signal) about the dynamics of the vehicle. Over time, enough data per vehicle will be collected to make educated assumptions about the conditions of vehicles being balanced. By analyzing this data using the algorithms previously discussed, a database of features sets can be established which predict required maintenance items based on historical data and changes in the acquired signal over time.

[0762] More specifically, as the balancing system **2000** is utilized, the available balancing signal data pool will increase in size. This data pool will also include features related to predictive maintenance (an example of which is shown in FIG. **127** of the drawings). As the data pool grows, similar signals will repeat. For example, wheel bearing chatter signals may appear in many vehicles with the same issue. As the data pool grows, the difference between a "normal" signal and a "maintenance required" signal will become clearer for a vehicle or subset of vehicles. Furthermore, the maintenance issues represented by the "maintenance required" signal will be further disambiguated (a "wheel bearing chatter" maintenance required signal will look very different than a "rotor scraping" one). A computer **1500** may collect and analyze these signals. As each maintenance issue signal is disambiguated, the properties of that signal are placed into a table along with other meta data (vehicle type, component mileage (e.g., miles since last bearing replacement), environmental conditions). Once this table is generated by the computer **1500**, it is available for use by the system at any time.

[0763] By way of example, the system has determined the signal for wheel bearing chatter in 2014 Toyota Rav4s, along with the most common mileage and environmental conditions associated with this wear. The system may compare an acquired signal to the signal for wheel bearing chatter to determine if maintenance on that component is required. Whether or not that signal is acquired, the system may also determine that maintenance is likely to be required on that component soon and alert the customer or operator.

[0764] The robotic automotive service system **1100** formed in accordance with the present invention and the individual systems, apparatus and methodology used thereby, by be embodied in various forms, such as a self-service station and a mobile service station, and may perform a variety of tire servicing procedures/operations including but not limited to tire alignment, wheel balancing, tire rotation, cleaning, waxing and buffing.

[0765] Making reference to FIG. **135** of the drawings, the robotic automotive service system **1100** formed in accordance with one form of the present invention may be embodied as a self-service station **6200** for tire and vehicle maintenance. The self-service station **6200** preferably comprises a system interface **6210**, an enclosure **1710**, a lift **170**,**1700** or lift system **5000**, and one or more of the robotic apparatus **1101**.

[0766] The system interface **6210** communicates with the electrical panel **1103** and computer **1500** to effect changes to the robotic automotive service system **1100**.

[0767] The enclosure **1710** consists of one or more safety sensors **129**O. These safety sensors **129**O may include lockout switches, light curtains, area scanners, or other sensors which may be utilized for detecting an object or person entering the workspace of the robotic automotive service system **1100**. The safety sensors **129**O communicate with the electrical panel **1103**, computer **1500**, and PLC **1540** and preferably powered by the electrical panel **1103**.

[0768] FIG. **136** of the drawings illustrates an exemplary system interface **6210**, which includes a payment portal, a tire selection screen, and a customer and vehicle information screen; however, other screens may also be incorporated into the system interface **6210** for inputting the information necessary for service.

[0769] The self-service station **6200** is configured such that a customer may drive their vehicle **1600** into the station and onto the lift **170**, **1700** or lift system **5000**. The self-service station **6200** may include a vehicle conveyor (not shown). More specifically, the customer may drive their vehicle **1600** onto a vehicle conveyor. Once the self-service station **6200** senses the customer is clear of the vehicle **1600**, the vehicle conveyor is actuated to move the vehicle **1600** onto the lift **170**, **1700** or lift system **5000**.

[0770] The self-service station **6200** is configured such that once the vehicle **1600** is on the lift **170**, **1700** or lift system **5000**, the enclosure **1710** bars the human from entering, either with a physical barrier or via safety sensors **129**O, which stop the system motion if they detect the presence of a human in the safety area. The safety sensors **129**O may detect the presence of a human by detecting motion or the thermal signature of a human in the space. A more detailed description of the enclosure and safety components thereof was described above.

[0771] Once inside the enclosure **1710**, the vehicle **1600** may be serviced by the robotic automotive service system **1100** according to the customer's selections on the system interface **6210**. The level of service is dependent on the capabilities of the robotic automotive service system **1100**, but may include tire changing, tire rotating, wheel balancing, cleaning, wheel alignment, or any other task of which the Robotic Automotive Service System **1100** is capable.

[0772] When service by the robotic automotive service system **1100** is complete, the vehicle **1600** is allowed to exit the enclosure **1710**. In alternate embodiments, the vehicle **1600** may be boarded and driven out by the customer or moved out by the vehicle conveyor **1720**. The customer's payment method is charged according to the services rendered by the self-service station **6200** and selected by the customer at the system interface **6210**.

[0773] The self-service station **6200** may further include the tire handling system **9000** described herein. The tire handling system **9000** allows the self-service station **6200** to house tires and dispense them to the robotic automotive service system **1100** depending on the customer selection at the system interface **6210**.

[0774] While power to the self-service station **6200** may be provided by an external power source, preferably, power is provided by a generator **6220**, solar panels **6230**, or some other integrated power-production device which allows the station to run without being connected to an external power source. The self-service station **6200** may also be connected

to an existing power grid via another structure, a utility pole, underground utility, the main power panel of another facility, wirelessly powered, or any other method of connecting power from one location to another.

[0775] Preferably, the self-service station **6200** is fully autonomous; however, the self-service station **6200** may also be operated manually or semi-autonomously. For example, the self-service station **6200** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0776] Now making reference to FIG. **137** of the drawings, the robotic automotive service system **1100** formed in accordance with one form of the present invention may be embodied as a mobile service station **6300** for tire and vehicle maintenance. The mobile service station **6300** is similar to the self-service station **6200**. Differences include that the mobile service station **6300** contains additional functionality in the system interface **6210** for maintenance, service, and operation of the robotic automotive service system **1100**. Additionally, the mobile service station **6300** has an operator who can perform additional service steps on the vehicle outside of or in addition to the capabilities of the robotic automotive service system **1100**. In the mobile service station **6300** the operator may drive the vehicle **1600** in and out of the enclosure **1720**.

[0777] Preferably, the mobile service station **6300** is powered by a generator **6220**, solar panels **6230**, or some other integrated power-production device which allows the station to run without being connected to an external power source. Nevertheless, the mobile service station **6300** may also be connected to an existing power grid via another structure, a utility pole, underground utility, the main power panel of another facility, wirelessly powered, or any other method of connecting power from one location to another. FIG. **137** of the drawings shows a preferred embodiment in which the mobile service station **6300** is configured as a vehicle with its own power source and can move between locations without assistance by an external transportation device. In an alternate embodiment, the mobile service station **6300** is configured to be fit onto a flat-bed truck, moving fan, forklift, or other transportation device, and moved to various locations.

[0778] Preferably, the mobile service station **6300** is fully autonomous; however, the mobile service station **6300** may also be operated manually or semi-autonomously. For example, the mobile service station **6300** may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0779] An alternate embodiment of the invention shown in FIG. **135**, is a secondary service bay, which is similar in principle and operation to the self-service station **6200** and the mobile service station **6300**.

[0780] The secondary service bay preferably comprises consists of a point-of-sale interface (POS), an enclosure **1710**, lift **170**, **1700** or lift system **5000**, a system interface **6210** and one or more of the robotic automotive service system **1100**. The enclosure **1710** may be freestanding or part of an existing structure such as a main shop wall or bay. The secondary service bay is used to expand the capabilities of a main shop by adding an additional bay to the main shop operations and also adding an autonomous system to the shop equipment.

[0781] In a preferred form, the secondary service bay is configured to function separately from its main shop and contains its own power panel, safety infrastructure, lighting, heating, ventilation, and cooling. In this way, the secondary service bay only requires a power connection from the main shop or existing utility and doesn't otherwise impose a burden on the main shop infrastructure.

[0782] The secondary service bay can provide any service that the robotic automotive service system **1100** is capable of, such as tire-changing, tire rotation, wheel balancing, wheel alignment, cleaning, or other services. The secondary service bay is also able to accept an operator who can perform additional service steps on the vehicle outside of or in addition to the capabilities of the robotic automotive service system **1100**.

[0783] In a preferred form, the secondary service bay is a freestanding structure that can act as a shop bay outside of the main shop in which the robotic automotive service system **1100** can be installed without taking up an existing bay in the main shop, allowing the main shop to expand on its autonomous operations according to the capabilities of the robotic automotive service system **1100** without having to expend one of its bays to do so.

[0784] In alternate forms, the secondary service bay may be contained in a sea-crate or similar, attached to the main shop, partially attached to the main shop or in any other useful configuration.

[0785] Preferably, the secondary service bay, it is powered by a generator **6220**, solar panels **6230**, or some other integrated power-production device which allows the station to run without being connected to an external power source. Nevertheless, the secondary service bay may be connected to an existing power grid via another structure, a utility pole, underground utility, the main power panel of another facility, wirelessly powered, or any other method of connecting power from one location to another.

[0786] Preferably, the secondary service bay is fully autonomous; however, the secondary service bay may also be operated manually or semi-autonomously. For example, the secondary service bay may be operated by hand, via a wired or remote panel on-site, via teleoperation or by any other means.

[0787] As describe above, the robotic automotive service system **1100** and/or a combination of the individual systems, apparatus and components thereof, as well as the methods and algorithms used thereby, may perform tire servicing operations/procedures, such as tire rotation.

[0788] Making reference to FIG. **132** of the drawings, the robotic automotive service system **1100** includes tooling capable of removing tires **1611** from rims **1612** while the rims **1612** remain on the vehicle **1600**. Expanding the capability of the robotic automotive service system **1100** shown in FIG. **132** of the drawings, a procedure may be provided in which the tires **1611** on the vehicle **1600** are removed from the rims **1612** and rotated in a process similar to wheel rotation in a typical shop. The same tires **1611** may be removed from the rims **1612** and placed on different rims **1612** on the vehicle. This is analogous to a traditional tire rotation in which each entire TWA **1610** is removed from the vehicle **1600** and rotated to different locations and reinstalled. The effect of the rotation is the same—evening out wear on the tires **1611** themselves. The benefits to performing tire rotations using the robotic automotive service system **1100** versus the traditional method are these: the robotic automotive service system **1100** is autonomous and requires much less human effort, labor costs. The provided method is

faster as it uses a robotic automotive service system **1100** and the rims **1612** do not have to be removed from the vehicle for rotation, allowing a shop to perform more rotations.

[0789] As describe above, the robotic automotive service system **1100** and/or a combination of the individual systems, apparatus and components thereof, as well as the methods and algorithms used thereby, may perform tire servicing operations/procedures, such as wheel alignments.

[0790] FIG. **133** illustrates an alignment tool **2800**, which may be a component of the robotic automotive service system **1100**. For example, alignment tool **2800** may comprise or be mounted to a linear actuator **1350** which is in turn mounted on the robotic apparatus **1101**. As can be seen in FIG. **143** of the drawings, the robotic apparatus **1101**, which may be a component of the robotic automotive service system **1100** formed in accordance with the present invention, contains sensors **1200** such as a vision system **1300**. The vision system **1300** measures the orientation of the TWA **1610** relative to the vehicle **1600**, the robotic apparatus **1101**, and the surrounding environment. By scanning the TWAs **1610** with the sensors comprising the robotic apparatus **1101**, measurements of TWA **1610** orientation may be established.

[0791] As can be seen in FIGS. **133** and **134** of the drawings, the robotic apparatus **1101**, in combination with the alignment tool **2800**, can adjust the wheel alignment by sensing the alignment with sensors **1200** or the vision system **1300**, adjusting the alignment with the tire alignment tool **2800**, and iterating until the alignment is within acceptable bounds. Alternatively, the robotic apparatus **1101** can sense the wheel alignment with sensors **1200** or vision system **1300**, and an operator can operate a wrench or tire alignment tool **2800** to manually modify the alignment. The robotic automotive service system **1100** makes the alignment status available to the operator for judging when the alignment is within acceptable bounds.

[0792] Exemplary process steps for utilizing the robotic apparatus **1101** and alignment tool **2800** to align the TWA **1610** of a vehicle **1600** are as follows:

[0793] 1. Using the vision system **1300**, scan the vehicle **1600** to determine the orientation of the TWAs **1610** to the vehicle **1600**. If the orientation (alignment) is out of spec, continue.

[0794] 2. Position the robotic apparatus **1101** such that, when extended, the alignment tool **2800** passes the TWA **1610** and gains access to the alignment screw **1650** of the vehicle **1600**.

[0795] 3. Using the linear actuator **1350** extend the alignment tool **2800** in the transverse direction of the vehicle **1600** until the alignment end effector **2820**, mounted to the alignment arm **2810**, is positioned in front of the alignment screw **1650**.

[0796] 4. Shift the position of the robotic apparatus **1101** in the longitudinal direction such that the alignment end effector **2820** engages the alignment screw **1650**.

[0797] 5. Using the alignment drive system **2830**, rotate the alignment screw **1650** with the alignment end effector **2820**.

[0798] 6. Using the vision system **1300**, scan the vehicle **1600** to determine the orientation of the TWAs **1610** to the vehicle **1600**. If the orientation (alignment) is out of spec, repeat steps 2-6 on the current TWA **1610**.

[0799] 7. If the orientation (alignment) is within spec, repeat steps 2-6 on the other TWA's **1610** of the vehicle **1600**.

[0800] As describe above, the robotic automotive service system **1100** and/or a combination of the individual systems, apparatus and components thereof, as well as the methods and algorithms used thereby, may perform tire servicing operations/procedures, such as cleaning. More specifically, the robotic automotive service system **1100** may utilize the cleaning tool system **2500**. As described above, the cleaning tool system **2500** generally comprises a cleaning arm **2513**, a cleaning end effector **2520**, a cleaning drive system **2530** and a linear actuator **1350**. Preferably, the robotic automotive service system **1100** formed in accordance with the present invention may use sensors **1200** or the vision system **1300** to scan the vehicle **1600** and determine locations on the vehicle **1600** in need of cleaning or buffing. These locations may be determined by color, IR signature, or other means. The robotic automotive service system **1100** may apply the cleaning tool system **2500** at these locations to clean, wax, or buff the vehicle **1600**.

[0801] An exemplary method of using the robotic automotive service system **1100** formed in accordance with the present invention and the individual systems, apparatus and components thereof, as well as the methods and algorithms used thereby, to replace the tire **1611** on a TWA **1610** and then balance the TWA **1610** on a vehicle **1600** is provided below:

Initial Setup

[0802] 1. A technician drives the vehicle **1600** onto the lift **170**, **1700** or lift system **5000**.

[0803] 2. The technician ensures the enclosure **1710** is clear of personnel and that the robotic automotive service system **1100** is in functional condition.

[0804] 3. The technician activates the robotic automotive service system **1100** and the components thereof

[0805] 4. If the robotic automotive service system **1100** is connected to the shop sales infrastructure, it pulls the service information (e.g., service type, vehicle make, model) from that infrastructure. Otherwise, the operator types these values in to the operator interface.

[0806] 5. The robotic apparatus **1101** moves to a TWA **1610** and scans it with the vision system **1300**. The control system uses this information to calculate the position and orientation of the TWA **1610**.

[0807] 6. The robotic apparatus **1101** aligns with the TWA **1610**.

Valve Stem Removal

[0808] 7. The gripper system **82200** grips the TWA **1610**.

[0809] 8. The robotic apparatus **1101** aligns the valve tool system **2700** with the valve stem **1614**, using the gripper system **82200** to rotate the TWA **1610** accordingly.

[0810] 9. The valve tool system **2700** removes the valve stem **1614**, de-inflating the TWA **1610**.

Tire Removal

[0811] 10. The gripper system **82200** grips the TWA **1610**.

[0812] 11. The lubrication tool system **2600** lubricates the TWA **1610** at the curve where the tire **1611** and rim **1612** meet.

[0813] 12. The bead breaker system **2000** engages the TWA **1610**, pushing the bead **1609** of the tire **1611** into the rim from both sides. The gripper system **82200** rotates the tire **1611** relative to the bead breaker system **2000** to affect breaking of the entire front and rear bead **1609** of the tire **1611**.

[0814] 13. The bead breaker system **2000** retracts.

[0815] 14. The bead tool system **82100** engages the TWA **1610**, pulling the tire **1611** from the rim **1612**. The gripper system **82200** rotates the tire **1611** relative to the bead tool system **82100** to affect removal of the entire front bead **1609** of the tire **1611**.

[0816] 15. The bead tool system **82100** retracts.

[0817] 16. The robotic apparatus **1101** retracts with the gripper system **82200** still gripping the tire **1611**, shifting the tire **1611** on the rim **1612** such that the rear bead **1609** of the tire **1611** is pressing against the front edge of the rim **1612**.

[0818] 17. The vehicle-side bead breaker system **2000** pushes the rear of the tire **1611** such that the rear bead **1609** of the tire **1611** is pushed over the front edge of the rim **1612**. The gripper system **82200** rotates the tire **1611** relative to the bead tool system **82100** to affect removal of the entire rear bead **1609** of the tire **1611**.

[0819] 18. The bead tool system **82100** retracts.

[0820] 19. At this point, the tire **1611** is removed from the rim **1612**.

[0821] 20. The robotic apparatus **1101** retracts, bringing the tire **1611** with it inside the grippe system **82200**.

[0822] 21. The tire handling system **9000** removes the old tire **1611** from the robotic apparatus **1101**.

Tire Installation

[0823] 22. The tire handling system **9000** loads a new tire **1611** into the robotic apparatus **1101**.

[0824] 23. The robotic apparatus **1101** re-aligns with the TWA **1610**.

[0825] 24. The robotic apparatus **1611** tilts away from the vehicle **1600** in the pitch direction (across the longitudinal vehicle axis).

[0826] 25. The robotic apparatus advances, slipping the bottom of the tire **1611** onto the rim **1612**.

[0827] 26. The robot-side bead breaker system **2000** engages the tire **1611**, pushing it forward against the rim **1612** at the bottom edge.

[0828] 27. The gripper system **82200** rotates the tire **1611** which, with the continued force from the bead breaker system **2000**, pushes the rear bead **1609** of the tire **1611** over the front edge of the rim **1612**.

[0829] 28. The bead breaker system **2000** retracts.

[0830] 29. The robotic apparatus **1101** tilts to align with the TWA **1610**.

[0831] 30. The robotic apparatus **1101** advances towards the rim **1612**, pushing the tire **1611** towards the rear of the rim until the front edge of the tire **1611** contacts the rim **1612**.

[0832] 31. The robot-side bead breaker system **2000** engages the tire **1611**, pushing it forward against the rim **1612** at the bottom edge.

[0833] 32. The gripper system **82200** rotates the tire **1611** which, with the continued force from the bead breaker system **2000**, pushes the front bead **1609** of the tire **1611** over the front edge of the rim **1612**.

[0834] 33. The bead breaker system **2000** retracts.

[0835] 34. The inflation tool system **2401** inflates the TWA **1610** via the valve stem **1614**.

Wheel Balancing

[0836] 35. The wheel weight application tool removes the wheel weights from the rim **1612**.

[0837] 36. The robotic apparatus **1101** moves the suspension support structure system **83400** underneath the suspension **1630** of the vehicle **1600**.

[0838] 37. The suspension support structure system **83400** engages and compresses the suspension **1630**.

[0839] 38. The gripper system **82200** rotates the TWA **1610** to balancing speed.

[0840] 39. Following the process shown in FIG. **114**, the wheel balance is sensed via the load cell **1230** in the suspension support structure system **83400**.

[0841] 40. If needed, the wheel weight application tool applies wheel weights to the rim **1612**.

[0842] 41. Steps 39-40 are repeated until the balancing process is complete.

Wheel Alignment

[0843] 42. Using the vision system **1300**, scan the vehicle **1600** to determine the orientation of the TWAs **1610** to the vehicle **1600**. If the orientation (alignment) is out of spec, continue.

[0844] 43. Position the robotic apparatus **1101** such that, when extended, the alignment tool **2800** passes the TWA **1610** and gains access to the alignment screw **1650** of the vehicle **1600**.

[0845] 44. Using the linear actuator **1350** extend the alignment tool **2800** in the transverse direction of the vehicle **1600** until the alignment end effector **2820**, mounted to the alignment arm **2810**, is positioned in front of the alignment screw **1650**.

[0846] 45. Shift the position of the robotic apparatus **1101** in the longitudinal direction such that the alignment end effector **2820** engages the alignment screw **1650**.

[0847] 46. Using the alignment drive system **2830**, rotate the alignment screw **1650** with the alignment end effector **2820**.

[0848] 47. Using the vision system **1300**, scan the vehicle **1600** to determine the orientation of the TWAs **1610** to the vehicle **1600**. If the orientation (alignment) is out of spec, repeat steps 43-47 on the current TWA **1610**.

[0849] 48. If the orientation (alignment) is within spec, repeat steps 43-47 on the other TWA's **1610** of the vehicle **1600**.

Vehicle Removal

[0850] 49. A technician lowers the lift **1700** and drives the vehicle **1600** out of the enclosure **1710**.

[0851] A transmission **8000** formed in accordance with another aspect of the present invention, which may be used in conjunction with one or more of the apparatus and/or components described above, such as the robotic apparatus **1101** and the gripper system **82200**, is disclosed below and generally shown in FIG. **138** of the drawings. For example,

the transmission **8000** may mechanically coupled to be inline with the gripper drive **2260**.

[0852] As can be seen in FIG. **138** of the drawings, the transmission **8000** preferably comprises four gears **8010**A-D, two one-way roller bearings **8020**A-B, a drive shaft **8030**, a driven shaft **8040** and a transmission drive system **8050**. Gears **8010**A and **8010**C are aligned with each other. Gears **8010**B and **8010**D are aligned with each other. Gears **8010**C and **8010**D are pressed onto the driven shaft **8040** such that they rotate as one unit. Gears **8010**C and **8010**D cannot move axially relative to the driven shaft **8040**. One-way roller bearings **8020** are pressed into gears **8010**A and **8010**B. The one-way roller bearings **8020**A and **8020**B are positioned on the drive shaft **8030** such that they cannot move axially along the shaft. The one-way roller bearings **8020**A and **8020**B are arranged such that one-way roller bearings **8020**A pressed into gear **8010**A can rotate freely relative to the shaft in the clockwise direction and locks to the shaft in the counterclockwise direction. The one-way roller bearings **8020**A and **8020**B are arranged such that one-way roller bearings **8020**B pressed into gear **8010**B can rotate freely relative to the shaft in the counterclockwise direction and locks to the shaft in the clockwise direction.

[0853] The transmission drive system **8050** can rotate the drive shaft **8030**. When rotating the drive shaft **8030**, gears **8010**A and **8010**C are driven together, and gears **8010**B and **8010**D are driven together. Rotating gear **8010**A clockwise causes gear **8010**C to rotate counterclockwise, rotating gear **8010**B clockwise causes gear **8010**D to rotate counterclockwise, and vice versa.

[0854] When rotating the drive shaft **8030** clockwise, reaction forces from gear **8010**A tend to try to rotate it counterclockwise. The one-way roller bearing **8020**A pressed into gear **8010**A locks in the counterclockwise direction, causing the drive shaft **8030** to apply torque to gear **8010**A and rotate gear **8010**C counterclockwise, causing the driven shaft to rotate counterclockwise.

[0855] When rotating the drive shaft **8030** clockwise, reaction forces from gear **8010**B tend to try to rotate it counterclockwise. The one-way roller bearing **8020**B pressed into gear **8010**B is free to rotate relative to the shaft in the counterclockwise direction, allowing gear **8010**B to freely rotate relative to the drive shaft **8030** and not apply significant torque to gear **8010**D.

[0856] When rotating the drive shaft **8030** counterclockwise, reaction forces from gear **8010**B tend to try to rotate it clockwise. The one-way roller bearing **8020**B pressed into gear **8010**B locks in the clockwise direction, causing the drive shaft **9030** to apply torque to gear **8010**B and rotate gear **8010**D clockwise, causing the driven shaft to rotate clockwise.

[0857] When rotating the drive shaft **8030** counterclockwise, reaction forces from gear **8010**A tend to try to rotate it clockwise. The one-way roller bearing **8020**A pressed into gear **8010**A is free to rotate relative to the shaft in the clockwise direction, allowing gear **8010**A to freely rotate relative to the drive shaft **8030** and not apply significant torque to gear **8010**C.

[0858] The design of the transmission **8000** is such that rotating the drive shaft **8030** clockwise causes one-way roller bearing **8020**A to lock, causing gear **8010**A to drive gear **8010**C, causing the driven shaft **8040** to rotate counterclockwise. At the same time, gear **8010**B is able to freewheel on the one-way roller bearing **8020**B and not provide significant torque to gear **8010**D, preventing the transmission from locking up.

[0859] The design of the transmission **8000** is such that rotating the drive shaft **8030** counterclockwise causes one-way roller bearing **8020**B to lock, causing gear **8010**B to drive gear **8010**D, causing the driven shaft **8040** to rotate clockwise. At the same time, gear **8010**A is able to freewheel on the one-way roller bearing **8020**A and not provide significant torque to gear **8010**C, preventing the transmission from locking up.

[0860] In the two-speed transmission **8000**, gears **8010**A-D may configured such that they are not the same size, producing a mechanical advantage between the gears **8010**A-D and altering the torque-speed relationship between the drive shaft **8030** and the driven shaft **8040**.

[0861] In a preferred form, gears **8010**A and **8010**D are the same size and gears **8010**B and **8010**C are the same size, for example where gears **8010**A and **8010**D are twice the diameter of gears **8010**B and **8010**C. In this configuration, rotating the drive shaft **8030** clockwise, the net gear ratio from the drive shaft **8030** to the driven shaft **8040** is 2:1, causing the driven shaft **8040** to rotate at twice the speed and with half the torque of the drive shaft **8030**. Rotating the drive shaft **8030** counterclockwise, the net gear ratio from the drive shaft **8030** to the driven shaft **8040** is 1:2, causing the driven shaft **8040** to rotate at half the speed and with twice the torque of the drive shaft **8030**.

[0862] In an alternative form of the transmission **8000** shown in FIG. **138**, which is shown in FIG. **139** of the drawings, the gears **8010**A and **8010**D may be of any size. More specifically, one-way roller bearings **8020**A and **8020**B are replaced with electromagnetic locking shaft collars **8060**A and **8060**B.

[0863] Electromagnetic locking shaft collars **8060**A and **8060**B are configured such that when they receive an electrical signal, they lock onto the drive shaft **8030**. When the signal is released, they spin freely on the drive shaft. The electromagnetic locking shaft collars **8060**A and **8060**B can be actuated separately or together.

[0864] In the invention shown in **107**, the electromagnetic locking shaft collars **8060**A and **8060**B may be actuated to cause one set of gears **8010**A and **8010**C or **8010**B and **8010**D to mesh, engage, and drive while the other set spins freely. This produces the same style of motion described in FIG. **138** with a selectable signal, rather than having the motion be controlled by the direction of rotation of the drive shaft **8030**. This allows any direction of rotation to be used while selecting a gear drive from gears **8010**A and **8010**D.

[0865] In other forms of the transmission **8000** formed in accordance with the present invention, gears **8010**A and **8010**D may be replaced with pulleys, magnets, wheels, friction clutches, shafts, pins, balls, or any component able to adequately drive torque between the drive shaft **8030** and the driven shaft **8040**.

[0866] In additional alternative forms of the transmission **8000** formed in accordance with the present invention, one-way roller bearings **8020**A and **8020**B may be clutches, magnets, springs, or any component which is able to lock rotation to the drive shaft **8030** in one direction while rotating relatively freely in the opposite direction.

[0867] In other alternative forms of the transmission **8000** formed in accordance with the present invention, the electromagnetic locking shaft collars **8060**A and **8060**B may be

clutches, magnets, springs, or any component which is able to selectively lock and unlock rotation to the drive shaft **8030**.

[0868] In other alternative forms of the transmission **8000** formed in accordance with the present invention, one-way roller bearings **8020**A and **8020**B and electromagnetic locking shaft collars **8060**A and **8060**B may be installed on the drive shaft **8030** or the driven shaft **8040** or any combination of the two.

[0869] In other alternative forms of the transmission **8000** formed in accordance with the present invention, the electromagnetic locking shaft collars **8060**A and **8060**B may be normally locking, normally free, or any combination of the two.

[0870] In other alternative forms of the transmission **8000** formed in accordance with the present invention, the electromagnetic locking shaft collars **8060**A and **8060**B and the one-way roller bearings **8020**A and **8020**B may have a torque limit at which they begin to slip, limiting torque to the drive shaft **8030**, driven shaft **8040**, or both.

[0871] In other alternative forms of the transmission **8000** formed in accordance with the present invention, any number of gears **8010** may be installed on the drive shaft **8030** and driven shaft **8040**.

[0872] In other alternative forms of the transmission **8000** formed in accordance with the present invention, multiple gear drives and one-way roller bearings **8020**A and **8020**B or electromagnetic locking shaft collars **8060**A and **8060**B combinations may be used which allow the transmission to provide a wider selection of gear ratios.

[0873] In other alternative forms of the transmission **8000** formed in accordance with the present invention, the gears **8010**, one way roller bearings **8020**, and electromagnetic locking shaft collars **8060** may be axially positioned on the drive shaft **8030** and driven shaft **8040** via retaining rings, grooves, shaft collars, pins, set screws, shoulders, or any other component or feature sufficient to prevent movement in the axial direction.

[0874] It should be understood that the foregoing description is only illustrative of the aspects of the present disclosure. Various alternatives and modifications can be devised by those skilled in the art without departing from the aspects of the present disclosure. Accordingly, the aspects of the present disclosure are intended to embrace all such alternatives, modifications and variances that fall within the scope of any claims appended hereto. Further, the mere fact that different features are recited in mutually different dependent or independent claims does not indicate that a combination of these features cannot be advantageously used, such a combination remaining within the scope of the aspects of the present disclosure.

1-30. (canceled)

31. A vehicle component balancing method for on vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components of a vehicle that impart vibrations to the vehicle, the vehicle having a tire wheel assembly, the tire wheel assembly having an axis of rotation and being rotatable about the axis of rotation, the tire wheel assembly having locations thereon onto which one or more tire balancing weights are selectively affixed to balance the one or more of the tire, the wheel, the bearings, the brake components and the vehicle components that impart vibrations to the vehicle, the one or more tire balancing weights having a respective magnitude, wherein one or more of the tire, the wheel, the bearings, the brake components and the vehicle components that impart vibrations of the vehicle generate one or more imbalance signals when the tire wheel assembly is rotated, the method comprising the steps of:

effecting rotation of the tire wheel assembly about its axis of rotation;

providing one or more sensors to measure the one or more imbalance signals;

measuring the one or more imbalance signals with the one or more sensors;

determining, based on the measurements of the one or more sensors and the magnitude of the one or more tire balancing weights, the locations on the tire wheel assembly to affix the one or more tire balancing weights to balance the one or more of the tire, the wheel, the bearings, the brake components and the vehicle components that impart vibrations to the vehicle; and

affixing the one or more tire balancing weights to the determined locations on the tire wheel assembly.

32. A vehicle component balancing method as defined by claim **31**, wherein the step of measuring the one or more imbalance signals with the one or more sensors is conducted during a gradient descent sequence.

33. A vehicle component balancing method as defined by claim **31**, which further comprises the step of:

mounting the one or more sensors to the tire wheel assembly.

34. A vehicle component balancing method as defined by claim **31**, which further comprises the step of:

mounting the one or more sensors to the suspension of the vehicle.

35. A vehicle component balancing method as defined by claim **31**, which further comprises the step of:

providing a gantry system, the gantry system being mountable to the tire wheel assembly, wherein the one more sensors is mounted to the gantry system.

36. A vehicle component balancing method as defined by claim **31**, wherein

the one or more sensors is a vision system.

37. A vehicle component balancing method as defined by claim **31**, wherein

the one or more sensors is one or more of a single-axis accelerometer, a multi-axis accelerometer, a inertial measurement unit and a magnetometer.

38. An instrumented tool for performing tire servicing operations, the instrumented tool being one or more of engageable with an end effector of a robotic system and mountable to a frame of the robotic system, the instrumented tool comprising:

at least one actuator;

a carriage, the at least one carriage being mechanically coupled to a portion of the actuator and being moveable thereon between at least a first position and a second position;

a drive, the drive being mechanically engaged with the at least one actuator and effecting the movement of the carriage between the first position and the second position;

tooling mounted to the carriage; and

one or more sensors, the one or more sensors being mounted to one or more of the at least one actuator, the drive, the carriage and the tooling.

39. An instrumented tool for performing tire servicing operations as defined by claim **38**, wherein the actuator is a linear actuator.

40. An instrumented tool for performing tire servicing operations as defined by claim **38**, wherein the tooling is one of a tire bead breaker tool, a tire alignment tool, a wheel weight installation tool, a wheel weight dispenser, a wheel weight gripper, a valve core installation tool, a valve core removal tool, a wheel cleaning tool, a valve stem tool, a valve stem cap removal tool, a tire deflation tool, a tire mount/dismount tool, a lubrication tool, an inflation tool, a gripper system, a bead tool, a tire balancer, a tire balancing bead dispenser, a lug wrench and a wheel assembly grip.

41. An instrumented tool for performing tire servicing operations as defined by claim **38**, wherein at least one of the one or more sensors is one of a proximity sensor, a distance sensor, a load cell, a travel sensor and a limit sensor.

42. A gripper system for manipulating a tire wheel assembly to perform tire servicing operations, the tire wheel assembly having an axis of rotation and being rotatable about the axis of rotation, the gripper system being one or more of engageable with an end effector of a robotic system and mountable to the robotic system, the gripper system comprising:

one or more grippers that are engageable with at least a portion of the tire wheel assembly;

at least one actuator, the one or more grippers being mechanically coupled to a portion of the actuator; and

at least one drive, the at least one drive being mechanically engaged with the at least one actuator and effecting the movement of the one or more grippers in at least a first direction and a second direction, the first direction being towards the tire wheel assembly and the second position being away from the tire wheel assembly.

43. A gripper system as defined by claim **42**, wherein the gripper has an axis of rotation and is rotatable about the axis of rotation, wherein the gripper system further comprises:

a rotational drive, the rotational drive being mechanically coupled to the gripper and effecting rotation of the gripper about its axis of rotation.

44. A gripper system as defined by claim **43**, wherein the rotational drive effects rotation of the gripper about its axis of rotation in a first direction and a second direction.

45. A gripper system as defined by claim **43**, wherein the rotation of the gripper about its axis of rotation effects rotation of the tire wheel assembly about its axis of rotation.

46. A sensor system for vehicle balancing of one or more of a tire, a wheel, bearings, brake components, and vehicle components of a vehicle that impart vibrations to the vehicle, the vehicle having a tire wheel assembly, the tire wheel assembly having an axis of rotation and being rotatable about the axis of rotation, wherein one or more of the tire, the wheel, the bearings, the brake components and the vehicle components that impart vibrations of the vehicle generate one or more imbalance signals when the tire wheel assembly is rotated, the sensor system comprising:

one or more sensors, the one or more sensors being mechanically coupled to the vehicle, wherein the one or more sensors receive the one or more imbalance signals and measure the one or more imbalance signals;

at least one data acquisition unit, the at least one data acquisition unit being in electrical communication with the one or more sensors; and

one or more of a gripper system and a roller system, the one or more of the gripper system and the roller system effecting rotation of the tire wheel assembly about its axis of rotation.

47. A sensor system for vehicle balancing as defined by claim **46**, wherein the one or more sensors is one or more of a single-axis accelerometer, a multi-axis accelerometer, a inertial measurement unit and a magnetometer.

48. A sensor system for vehicle balancing as defined by claim **46**, wherein the one or more sensors is a vision system.

49. A sensor system for vehicle balancing as defined by claim **46**, which further comprises a gantry system, the gantry system being mounted to the tire wheel assembly, wherein the one or more sensors is mounted to the gantry system.

50. A sensor system for vehicle balancing as defined by claim **46**, wherein the one or more sensors is situated within a tire pressure monitoring system assembly, which is mounted to a portion of the tire wheel assembly.

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