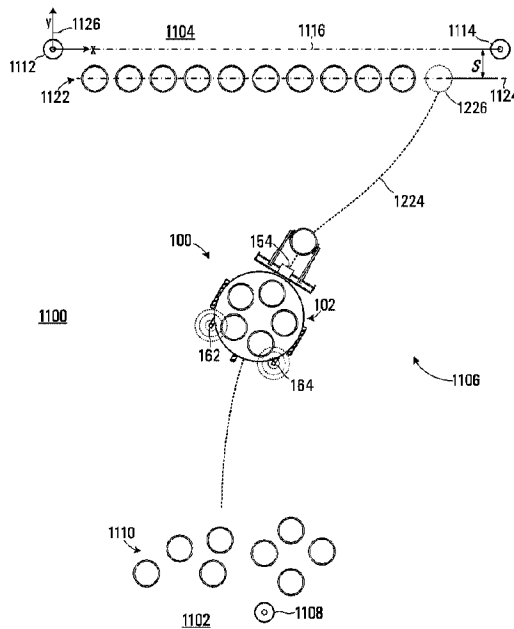




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(54) Title: MOBILE WORK STATION FOR TRANSPORTING A PLURALITY OF ARTICLES



(57) **Abrégé/Abstract:**

A system and method for transporting a plurality of articles between a pickup location and an intended drop-off location is disclosed and includes a wheeled chassis having a pair of transceivers disposed spaced apart on the chassis. The system includes a pickup beacon positioned proximate the plurality of articles at the pickup location, a left and a right drop-off beacon positioned on either side of the drop-off location for indicating a desired alignment of the articles at the drop-off location, each beacon including a transceiver. The transceivers on the beacons and the chassis receive location signals and process signals to determine a location and orientation of the chassis with respect to the beacons for navigating to pick up articles proximate the pickup location, to move to the drop-off location, and to place articles at the drop-off location in aligned relation with respect to the left and right drop-off beacons.

ABSTRACT

A system and method for transporting a plurality of articles between a pickup location and an intended drop-off location is disclosed and includes a wheeled chassis having a pair of transceivers disposed spaced
5 apart on the chassis. The system includes a pickup beacon positioned proximate the plurality of articles at the pickup location, a left and a right drop-off beacon positioned on either side of the drop-off location for indicating a desired alignment of the articles at the drop-off location, each beacon including a transceiver. The transceivers on the beacons and the chassis receive location signals and process signals to determine a location and orientation of the chassis with respect to the beacons for navigating to pick up articles
10 proximate the pickup location, to move to the drop-off location, and to place articles at the drop-off location in aligned relation with respect to the left and right drop-off beacons.

MOBILE WORK STATION FOR TRANSPORTING A PLURALITY OF ARTICLES

BACKGROUND

1. Field

This disclosure relates generally to transporting articles and more particularly to a robotic mobile work station for transporting and performing operations on a plurality of articles.

2. Description of Related Art

Robotic vehicles may be configured for autonomous or semi-autonomous operation for a wide range of applications including product transportation, material handling, security, and military missions. Autonomous mobile robotic vehicles typically have the ability to navigate and to detect objects automatically and may be used alongside human workers, thereby potentially reducing the cost and time required to complete otherwise inefficient operations such as basic labor, transportation, and maintenance. Some autonomous vehicles track movement of driven wheels of the vehicle using encoders to determine a position of the vehicle within a workspace.

SUMMARY

In accordance with one disclosed aspect there is provided a method for transporting a plurality of articles between a pickup location and an intended drop-off location on a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis. The method involves positioning a pickup beacon proximate the plurality of articles at the pickup location, positioning a left drop-off beacon and a right drop-off beacon on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the intended drop-off location, receiving location signals at transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis, processing the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons, navigating the wheeled chassis using the determined location and orientation of the wheeled chassis to pick up successive articles of the plurality of articles proximate the pickup location, move between the pickup location and the drop-off location, and place articles at the drop-off location in an aligned relation with respect to the left and right drop-off beacons.

Receiving the location signals may involve transmitting ultra-wideband (UWB) signals at the transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis, and receiving the UWB signals at the other transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis.

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Navigating may involve using the location signals to determine a real-time location and orientation for steering the wheeled chassis along a path between the pickup location and drop-off location, receiving proximity signals indicative of obstacles in the path of the wheeled chassis, and using the received proximity signals and location signals to modify the path of the wheeled chassis to avoid detected obstacles.

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Receiving the proximity signals may involve generating the proximity signals using at least one of an optical sensor, an infrared sensor, light detection and ranging (LIDAR) sensor, and an ultrasonic sensor.

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Receiving the proximity signals may involve receiving a first proximity signal from an infrared sensor operably configured to indicate close range obstacles, and a second proximity signal from a light detection and ranging (LIDAR) sensor indicating mid and far range obstacles.

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The method of may further involve, when the path of the wheeled chassis is within a pre-determined range of the pickup location, processing the received proximity signals to determine whether the detected obstacles in the path of the wheeled chassis correspond to any of the plurality of articles to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles.

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The method of may further involve, when the path of the wheeled chassis is within a pre-determined range of the drop-off location, causing the wheeled chassis to steer to a first location defined with respect to one of the left drop-off beacon and a right drop-off beacon for unloading of a first article.

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The method may involve causing the wheeled chassis to steer to successive locations defined with respect to the one of the left drop-off beacon and a right drop-off beacon for unloading of a second article and subsequent articles in the plurality of articles.

In accordance with another disclosed aspect there is provided a system for transporting a plurality of articles between a pickup location and an intended drop-off location. The system includes a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis, a pickup beacon positioned proximate the plurality of articles at the pickup location, a left drop-off beacon and a right drop-off beacon positioned on either side of the intended drop-off location. The left and right drop-off beacons indicate a desired alignment of the plurality of articles at the intended drop-off location, each beacon including a transceiver. The transceivers on the beacons and the pair of transceivers on the wheeled chassis are operably configured to receive location signals and process the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons for navigating the wheeled chassis to pick up articles in the plurality of articles proximate the pickup location, to move between the pickup location and the drop-off location, and to place articles in the plurality of articles at the drop-off location in aligned relation with respect to the left and right drop-off beacons.

The transceivers disposed on each beacon and the pair of transceivers on the wheeled chassis may include ultra-wideband (UWB) transceivers.

The system may include at least one proximity sensor disposed on the wheeled chassis, the proximity sensor being operable to provide an indication of obstacles in the path of the wheeled chassis.

The platform may include a plurality of article supports for receiving and supporting the article and the method may involve causing the manipulator to load or unload the first article from a first article support.

Other aspects and features will become apparent to those ordinarily skilled in the art upon review of the following description of specific disclosed embodiments in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate disclosed embodiments,

- 5 Figure **1** is a perspective view of an apparatus for transporting a plurality of articles according to a first disclosed embodiment;
- Figure **2** is a cut-away perspective view of the apparatus shown in Figure **1**;
- 10 Figure **3** is a perspective view of a manipulator of the apparatus shown in Figure **1**;
- Figure **4** is a perspective view of an alternative manipulator embodiment for the apparatus shown in Figure **1**;
- 15 Figure **5** is a partially exploded perspective view of the manipulator shown in Figure **4**;
- Figure **6** is a block diagram of a processor circuit for implementing an on-board controller of the apparatus shown in Figure **1**;
- 20 Figure **7** is a flowchart depicting blocks of code for directing the processor circuit of Figure **6** to control autonomous loading operations of the apparatus shown in Figure **1**;
- Figure **8A to 8E** are a series of plan views of the apparatus shown in Figure **1** performing the loading process shown in Figure **7**;
- 25 Figure **9** is an alternative embodiment of a portion of the process shown in Figure **7**;
- Figure **10** is a flowchart depicting blocks of code for directing the processor circuit shown in Figure **6** to control autonomous unloading operations of the apparatus shown in Figure **1**;
- 30 Figure **11A to 11C** are a series of plan views of the apparatus shown in Figure **1** performing the unloading process shown in Figure **10**;

Figure **12** is a perspective view of an apparatus for transporting a plurality of articles according to an alternative disclosed embodiment;

5 Figure **13** is a plan view of a positioning system for determining a position of the apparatus shown in Figure **1** within an area;

Figure **14** is a flowchart depicting blocks of code for directing a controller to locate arbitrarily positioned beacons of the positioning system shown in Figure **13**; and

10 Figure **15** is a flowchart depicting blocks of code for directing the controller and the processor circuit shown in Figure **6** to locate arbitrarily positioned beacons of the positioning system.

DETAILED DESCRIPTION

Referring to Figure **1**, an apparatus for transporting a plurality of articles according to a first disclosed embodiment is shown generally at **100**. The apparatus **100** includes a wheeled chassis **102**. In the 15 embodiment shown, the wheeled chassis **102** includes a pair of drive wheels **104**, a pair of front castor wheels **106** (only one of each of the pairs of wheels is visible in Figure **1**), and a further rear castor wheel (not visible in Figure **1** but shown at **108** in Figure **2**). The castor wheels **106** and **108** are able to swivel to permit the wheeled chassis **102** to move in a direction determined by the drive provided to the pair of drive 20 wheels **104**. The wheeled chassis **102** has a rounded shape, but in other embodiments may be otherwise shaped.

The apparatus **100** also includes a platform **110** disposed on the wheeled chassis **102**. The platform **110** has an upper surface **112** for receiving a plurality of articles **114** to be transported. In Figure **1**, two articles **116** 25 and **118** of a plurality of articles **114** have been received on the platform **110** and a third article **120** is about to be loaded onto the platform **110**. The apparatus **100** also includes a manipulator **122** coupled to the wheeled chassis **102**. The manipulator **122** has a pair of end effectors **124** and **126** for grasping the article **120**. The movements of the end effectors **124** and **126** are actuated by actuators housed in an actuator housing **152**. In other applications, the pair of end effectors **124** and **126** may be otherwise configured in 30 accordance with the articles to be loaded and unloaded.

In operation, the apparatus **100** is configured to permit successive relative rotational movements between the manipulator **122** and the platform **110** in a direction indicated by the arrow **128**. The successive relative rotational movements provide access for loading each subsequent article in the plurality of articles **114** onto the platform **110** at successive rotationally spaced apart positions. For example, as shown in Figure **1**, the platform **110** has been positioned to permit access to a position **130** for receiving the article **120**. The platform **110** may have a pair of article supports **131** at each position such as shown for the position **130** in Figure **1**.

In the embodiment shown the plurality of articles **114** are plant pots and the apparatus **100** may be used in a plant nursery. Another application of the apparatus **100** may involve transporting blood samples from one location to another within a health care facility.

The apparatus **100** is shown with the platform **110** partially cut away in Figure **2**. Referring to Figure **2**, in this embodiment the apparatus **100** includes a base **132** coupled to the wheeled chassis. The platform **110** includes a gear **134** coupled to an underside **137** of the platform **110**. The gear **134** and platform are mounted via a shaft **138** to the base **132**. The apparatus **100** also includes a platform actuator **140** for providing a rotation torque to a drive gear **136** that meshes with the gear **134**. The platform actuator **140** includes a rotational encoder (not shown) that measures the angular rotation of the platform **110**. In this embodiment the platform actuator **140** is implemented using an electrical motor that generates a torque for causing rotational movement of the drive gear **136**, which in turn causes the gear **134** and the platform **110** to rotate about the shaft **138** in the direction **128** with respect to the base **132**.

In the embodiment shown, the base **132** is also rotatable with respect to the wheeled chassis **102** and includes a gear **142** coupled to the wheeled chassis. The base **132** includes a base actuator **144** having a drive gear **146** that engages with the gear **142**. In this embodiment the base actuator **144** is implemented using an electrical motor that generates a torque for causing rotational movement of the drive gear **146**, which causes the base **132** to rotate about the gear **142**, and thus the wheeled chassis **102**, in a direction indicated by the arrow **148**. The base actuator **144** is mounted to a cover plate **149** (shown partially cut away in Figure **2**) that covers the base **132**. The base actuator **144** includes a rotational encoder **151** for measuring the angular rotation of the base **132**. The cover plate **149**, which is shown cut away in Figure **2**, extends across and covers the base **132** and carries a plurality of rollers (of which a roller **153** is shown in

Figure 2). The rollers are distributed peripherally on the cover plate and support the underside 137 platform 110 during loading, transporting, and unloading operations.

5 In this embodiment, the manipulator 122 is coupled to and moves with the base 132. Since the platform 110 is also coupled to the base 132, the platform will move in the direction 148 when the base moves and relative rotational movements of the platform 110 with respect to the base are actuated by causing the platform actuator 140 to drive the drive gear 136.

10 In other embodiments the platform 110 and base 132 may be independently rotatable relative to the wheeled chassis 102. Alternatively, in some embodiments the base 132 may be fixed to the wheeled chassis and not able to rotate independently of the wheeled chassis 102.

15 In the embodiment shown in Figure 1 and Figure 2 both of the pair of the wheels 104 are independently driven by a hub drive 150. The front castor wheels 106 and rear castor wheel 108 are not driven but rather provide stability for the wheeled chassis 102. In other embodiments the pair of driven wheels 104 may have a common drive and one of the castor wheels 106 and 108 may be steerable.

20 The apparatus 100 also includes a proximity sensor 154, which is operable to provide an indication of obstacles in the path of the wheeled chassis 102. In the embodiment shown the proximity sensor 154 is implemented using an optical light detection and ranging (LIDAR) sensor. Other proximity sensors such as an infrared sensor or ultrasonic sensor may be alternatively or additionally used to implement the proximity sensor 154.

25 The manipulator 122 is shown in isolation in Figure 3 with a cover (shown in Figure 2) of the actuator housing 152 removed to reveal details of actuators for activating movements of the manipulator. Referring to Figure 3, the manipulator 122 includes a frame 300, a pair of endplates 302 and 304. In the embodiment shown, the end effectors 124 and 126 are coupled to respective arms 306 and 308. Each arm 306 and 308 is mounted for rotation on a respective spline shaft 310 and 312. The manipulator 122 also includes an arm actuator 314, which is coupled to the respective spline shafts 310 and 312. The spline shaft 310 extends 30 between a bearing 316 mounted on the endplate 302 and the actuator housing 152 and is coupled to the arm actuator 314. Similarly, the spline shaft 312 extends between a bearing 318 mounted on the endplate 304 and the actuator housing 152 and is also coupled to the arm actuator 314.

The arm actuator **314** is operable to generate a rotational torque on the spline shafts **310** and **312** for causing the arms **306** and **308** to be rotated about the shafts for raising or lowering the respective end effectors **124** and **126**. The arm actuator **314** includes an encoder (not shown) that provides a measurement of the rotational position of the spline shafts **310** and **312** and thus the arms **306** and **308**. In the embodiment shown, the end effectors **124** and **126** are mounted on a pulley belt **320**, which is coupled to between a pulley wheel on the spline shaft **312** (not shown) and a pulley wheel **322**. When the pulley wheel on the spline shaft **312** rotates, the pulley belt **320** causes a corresponding synchronous rotation of the pulley wheel **322** such that the end effector **126** remains in the orientation shown (i.e. generally vertically oriented) when the arm **308** is raised or lowered. The arm **306** is similarly configured.

The manipulator **122** also includes a guide rod **324** extending between the endplate **302** and the actuator housing **152** and a guide rod **326** extending between the endplate **304** and the actuator housing. The arms **306** and **308** are coupled to respective linear guides **328** and **330** that are received on the respective guide rods **324** and **326**. The linear guides **328** and **330** facilitate translational movements of the arms **306** and **308** along the respective guide rods **324** and **326**. The manipulator **122** further includes a leadscrew **332**, a leadscrew **334**, and a translation actuator **336**. The leadscrew **332** extends between a bearing **338** mounted on the endplate **302** and the actuator housing **152** and is coupled to the translation actuator **336**. Similarly, the leadscrew **334** extends between a bearing **340** mounted on the endplate **304** and the actuator housing **152** and is coupled to the translation actuator **336**. Each linear guide **328** and **330** has a leadscrew nut (only the leadscrew nut **342** associated with the guide **328** is visible in Figure 3), which is received on the respective leadscrews for causing translational movement of the linear guides to reduce or increase a lateral distance between the pair of end effectors **124** and **126** for accommodating different sized articles. In this embodiment the leadscrew **332** and leadscrew **334** have opposite thread directions, such that rotation of the respective leadscrews by the translation actuator **336** causes opposite movements of the respective linear guides **328** and **330** along the guide rods **324** and **326**. The translation actuator **336** includes a rotary encoder (not shown) that provides a measurement of the rotational drive provided to the leadscrews **332** and **334**, which is converted into a linear translation distance based on the leadscrew thread pitch.

An alternative manipulator embodiment is shown in Figure 4 at **450**. Referring to Figure 4, the manipulator **450** includes a frame **452**, which attaches to the apparatus **100** via a bracket **454**. The manipulator **450**

includes a pair of arms **456** and **458** having respective end effectors **460** and **462**. Further details of the manipulator **450** are shown in the partially exploded view of Figure 5. Referring to Figure 5, the arms **456** and **458** are similarly configured to the arms **306** and **308** shown in Figure 3, and include a pulley belt **464** coupled to between pulley wheels **466** and **468** for providing synchronous rotation such that the end effectors **460** and **462** maintain their orientation when the arms are raised or lowered.

The manipulator **450** includes pivots **470** and **472** mounted on the frame **452** for pivotably mounting each of the arms **456** and **458**. In Figure 5, the arm **456** is shown removed from the pivot **470** to better show details of the manipulator **450**. The pivot **470** has a vertically extending portion **474** for engaging a channel (not shown) in the pulley wheel **466** such that the pulley wheel is able to rotate freely about the vertically extending portion of the pivot in a direction indicated by the arrow **476**. The manipulator **450** also includes an arm actuator **478** operable to raise or lower the arms **456** and **458** by causing rotation of a shaft **480**, which is coupled to arm mounting brackets **482** and **484**. When the shaft **480** causes the arm **456** to be raised or lowered, the vertically extending portion **474** of the pivot **470** prevents the pulley **466** from rotating and the pulley belt **464** is moved causing a rotational movement to the pulley wheel **468** in proportion to the upward or downward movement of the arm. In this manner, the end effector **460** remains oriented as shown in Figure 4 when the arm is raised or lowered. The arm **458** is configured in the same way.

The manipulator **450** also includes respective stepper motors **486** and **488** for causing lateral rotation of the respective arms **456** and **458**. The stepper motor **488** associated with the arm **458** is shown with an outer covering removed in Figure 5. The stepper motor is coupled via a drive shaft **490** to a beam **492** of the arm **458** and causes lateral rotation of the beam and arm about the drive shaft in a direction shown by the arrow **494**.

The manipulator **450** thus differs from the manipulator **122** in that the arms **456** and **458** are configured for a “pincer” type movement for gripping and releasing articles rather than for a lateral translation as in the case of the arms **306** and **308**.

Referring back to Figure 2, in the embodiment shown the apparatus **100** further includes an on-board controller **160** for autonomously controlling operations of the apparatus. The controller **160** is shown in more detail in Figure 6 and may be implemented using an embedded processor circuit such as a Microsoft

Windows® industrial PC. Referring to Figure 6, the controller **160** includes a microprocessor **400**, a memory **402**, and an input output (I/O) **404**, all of which are in communication with the microprocessor **400**. The I/O **404** includes a wireless interface **406** (such as an IEEE 802.11 interface) for wirelessly receiving and transmitting data communication signals between the controller **160** and a network **408**. The I/O **404** also includes a wired network interface **410** (such as an Ethernet interface) for connecting to the LIDAR proximity sensor **154**. The I/O **404** further includes a USB interface **412** for connecting to a digital to analog converter (DAC) **414** and to ultra-wideband transceivers (UWB) **416** and **417**.

The DAC **414** includes a plurality of ports for receiving analog signals and converting the analog signals into digital data representing the signals and/or producing analog control signals. In the embodiment shown the DAC **414** includes a port **418** for producing control signals for controlling the platform actuator **140**. The rotary encoder of the platform actuator **140** produces a signal indicating a rotational position of the platform **110**, which are received at the port **418**. The DAC **414** also includes a port **420** for producing control signals for controlling the base actuator **144**. The rotational encoder **151** of the base actuator **144** produces a signal indicating a rotational position of the base **132**, which are received at the port **420**. The DAC **414** also includes a port **422** for producing control signals for controlling the arm actuator **314** and a port **424** for producing control signals for controlling the translation actuator **336** of the manipulator **122**. Signals from the encoders associated with the actuators **314** and **336** are received at the respective ports **422** and **424**. The DAC **414** also includes a port **426** for producing control signals for controlling the hub drives **150** of the respective drive wheels **104** for moving and steering the wheeled chassis **102** of the apparatus **100**.

Program codes for directing the microprocessor **400** to carry out various functions are stored in a location **430** of the memory **402**, which may be implemented as a flash memory, for example. The program codes **430** direct the microprocessor **400** to implement an operating system (such as Microsoft Windows for example) and to perform various other system functions associated with operation of the apparatus **100**. The memory **402** also includes variable storage locations **432** for storing variable and parameter data associated with operation of the apparatus **100**.

In other embodiments (not shown), the controller **160** may be partly or fully implemented using a hardware logic circuit including discrete logic circuits, an application specific integrated circuit (ASIC), and/or a field-programmable gate array (FPGA), for example.

Referring to Figure 7, a flowchart depicting blocks of code for directing the controller processor circuit 160 to control autonomous loading operations of the apparatus 100 is shown at 500. The blocks generally represent codes that may be read from the program codes location 430 of the memory 402 for directing the microprocessor 400 to perform various loading functions. The actual code to implement each block may be written in any suitable program language, such as C, C++, C#, Java, and/or assembly code, for example.

A plan view of the apparatus 100 performing the loading process 500 is provided in Figures 8A – 8F as an example of a typical loading operation for the apparatus 100. The loading process 500 starts at block 502, which directs the microprocessor 400 to receive signals produced by the LIDAR proximity sensor 154 at the wired network interface 410 of the I/O 404. Referring to Figure 8A, a plurality of articles to be loaded at a pickup location 602 is shown generally at 604. The LIDAR proximity sensor 154 is operable to detect articles within a range of angles indicated by broken lines 608 and 610 in Figure 8A. In one embodiment, standard dimensions for articles to be loaded are stored in the memory 402 (for example a height H and a width W) and block 502 directs the microprocessor 400 read the H and W values and to determine whether the received LIDAR signals include data that corresponds to these dimensions. Articles that generate LIDAR data signals that generally match the standard dimensions are identified as articles to be loaded at the pickup location 602.

Block 504 directs the microprocessor 400 to output signals at the USB interface 412 of the I/O 404, which cause the DAC 414 to generate wheel drive signals at the port 426 for controlling the respective hub drives 150 of the drive wheels 104. The generated drive signals control the respective hub drives 150 for steering the wheeled chassis 102 toward a first detected article 606 of the plurality of articles 604.

Block 506 then directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 422 for causing the arms 306 and 308 to be positioned for loading by causing the arm translation actuator 336 to translate the arms outwardly to accommodate the width of the detected article. Block 506 also directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 422 for causing the arm rotation actuator 314 rotate the arms 306 and 308 about the spline shafts 310 and 312 until the end effectors 124 and 126 are positioned at height corresponding to the height H of the article 604. Referring to Figure 8B, in this embodiment the when positioned for loading, the arms 306 and 308 are spaced apart at a distance

slightly exceeding the width W of the article **606**, either based on the standard dimensions saved in memory **402** or based on a measured dimension of the article from the LIDAR data.

5 Block **508** then directs the microprocessor **400** to generate wheel drive signals at the port **426** to advance and steer the wheeled chassis **102** to align the arms **306** and **308** such that the respective end effectors **124** and **126** are aligned to grasp the article **606** at diametrically opposing surfaces thereof, as shown in Figure **8B**. Block **510** then directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **422** for causing the arms **306** and **308** to translate inwardly to engage the article **606**.

10 The loading process **500** then continues at block **512**, which directs the microprocessor **400** to determine whether there is a vacant loading position available on the platform **110**. If there is a vacant loading position available (in the example shown in Figure **8B** the platform is empty), then the microprocessor **400** is directed to block **514**. In one embodiment, the number of positions on the platform **110** than can be occupied by articles **604** is determined based on the width W of the articles. A register of the number of
15 positions already filled may also be stored in memory **402** and used by the microprocessor **400** to determine whether there is a vacant position remaining on the platform **110**.

Block **514** directs the microprocessor **400** to cause the DAC **414** to generate platform actuation signals at the port **418** for causing the platform **110** to rotate to align a vacant position **612** (shown in broken outline)
20 behind the arms **306** and **308** of the manipulator **122**. In the example shown in Figure **8B**, since the platform **110** is empty, no rotational movement of the platform is necessary, but if any articles had already been loaded the platform would need to be rotated to align a vacant position behind the arms **306** and **308** of the manipulator **122**.

25 While blocks **512** and **514** are depicted as following sequentially after blocks **502** – **510**, in practice the functions of these blocks may be performed in parallel with other functions. Similarly, the functions of blocks **506** and **510** may also be performed in parallel with functions **504** and **508**.

Block **516** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **422** to
30 cause the the arm rotation actuator **314** to rotate the arms **306** and **308** upwardly about the spline shafts **310** and **312** towards the platform **110** (as shown in broken outline in Figure **8C**) and over the center toward the vacant position **612** on the platform **110**.

Block **518** then directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **424** for causing the arm translation actuator **336** to translate the arms **306** and **308** outwardly to disengage the article **606**, as shown in Figure **8C**. Block **518** also direct the microprocessor **400** to return the arms to the loading position by causing the DAC **414** to output signals for causing the arm actuator **314** to rotate the arms **306** and **308** back to the forward oriented position as shown in Figure **8B**. Block **518** may also cause blocks **512** and **514** to be repeated to cause the platform actuator **140** to rotate the platform **110** to align a vacant position for loading the next article behind the arms **306** and **308** of the manipulator.

The loading process **500** then continues at block **520**, which directs the microprocessor **400** to receive signals produced by the LIDAR proximity sensor **154** at the wired network interface **410** of the I/O **404**. Block **522** then directs the microprocessor **400** to determine whether further articles are detected, in which case block **522** directs the microprocessor back to block **504** to repeat blocks **504** – **512**. If no further articles are detected, then block **522** directs the microprocessor **400** to block **526**, which causes the DAC **414** to generate wheel drive signals at the port **426** for steering the wheeled chassis **102** toward a drop-off location (not shown in Figure **8**).

If at block **512**, there is no vacant loading position on the platform **110**, the microprocessor **400** is directed to block **524**. Block **524** directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **422** for causing the arm actuator **314** to elevate the article **606** off the ground and to hold the article in the arms for transport. Advantageously, even though there are no vacant positions on the platform **110**, an additional article may be carried in the pair of end effectors **124** and **126**. Block **526** then directs the microprocessor **400** to cause the DAC **414** to generate wheel drive signals at the port **426** for steering the wheeled chassis **102** toward a drop-off location (not shown in Figure **8**).

In the process **500** as described above, the platform actuator **140** positions the platform **110** such that successive vacant loading positions on the platform are disposed to receive articles **604**. Additionally or alternatively, the base actuator **144** may be actuated together with the platform actuator **140** at block **506** to facilitate efficient movement of loading of articles. An alternative embodiment of the functions implemented at block **506** is shown in Figure **9**. Referring back to Figure **8C**, following loading of the article **606**, the LIDAR proximity sensor **154** may detect an article **614** in the plurality of articles **604** as the next article to be loaded. Referring to Figure **9**, block **700** directs the microprocessor **400** to cause the DAC **414**

to generate signals for rotating the arms **306** and **306** to a correct loading height H for picking up the article **614** and block **702** directs the microprocessor **400** to cause the DAC **414** to generate signals for translating the arms **306** and **306** to a correct width W for engaging the article **614**.

5 Block **704** then directs the microprocessor **400** to cause the DAC **414** to generate wheel drive signals at the port **426** to move the wheeled chassis toward the article **614**. As shown in Figure **8C**, the wheels remain oriented to move the wheeled chassis **102** in a direction indicated by the arrow **616**. Referring to Figure **8D**, and Figure **9**, block **706** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **420** for causing the base actuator **144** to rotate the base **132** and the attached manipulator **122** in the
10 direction indicated by the arrow **618**. Block **708** then directs the microprocessor **400** to receive proximity signals from the proximity sensor **154** at the wired network interface **410** of the I/O **404**. Block **710** then directs the microprocessor **400** to determine whether the apparatus **100** is aligned for loading of the article **614**. If at block **710** the apparatus **100** is not yet aligned for loading of the article **614**, block **710** directs the microprocessor back to block **704** and blocks **704** – **708** are repeated to perform further movement
15 iterations until at block **710**, it is determined that the apparatus is aligned for loading as shown in Figure **8D**. While blocks **704** and **708** are shown being sequential in Figure **9**, the movement functions could also be performed in parallel. The article **614** is then loaded into a vacant position **620** as described above in connection with blocks **512** – **520** or blocks **524** and **526**. When the platform **110** is rotated to place the vacant position **620** behind the manipulator arms **306** and **308**, the rotation of the base **132** is taken into
20 account and the loading operation thus involves coordinated movements of the wheeled chassis **102**, base **132**, and platform **110**. Block **710** then directs the microprocessor **400** to block **510** of the process **500**, where the microprocessor is directed to cause the DAC **414** to produce signals at the port **422** for causing the arms **306** and **308** to translate inwardly to engage the article.

25 Referring to Figure **8E**, on completion of the process loading process **500**, the platform **110** has **5** of the plurality of articles **604** loaded on the platform **110** and a sixth article **622** held for transport in end effectors **124** and **126**. As described above, block **526** directs the microprocessor **400** to generate wheel drive signals to steer the wheeled chassis toward a drop-off location **624**. In the embodiment shown in Figure **8E**, two articles **626** have already been dropped off at the drop-off location **624**. The on-board
30 controller **160** monitors signals produced by the LIDAR proximity sensor **154** to avoid colliding with any obstacles, such as a forklift truck **628**.

Referring to Figure 10, a flowchart depicting blocks of code for directing the controller processor circuit 160 to control autonomous unloading operations of the apparatus 100 is shown at 800. The process begins at block 802, which directs the microprocessor 400 to receive LIDAR signals from the proximity sensor 154 at the wired network interface 410 of the I/O 404 and to process the signals to detect already unloaded articles at the drop-off location 624.

Two articles 626 have already been unloaded at the drop-off location 624. Block 804 then directs the microprocessor 400 to identify a next open space with respect to the articles 626. Referring to Figure 11A, in the embodiment shown articles are to be spaced apart by a distance D and aligned along a datum line 900. The distance D may be calculated based on the width W of the articles and such that there remains sufficient space between adjacent articles to permit the end effectors 124 and 126 to be maneuvered. The next open space is identified at 902, and block 806 directs the microprocessor 400 to cause the DAC 414 to generate wheel drive signals at the port 426 to cause the wheeled chassis 102 to move toward the next open space 902 and to position the article 622 (held in the end effectors 124 and 126) above the open space. Block 808 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 422 to cause the arms 306 and 308 to rotate to lower the article 622 into the open space 902. Block 808 also directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 424 to translate the arms 306 and 308 outwardly to disengage the article 622.

Block 810 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 422 to cause the arms 306 and 308 to be raised to clear the article. Block 812 then directs the microprocessor 400 to cause the DAC 414 to generate wheel drive signals to orient the wheeled chassis 102 for lateral movement in a direction 904 aligned with the datum line 900 along which the already unloaded articles 626 and 622 are aligned. Block 814 then directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 420 to cause the base actuator 144 to rotate the base 132 to re-orient the manipulator 122 toward the articles 626 as shown in Figure 11B. Block 814 further directs the microprocessor 400 to cause the DAC 414 to generate signals at the port 418 to cause the platform actuator 140 to rotate the platform 110 in a direction indicated by the arrow 906 to align an article 908 on the platform behind the manipulator 122. Block 816 then directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 422 to align the arms 306 and 308 such that the respective end effectors 124 and 126 are aligned to grasp the article 908 at diametrically opposing surfaces thereof, as shown in Figure 11B. Block 816 also directs the microprocessor 400 to cause the DAC 414 to produce signals at the port 424 to cause

the end effectors **124** and **126** to grasp the article **908**, and to produce signals at the port **422** to lift the article over the center and lower the article into a next open space **910**. Block **818** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **424** to translate the arms **306** and **308** outwardly to disengage the article **908**. The article **908** is again aligned with the datum line **900** and placed a distance D from the article **622**.

The process **800** then continues at block **820**, which directs the microprocessor **400** to determine whether there are further articles remaining on the platform to be unloaded. As described above, a register for the number of loaded articles is stored in the memory **402** and is read and updated by the microprocessor each time an article is unloaded from the platform **110**. If at block **820** further articles are still to be unloaded, the microprocessor **400** is directed to block **822**, which directs the microprocessor to cause the DAC **414** to generate wheel drive signals at the port **426** to cause a further lateral movement corresponding to the distance D in the direction **904** for unloading the next article into an open space **914**. Block **822** then directs the microprocessor **400** back to block **814** and blocks **814** – **820** are repeated for each remaining article on the platform **110**.

If at block **820**, no further articles remain on the platform, then the unloading process ends at **824**. In the embodiment shown, the combination of the rotatable base **132** and rotatable platform **110** advantageously allow orientation of the wheels **104** for movement in the direction **904**. Subsequent lateral movements of the wheeled chassis **102** by the distance D facilitate rapid unloading of articles from the platform. In embodiments having a fixed base **132**, following placement of the article in the open space **902**, each subsequent unload would require a reversing movement of the wheeled chassis **102** to clear the unloaded article followed by a forward movement of the wheeled chassis to align with the next open space.

In the embodiment shown in Figures **11A** – **11C**, the articles are aligned along a single datum line **900**. In other embodiments, articles may be unloaded to align with a plurality of spaced apart datum lines such that articles are placed in several rows. The autonomous unloading operations of the apparatus **100** result in a precise alignment of the articles and also precise spacing D between articles. The precise alignment and spacing provided by the autonomous unloading has the advantage of conserving space at the drop-off location **624**, which may accommodate a greater number of articles than if manually placed.

An alternative embodiment of an apparatus for transporting a plurality of articles is shown in Figure 12 at 1000. Referring to Figure 12, the apparatus 1000 includes all of the components of the apparatus 100 shown in Figure 1, including the wheeled chassis 102 having drive wheels 104 and castor wheels 106, the base 132 and platform 110, and the manipulator 122. The apparatus 1000 further includes one or more tools operably configured to perform an operation on the plurality of articles 114 while being transported on the wheeled chassis 102. In the embodiment shown, a plurality of tool supports 1002, 1004, 1006, and 1008 are coupled to the base 132. The tool support 1002 has a spraying tool 1010 mounted on the support. The spraying tool 1010 is operable to draw a liquid plant protection product, such as a pesticide, contained in a reservoir 1012 and to spray the liquid onto a plant articles in the plurality of articles 114 disposed in a path of the spray. The tool support 1004 has a robotic arm 1014 mounted on the support. In one embodiment the robotic arm 1014 may be an articulated robot such as a SCARA (Selective Compliance Articulated Robot Arm), which is simple to mount on the tool support 1004 and has a small footprint. In embodiments where the articles 114 are plant pots operations such as trimming, sticking, or other operations may be performed by the articulated robot. The apparatus 1000 also includes a plurality of cameras 1018, 1020, 1022, and 1024 mounted on respective supports 1006 and 1008, which are operable to generate images facilitating inspection of the plurality of articles 114. In other embodiments, the apparatus 1000 may only have a single tool and tool support. Alternatively, in some embodiments more than four tools may be provided.

Further examples of tools that may be mounted on one of the plurality of tool supports 1002 – 1008, include a labeling machine, a 3D printer head, a drilling and/or milling machine, a cutting and trimming machine, a monitoring apparatus, etc.

Actuation of the platform actuator 140 causes the platform 110 to rotate in the direction 128 to dispose successive articles in the plurality of articles 114 to be operated on by the spraying tool 1010, robotic arm 1014, and inspection cameras 1016 – 1022. In the embodiment shown where the base 132 is rotatable with respect to the wheeled chassis 102, the plurality of tool supports 1002 – 1008 would thus also move with the base. As an alternative, the platform 110 may be held in a fixed rotational orientation while the base 132 is rotated to cause the tools, 1012, 1014, and 1016 – 1022 to be successively disposed to perform operations on each of the plurality of articles 114. In the embodiment described above where the platform is not rotatable, the rotatable base 132 would thus provide for rotational movement to dispose each tool to operate on the articles. In the other disclosed embodiment, where the base 132 is fixed and the

manipulator **122** is thus not moveable with respect to the wheeled chassis **102**, rotational movement of the platform **110** thus disposes each of the plurality of articles **114** to be operated on by each tool.

5 The upper surface **112** of the platform **110** thus accommodates several articles on which operations can be performed while the apparatus **100** is moving between the pickup location **602** and the drop-off location **624**. This has the advantage over prior-art systems that need to transport articles to a fixed station where operations are performed on the plurality of articles **114** before transporting the articles to the drop-off location **624**. The relatively large upper surface **112** of the platform **110** also accommodates several articles (in this case **6** articles) for both transport to the drop-off location **624** and simultaneous performing of
10 operations using the tools **1012**, **1014**, and **1016 – 1022**.

In Figure **1**, the proximity sensor **154** of the apparatus embodiment **100** was disclosed as being implemented using a single LIDAR sensor. In the apparatus embodiment **1000** shown in Figure **12**, the proximity sensor **154** is implemented using a LIDAR sensor **1024** and an infrared sensor **1026**, where the
15 infrared sensor **1026** performs close range proximity detection and the LIDAR sensor performs mid-range and long-range proximity detection. Some LIDAR sensors do not provide sufficient resolution for close range objects, while new LIDAR sensors that have recently become available may provide sufficient resolution at close range. As an example, the infrared sensor **1026** may be used for detection of objects within a range of about **100** cm, while the LIDAR sensor **1024** may be used to cover ranges between about
20 **15** cm and **6** meters.

Referring back to Figure **1**, the apparatus **100** may further include a pair of spaced apart mounts **162** and **164** that carry the respective UWB transceivers **416** and **417** (shown in Figure **6**). The UWB transceivers **416** and **417** are operable to receive and/or transmit radio frequency (RF) positioning signals. Ultra-wideband
25 transceivers use a low energy level RF pulse transmission over a wide bandwidth for short-range communications and are commonly used in precision locating and tracking applications. UWB pulses have low energy and in addition to requiring less operating power, also generally do not conflict with other wireless signals. In the embodiment shown, the UWB transceivers **416** and **417** are implemented using the DWM1000 UWB wireless transceiver module manufactured by DecaWave of Dublin, Ireland, which
30 facilitates location of objects to a precision of about **10** centimeters indoors over a range of up to about **300** meters. For the UWB transceivers **416** and **417** on the apparatus **100**, the DWM1000 module is configured as a “tag”, for which the position is to be tracked.

Figure **13** shows a plan view of an area **1100** such as a plant nursery floor. A plurality of articles (in this case, plants in pots) are to be transported on the wheeled chassis **102** of the apparatus **100** between a pickup location **1102** and an intended drop-off location **1104** within the area **1100**. Referring to Figure **13**, a positioning system shown generally at **1106** includes a pickup beacon **1108** positioned proximate a plurality of articles **1110** at the pickup location **1102**. The positioning system **1106** also includes a left drop-off beacon **1112** positioned proximate the intended drop-off location **1104** and a right drop-off beacon **1114** positioned proximate drop-off location **1104**. The left drop-off beacon **1112** and right drop-off beacon **1114** define a datum **1116** for indicating a desired alignment of articles at the drop-off location **1104**.

Each of the beacons **1108**, **1112**, and **1114** includes a transceiver for receiving and/or transmitting positioning signals. In one embodiment of the positioning system **1106**, the beacons **1108**, **1112**, and **1114** may also each include a DWM1000 UWB wireless transceiver module configured as an “anchor”, which provides fixed reference points for locating the apparatus **100** within the area **1100**. The UWB transceivers **416** and **417** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** each include a wireless interface, and are able to transmit and receive data signals from each other including timing information. In one embodiment communications between the UWB transceivers **416** and **417** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** may be in accordance with the IEEE 802.15.4 protocol for low-rate wireless personal area networks. The UWB transceivers **416** and **417** on the apparatus **100** are in communication with the on-board controller **160** via a USB interface **412**, as shown in Figure **6**. Advantageously, the UWB transceivers **416** and **417** and the UWB transceivers on the beacons **1108**, **1112**, and **1114** provide accurate real time positioning of the apparatus **100** within a workspace that does not rely on tracking movements of the drive wheels **104** or hub drive **150**.

The pickup beacon **1108** is used to generally indicate the pickup location **1104** where the plurality of articles **1110** are located. In this embodiment the datum **1116** provided by the left drop-off beacon **1112** and right drop-off beacon **1114** indicate a desired alignment of a plurality of articles **1122** at the drop-off location **1106**. In Figure **13** articles in the plurality of articles **1122** that have already been unloaded have been aligned along a line **1124**, which is spaced apart from the datum **1116** by a distance *S*.

In order to determine the position of the UWB transceivers **416** and **417** it is necessary to first establish the location of each of the beacons **1108**, **1112**, and **1114** in a local coordinate frame **1126**. In one

embodiment, the beacons **1108**, **1112**, and **1114** may be placed at arbitrary fixed positions and the UWB transceivers **416** and **417** and on-board controller **160** may be configured to locate each of the beacons within the local coordinate frame **1126**.

5 Referring to Figure **14**, a flowchart depicting blocks of code for directing the controller **160** to locate arbitrarily positioned beacons **1108**, **1112**, and **1114** in the local coordinate frame **1126** is shown generally at **1200**. The process **1200** begins at block **1202**, which directs the controller **160** to cause the UWB transceivers **416** and **417** on the apparatus **100** to initiate transmission of positioning signals, which are received by the UWB transceivers on each beacon **1108**, **1112**, and **1114**. The UWB transceivers transmit
10 signals over a wide bandwidth, which is equivalent to transmission of a very precise narrow pulse (about **1** nanosecond) in the time domain and facilitates accurate determination of a time of flight (*TOF*) for each transmitted pulse. In one embodiment the UWB transceivers may implement two-way ranging in which the transceivers exchange timing information over several transmissions between the transceivers to provide for precise *TOF* measurements. Signals received back at the transceivers **416** and **417** from the beacons
15 **1108**, **1112**, and **1114** are processed to calculate distances d_i corresponding to the determined *TOF* for each pulse transmission. The distances between each beacon are given by:

$$d_i = TOF * c; \quad \text{Eqn 1}$$

where d_i is the calculated distance and c is the speed of light. When two-way ranging is implemented, each distance d_i is calculated based on several transmissions between transceivers, and thus provides an
20 improved distance measurement between beacons. As described above in connection with Figure **6**, the UWB transceivers **416** and **417** are in communication with the microprocessor **400** of the on-board controller **160** and the *TOF* and/or the distances d_i are thus made available to the controller **160** for further processing via the USB interface **412** to the transceivers. In some embodiments the on-board controller **160** may receive *TOF* information and calculate the distances at the controller. In other embodiments
25 received position data may already be converted into distances.

Block **1206** then directs the controller **160** to establish the local coordinate frame **1126** with respect to the beacons **1108**, **1112**, and **1114**. This involves designating one beacon as an origin of the local coordinate frame **1126** (in this case the left drop-off beacon **1112**), designating another beacon as defining a direction
30 of the positive x-axis (in this case the right drop-off beacon **1114**), and establishing the y-axis perpendicular to the x-axis. Block **1208** then directs the controller **160** to use the calculated distances to determine the position of the remaining beacons (i.e. in this case the beacon **1108**) within the local coordinate frame

1126. The beacons **1108**, **1112**, and **1114**, while placed in arbitrary positions thus facilitate establishment of a fixed frame of reference **1126** for the positioning system **1106**.

5 Referring to Figure **15**, a flowchart depicting blocks of code for directing the on-board controller **160** of the apparatus **100** determine its position within the area **1100** is shown generally at **1300**. The process **1300** begins at block **1302**, which directs the microprocessor **400** of the on-board controller **160** to cause the UWB transceivers **416** and **417** to transmit positioning pulses, generally as described above. The transmission of the positioning pulses, when received at the beacons **1108**, **1112**, and **1114** cause transmission of return positioning pulses from the beacons including data related to the *TOF* associated
10 with the pulse transmission. The process **1300** then continues at block **1304**, where the positioning pulses are received back at the UWB transceivers **416** and **417** and three distances d_i are calculated for each of the UWB transceivers based on the determined *TOF* as described above.

At block **1306**, the distances d_i are provided to the microprocessor **400** for further processing. Block **1308**
15 then directs the microprocessor **400** to uniquely locate the UWB transceivers **416** and **417** in the local coordinate frame **1126** with respect to the beacons **1108**, **1112**, and **1114**. The location process generally involves finding the intersection between circles centered at each of the beacons **1108**, **1112**, and **1114** and having a respective radius of d_i . In practice, noise and other errors will likely not yield a unique intersection point, but probabilistic methods such as a least squares approximation may be used to provide a relatively
20 precise estimate of the location of each sensor. If a more a precise estimation of the location of the sensors **416** and **418** is required, an additional beacon (not shown) may be added to further reduce uncertainties associated with the position calculation. The process **1300** will generally be repeated at a repetition rate sufficient to locate the apparatus **100** in real-time or near-real time, while reducing the power consumption of the transceivers that may be powered by batteries.

25
The apparatus **100** may use the positional information for navigating the wheeled chassis to pick up articles from the plurality of articles **1110** at the pickup location **1104** and to move between the pickup location and the drop-off location **1106**, and to place articles in the plurality of articles proximate the destination location. The position of the apparatus **100** may be derived from the positions of the UWB transceivers **416**
30 and **417**, for example by taking a midpoint between the positions for each of the UWB transceivers **416** and **417** or some other reference point on the wheeled chassis **102**. Additionally, the respective positions provided for the spaced apart mounts **162** and **164** provide sufficient separation between the UWB

transceivers **416** and **417** to permit determination of an orientation or heading of the apparatus **100** within the local coordinate frame **1126** for the positioning information provided by the respective transceivers.

5 In one embodiment, the real-time location and orientation provided by the positioning system may be used for steering the wheeled chassis along a path **1224** between the pickup location **1104** and drop-off location **1106**. Additionally, the LIDAR proximity sensor **154** may simultaneously receive proximity signals indicative of obstacles in the path of the wheeled chassis **102**. The microprocessor **400** may use the received proximity signals from the LIDAR proximity sensor **154** and the positional information provided by the positioning system to modify the path **1224** of the wheeled chassis to avoid detected obstacles.

10
When the wheeled chassis **102** is within a pre-determined range of the pickup location **1104**, the proximity signals received from the proximity sensor **154** may be processed by the microprocessor **400** to determine whether obstacles in the path of the wheeled chassis **102** correspond to any of the plurality of articles **1110** to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles. In general, LIDAR and/or other proximity signals provided by the proximity sensor **154**
15 may be used in combination with data provided by the UWB transceivers **416**, **417** on the apparatus **100** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** to provide details of the environment, articles **1110** and **1122**, obstacles, and the position of the apparatus **100** within the area **1100**. Based on this information, the apparatus **100** may determine the path **1224** and make necessary adjustments to the
20 path during movement.

Similarly, when path **1224** of the wheeled chassis **100** is within a pre-determined range of the drop-off location **1106**, the microprocessor **400** may cause the wheeled chassis **102** to steer to a first location defined with respect to the second beacon **1114** (and/or the first beacon **1112**) for unloading a first article
25 at the **1106**. Subsequently, for additional articles in the plurality of articles **1110** the microprocessor **400** may cause the wheeled chassis to steer to successive locations (for example the location **1226**) defined with respect to the first and second beacons **1112** and **1114** for unloading of subsequent articles in the plurality of articles.

30 While specific embodiments have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.

What is claimed is:

- 1.** A method for transporting a plurality of articles between a pickup location and an intended drop-off location on a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis, the method comprising:

5 positioning a pickup beacon proximate the plurality of articles at the pickup location;

 positioning a left drop-off beacon and a right drop-off beacon on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the intended drop-off location;

 receiving location signals at transceivers disposed on each of the beacons and at the pair of

10 transceivers on the wheeled chassis;

 processing the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons;

 navigating the wheeled chassis using the determined location and orientation of the wheeled chassis to:

15 pick up successive articles of the plurality of articles proximate the pickup location;

 move between the pickup location and the drop-off location; and

 place articles at the drop-off location in an aligned relation with respect to the left and right drop-off beacons.

- 2.** The method of claim **1** wherein receiving the location signals comprises:

20 transmitting ultra-wideband (UWB) signals at the transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis; and

 receiving the UWB signals at the other transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis.

3. The method of claim 1 wherein navigating comprises:

using the location signals to determine a real-time location and orientation for steering the wheeled chassis along a path between the pickup location and drop-off location;

receiving proximity signals indicative of obstacles in the path of the wheeled chassis; and

5 using the received proximity signals and location signals to modify the path of the wheeled chassis to avoid detected obstacles.

4. The method of claim 3 wherein receiving the proximity signals comprises generating the proximity signals using at least one of an optical sensor, an infrared sensor, light detection and ranging (LIDAR) sensor, and an ultrasonic sensor.

10 5. The method of claim 3 wherein receiving the proximity signals comprises receiving:

a first proximity signal from an infrared sensor operably configured to indicate close range obstacles; and

a second proximity signal from a light detection and ranging (LIDAR) sensor indicating mid and far range obstacles.

15 6. The method of claim 3 further comprising, when the path of the wheeled chassis is within a pre-determined range of the pickup location, processing the received proximity signals to determine whether the detected obstacles in the path of the wheeled chassis correspond to any of the plurality of articles to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles.

20 7. The method of claim 3 further comprising, when the path of the wheeled chassis is within a pre-determined range of the drop-off location, causing the wheeled chassis to steer to a first location defined with respect to one of the left drop-off beacon and the right drop-off beacon for unloading of a first article.

25 8. The method of claim 7 further comprising causing the wheeled chassis to steer to successive locations defined with respect to the one of the left drop-off beacon and the right drop-off beacon for unloading of a second article and subsequent articles in the plurality of articles.

9. A system for transporting a plurality of articles between a pickup location and an intended drop-off location, the system comprising:

a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis;

5 a pickup beacon positioned proximate the plurality of articles at the pickup location;

a left drop-off beacon and a right drop-off beacon positioned on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the intended drop-off location, each beacon including a transceiver; and

10 wherein the transceivers on the beacons and the pair of transceivers on the wheeled chassis are operably configured to receive location signals and process the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons for navigating the wheeled chassis to pick up articles in the plurality of articles proximate the pickup location, to move between the pickup location and the drop-off location, and to place
15 articles in the plurality of articles at the drop-off location in aligned relation with respect to the left and right drop-off beacons.

10. The system of claim **9** wherein the transceivers disposed on each beacon and the pair of transceivers on the wheeled chassis comprise ultra-wideband (UWB) transceivers.

11. The system of claim **9** further comprising at least one proximity sensor disposed on the wheeled
20 chassis, the proximity sensor being operable to provide an indication of obstacles in the path of the wheeled chassis.

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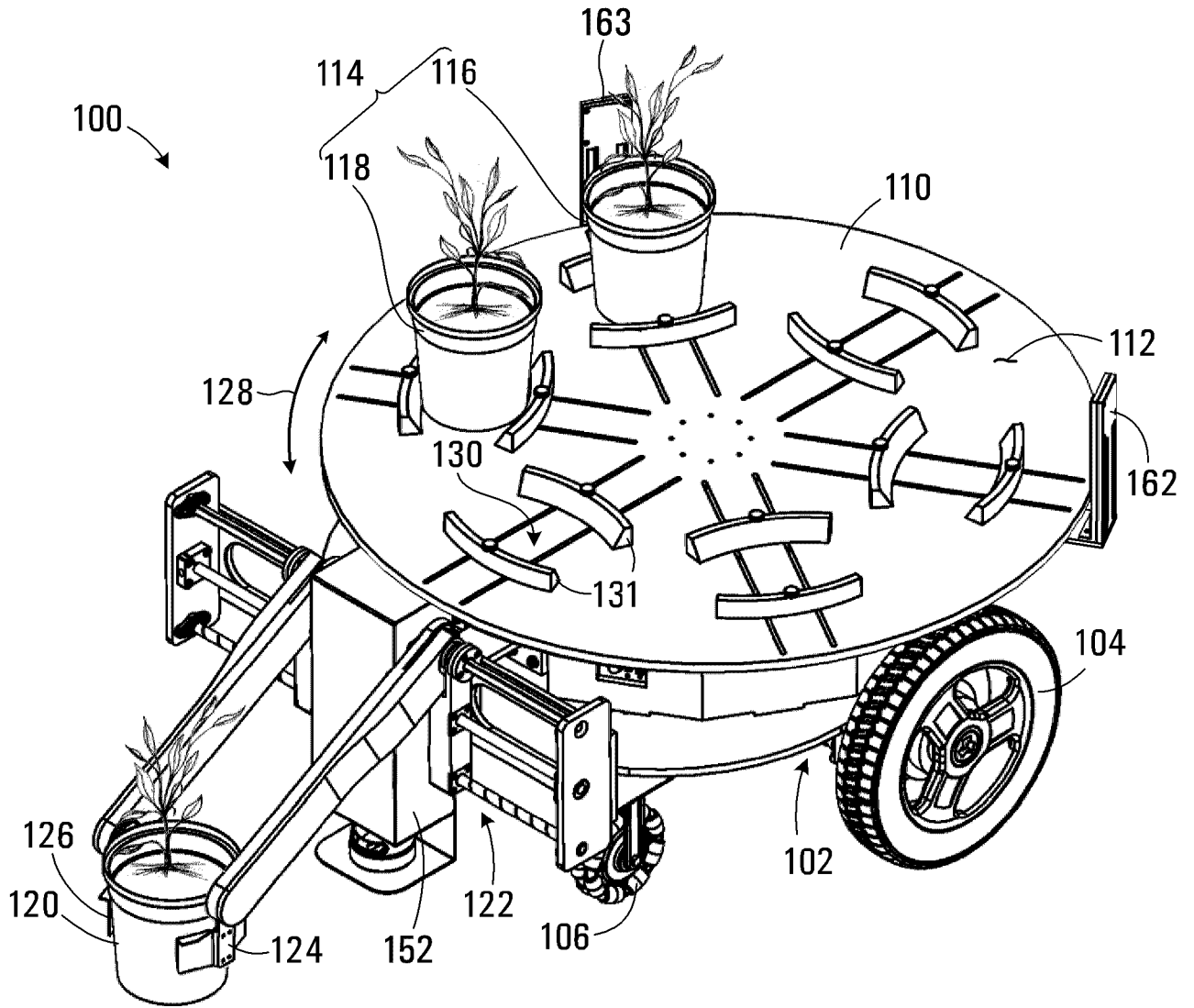


FIG. 1

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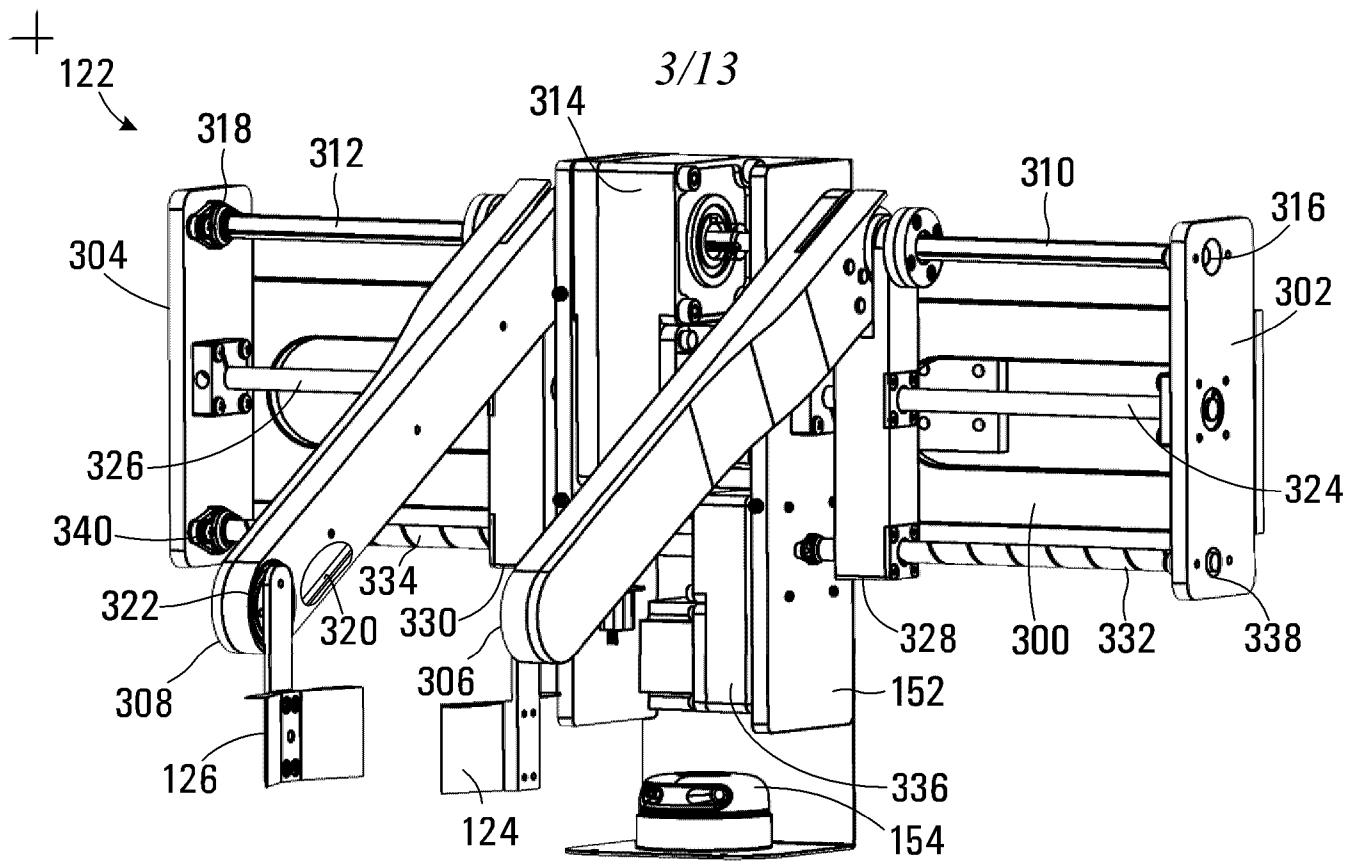


FIG. 3

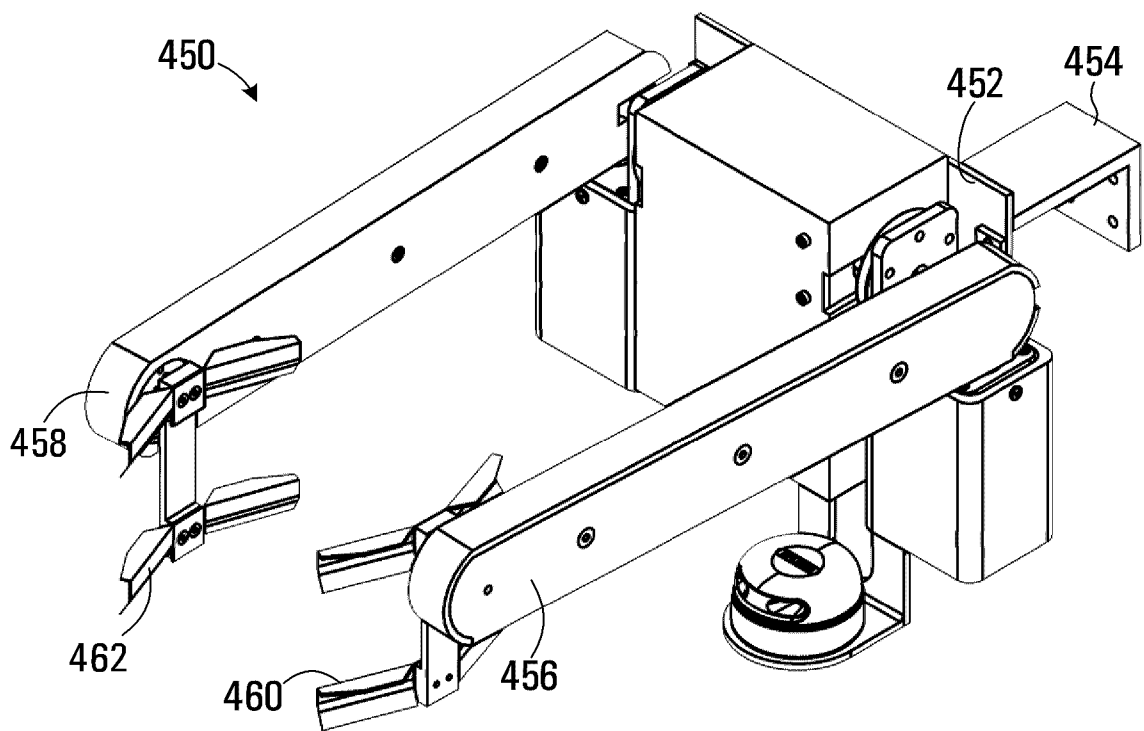


FIG. 4



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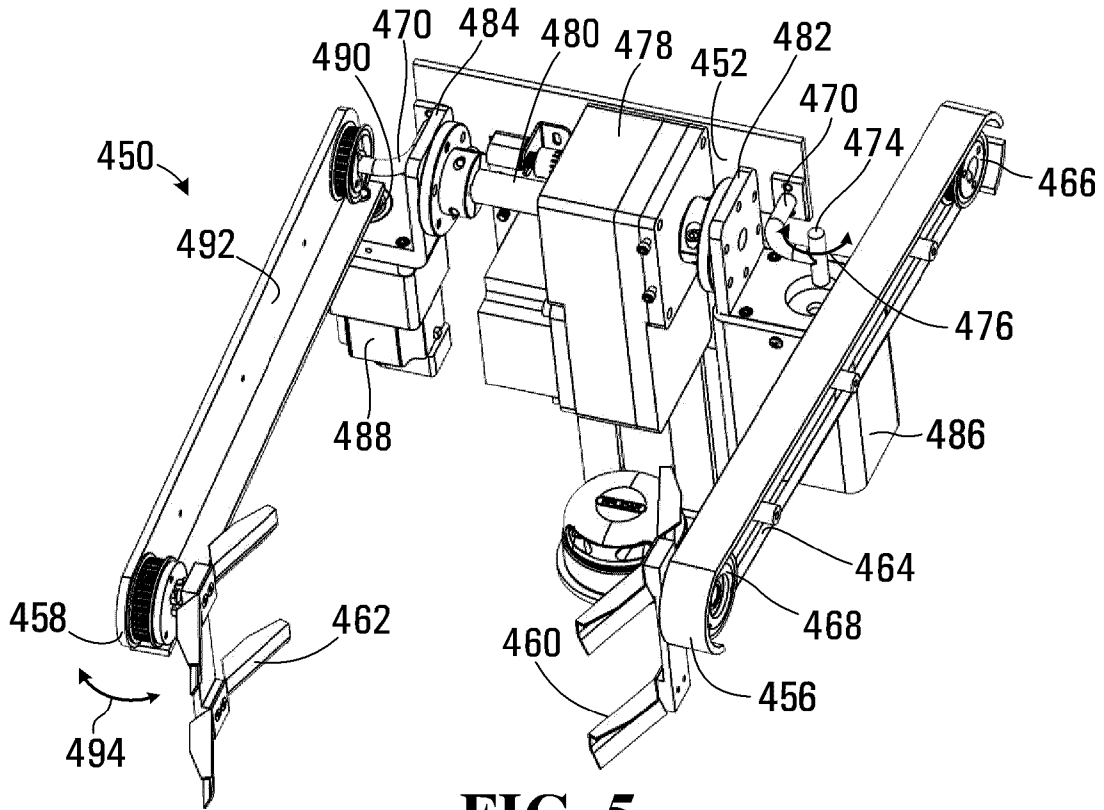


FIG. 5

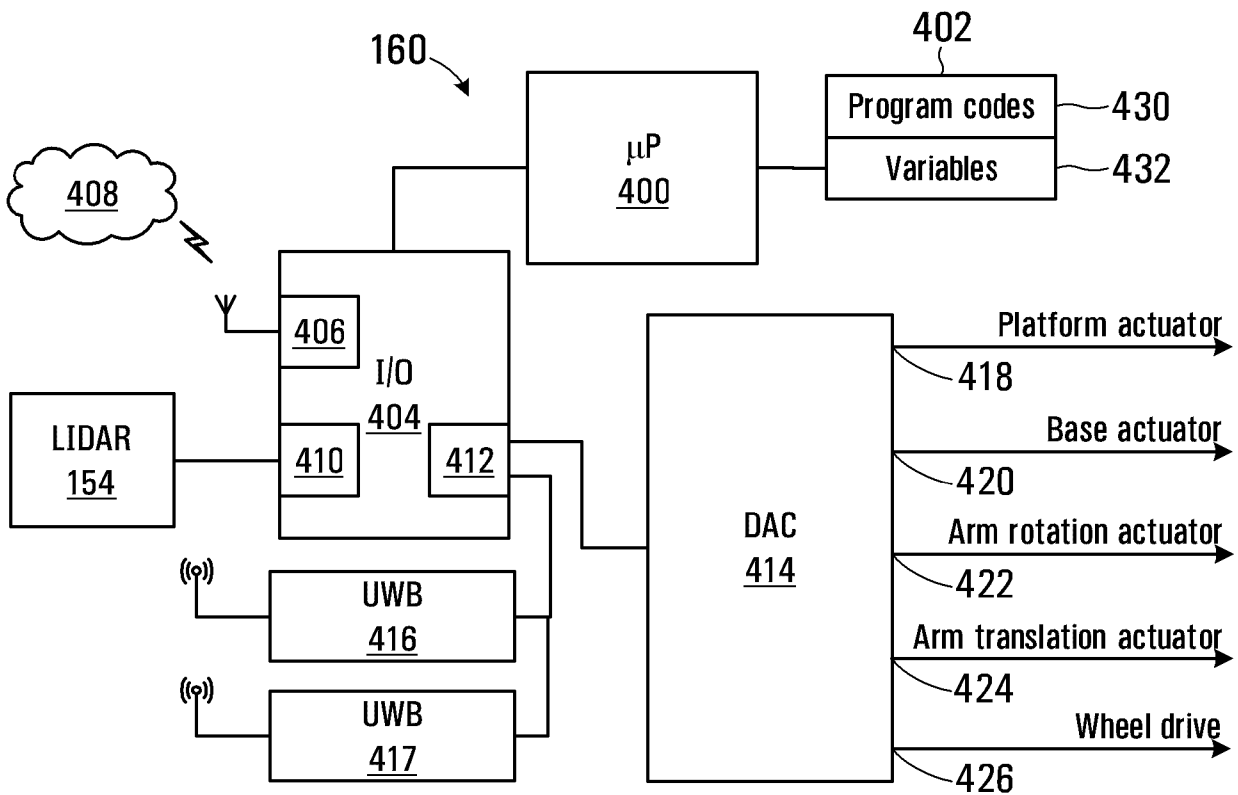


FIG. 6

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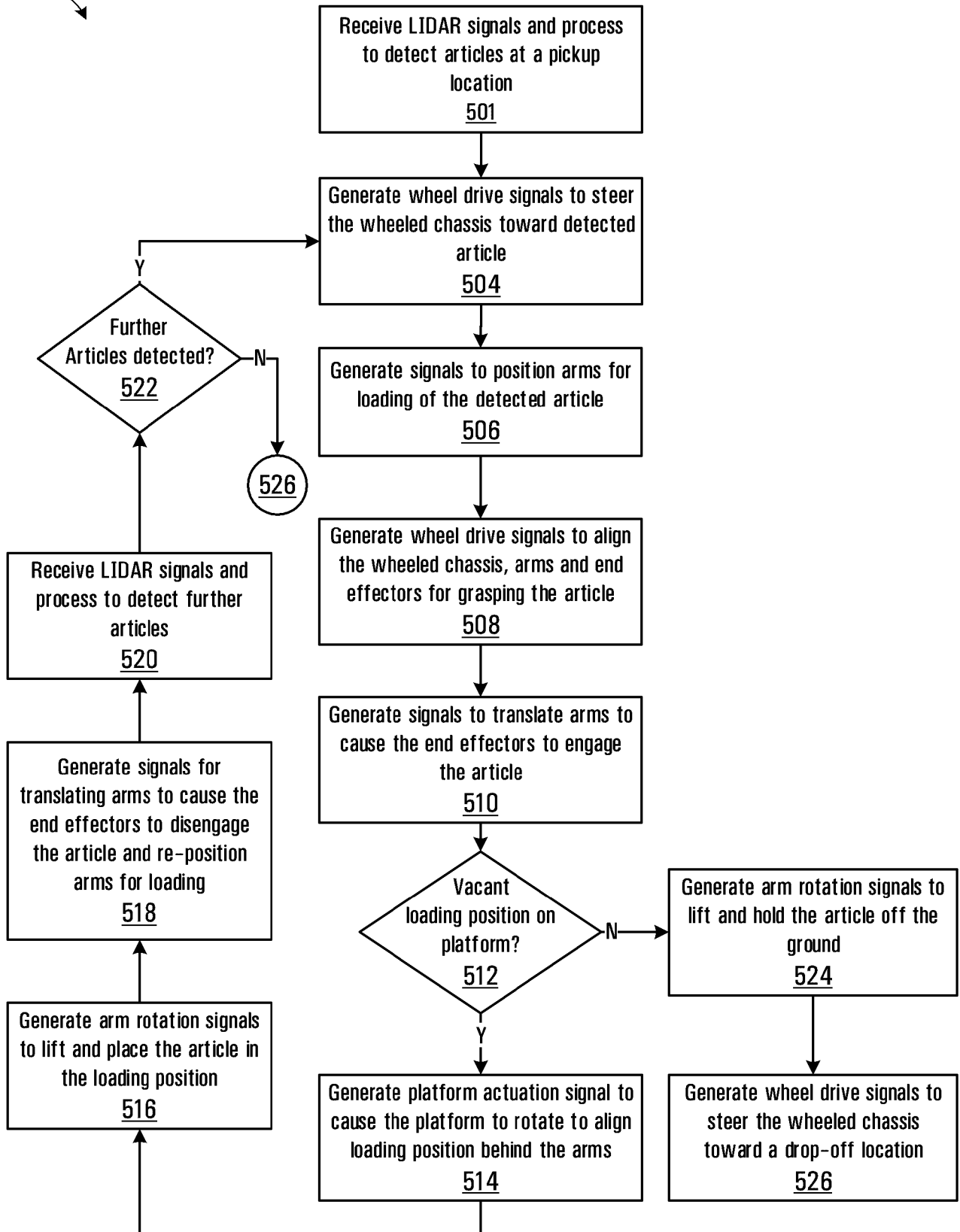


FIG. 7

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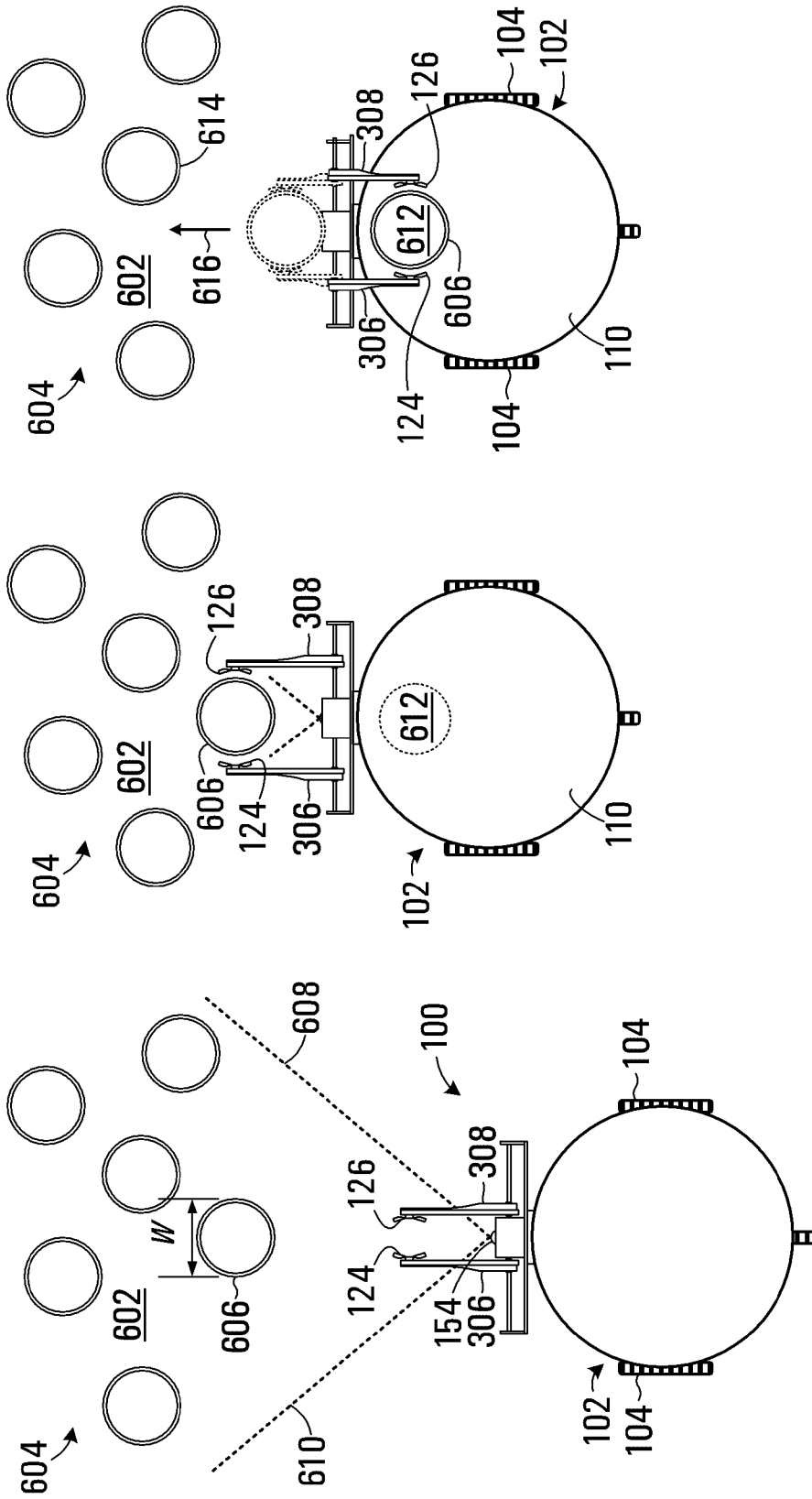


FIG. 8C

FIG. 8B

FIG. 8A

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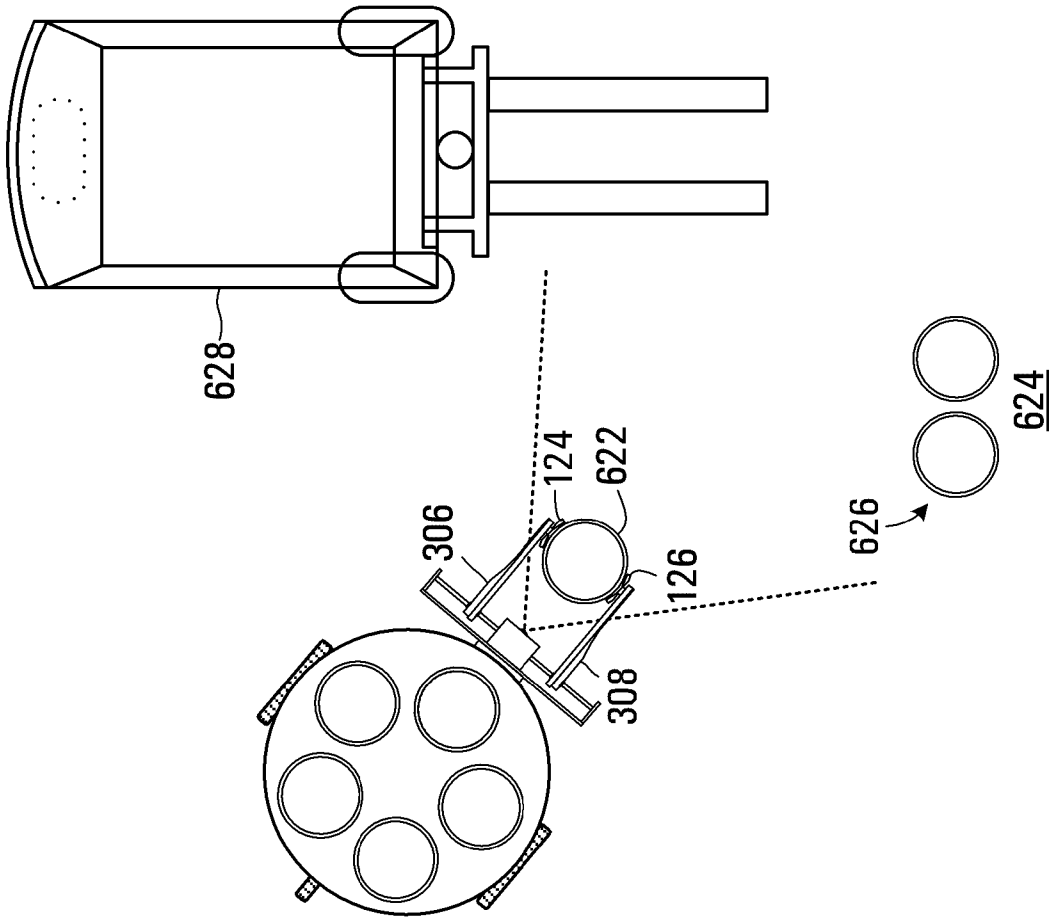


FIG. 8E

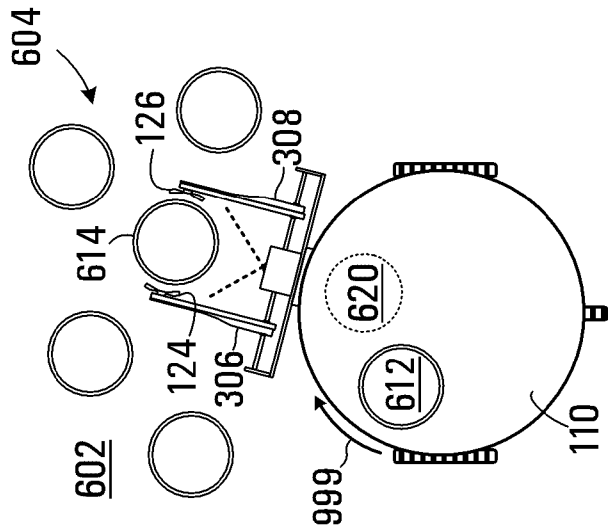


FIG. 8D

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506 →

8/13

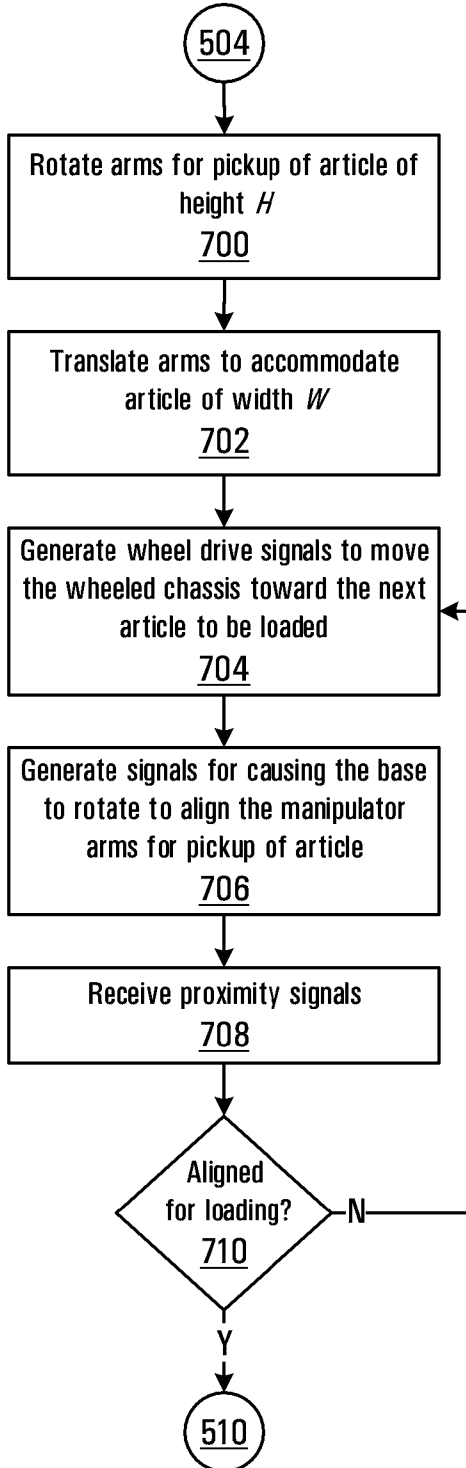


FIG. 9

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800

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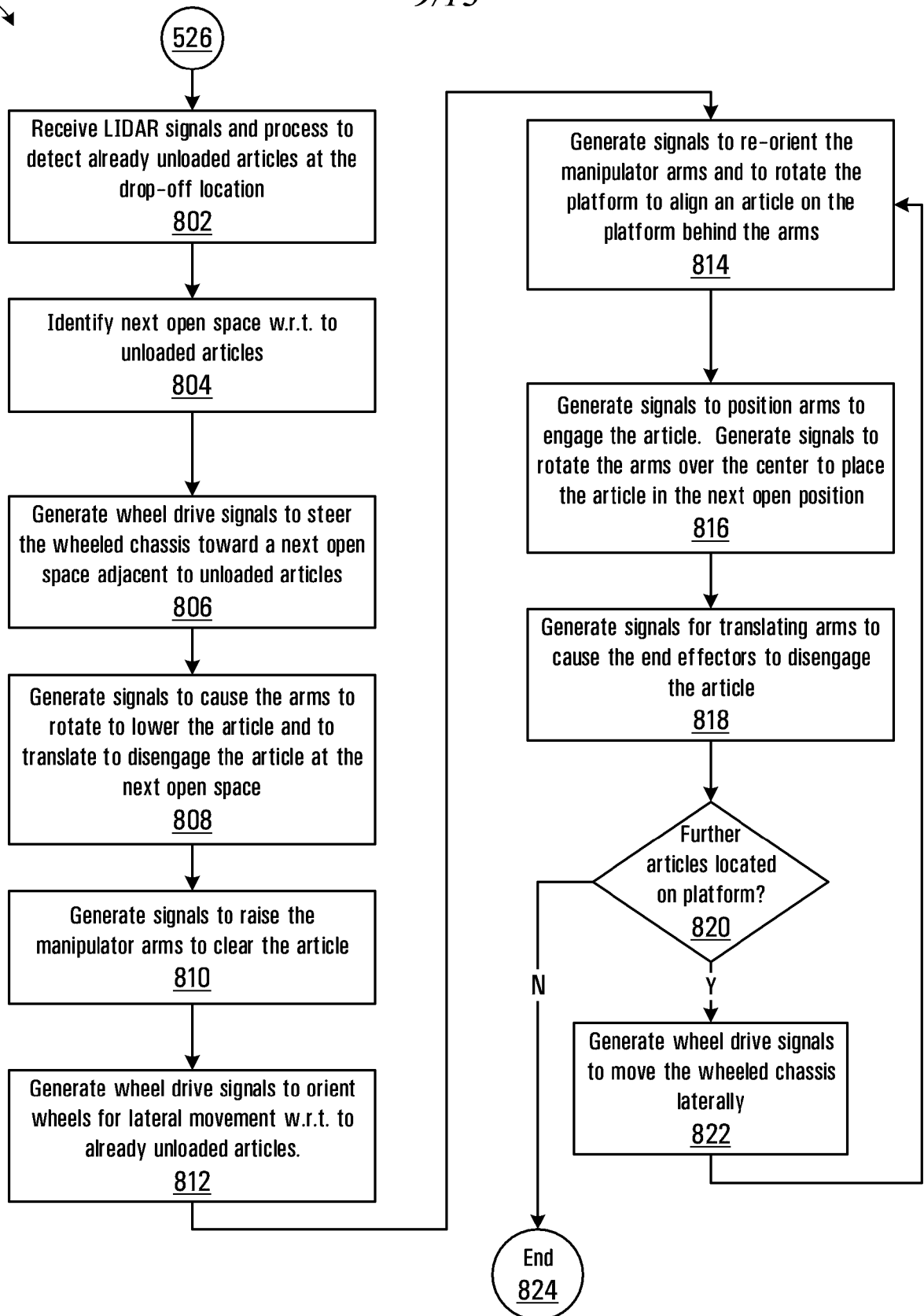


FIG. 10



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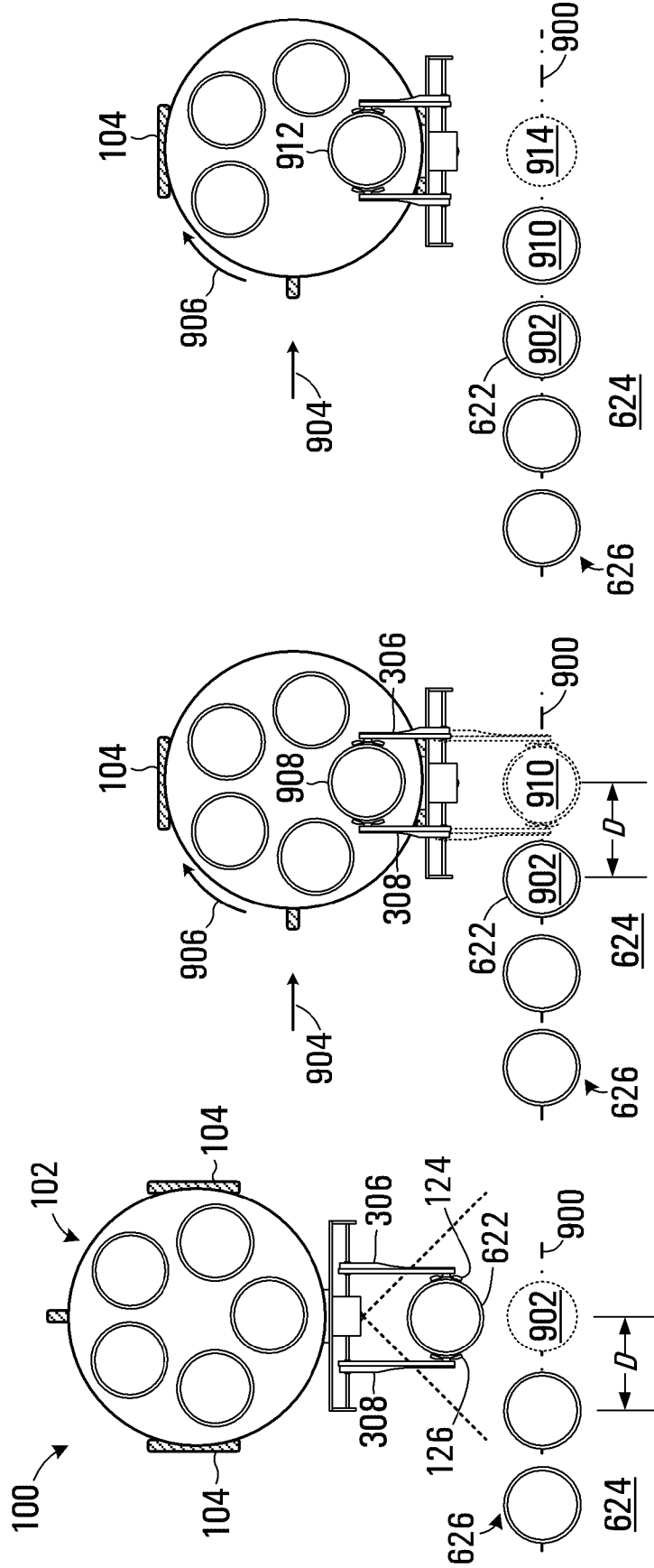


FIG. 11C

FIG. 11B

FIG. 11A

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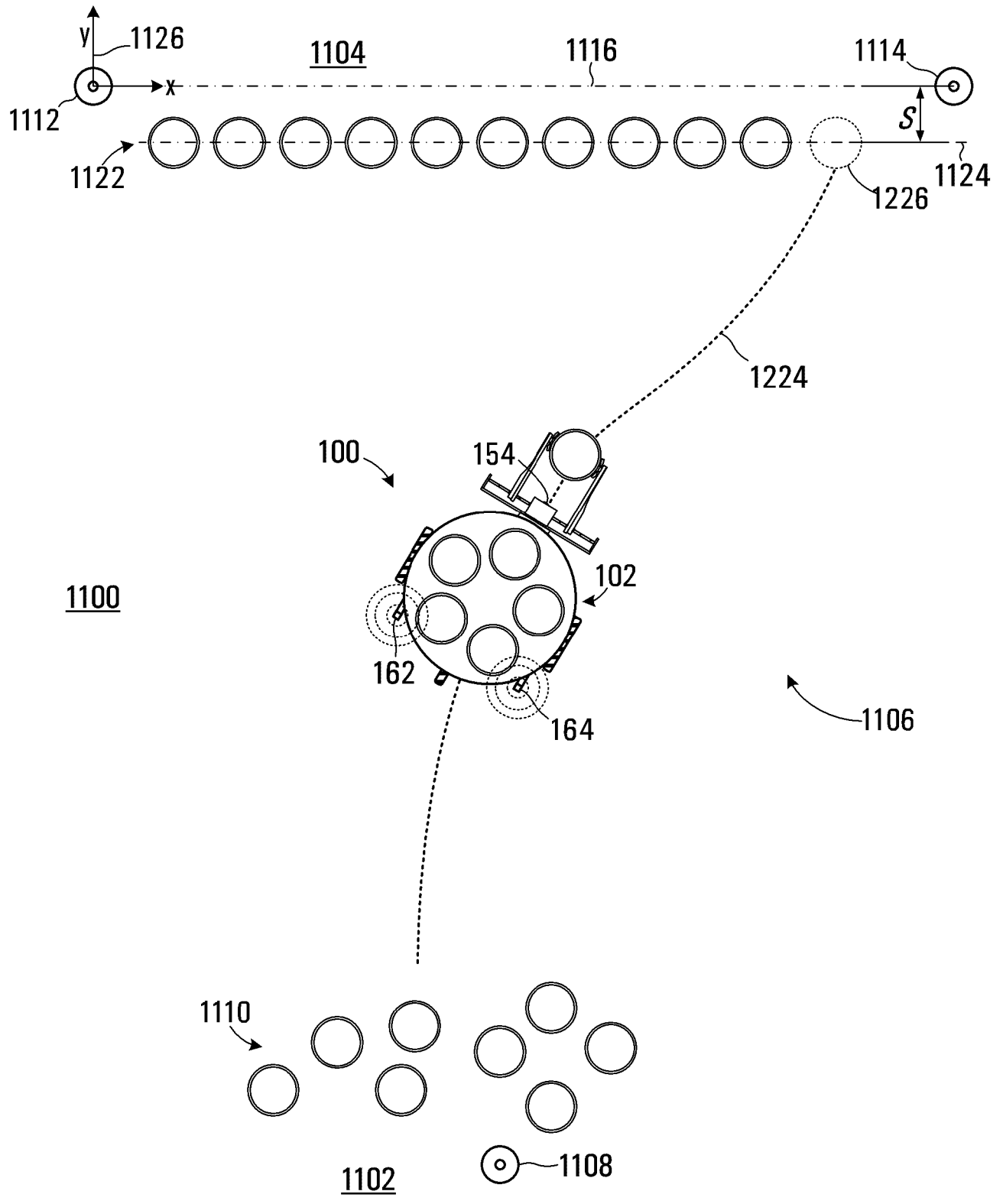


FIG. 13



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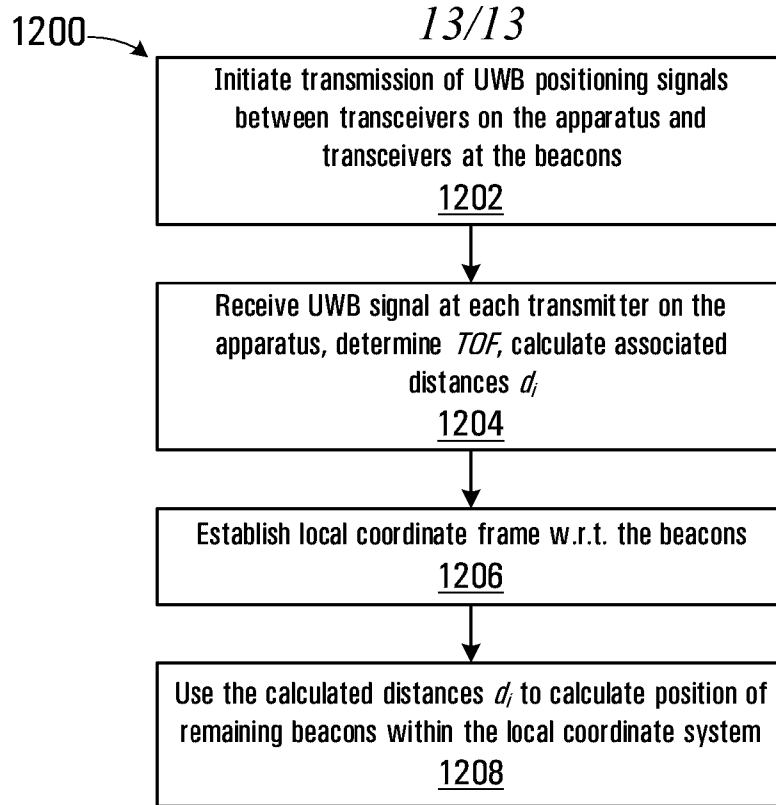


FIG. 14

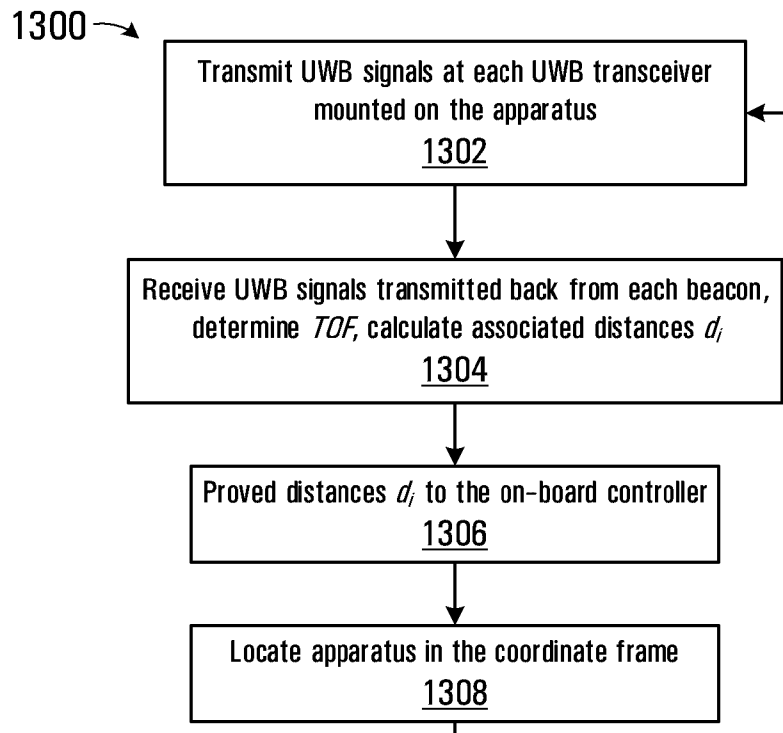


FIG. 15

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