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- *as to the identity of the inventor (Rule 4.17(i))*
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- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*
- *of inventorship (Rule 4.17(iv))*

[Continued on next page]

(54) Title: IN-LINE LEGGED ROBOT VEHICLE AND METHOD FOR OPERATING

(57) Abstract: A legged vehicle includes a body, wherein the body includes a major axis corresponding to a primary direction of travel; a plurality of leg mechanisms attached to the body, wherein each leg is attached at its proximal end at one or more discrete attachment points, wherein the attachment points are arranged in-line, one behind the other, with respect to the body, each of the legs including actuators attached between the legs and the body and between adjacent leg members, said legs being actuated for movement of a distal end in three dimensions; a control system in communication with the leg mechanisms to coordinate movements of the leg mechanisms according to approximately single track foot placement, and movement of the legged vehicle in three dimensions over the ground; and a power source connected to and driving the control system components and the plurality of actuators and joints which drive the legs.

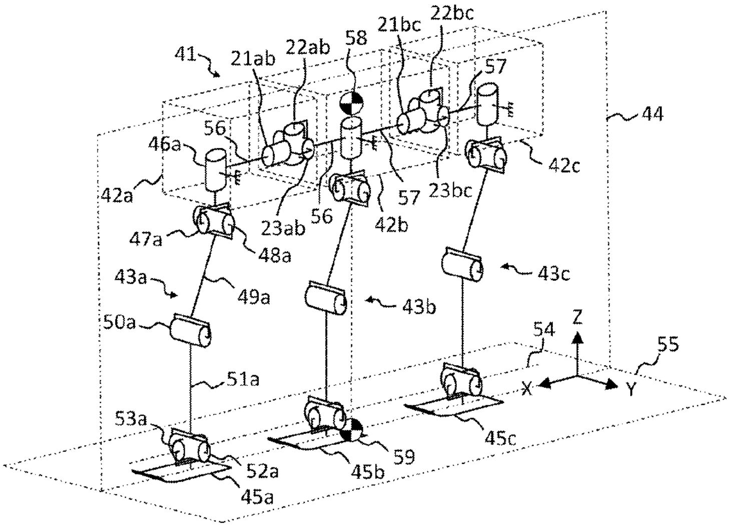

FIG. 2

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In-Line Legged Robot Vehicle and Method for Operating

John R. Goulding

SPECIFICATION

PRIORITY

This International application claims priority from U.S. Application 13/052,821 filed on March 21, 2011 and U.S. Provisional Application 61/316,213 filed on March 22, 2010.

FIELD OF THE INVENTION

The present invention relates to a legged mobile robot and, more particularly, to a legged mobile robot having a plurality of legs arranged in a narrow profile to walk and maneuver along paths by placing successive footfalls in a generally single-track or in-line fashion. Furthermore, the invention relates to an automatic system for sensing and preventing turnover of single-track legged mobile robots while enabling normal riding techniques in all but out of control situations.

BACKGROUND OF THE INVENTION

Prior-art legged vehicles, especially those adapted for moving over rough or uneven terrain have been proposed. The terms vehicle, walking machine, and robot are to be construed broadly and includes any means of transportation, whether merely of itself or of objects other than itself. As early as 1898, H.G. Wells described a fictional 100 foot tall, three-legged walking machine in his science fiction novella entitled “War of the Worlds”, and it was first drawn by Warwick Globe circa 1898. In the drawing, the three legs are symmetrically positioned in a triangular pattern to form a tripod stance.

Further developments in legged locomotion occurred in the 1960’s when research progressed from observation to modeling. These designs employed statically stable, symmetric walking gaits, and required moving pairs of opposing legs to keep the body in static equilibrium at all times. These gaits have also been modeled mathematically and diagrammatically, wherein fundamental terminology was defined, such as stance, swing, stride length, duty factor, phase, stability, and so on. For example, a leg is either on the ground, called the stance state or phase, or in the air, called the swing or flight state or phase, and a stride measures the distance the body moves in one stance-to-swing locomotion cycle. The aforementioned prior art vehicles are generally very large, bulky, and cumbersome, and such prior art legged vehicles generally move slower than comparable wheeled vehicles. This highly limits their usefulness.

Further developments in legged walking machines used a computer to control the motion of an eight degrees-of-freedom (DOF) quadruped. General Electric Corporation built a 3000 pound, hydraulically-actuated quadruped that had three DOF per leg, two DOF at the hip and one DOF at the knee. Such efforts led to the development of various theories and algorithms for coordinating leg movements in bipeds, quadrupeds, hexapods, and other symmetric legged walking machines to walk over rough terrain, evaluate footholds, and walk outdoors on various types of terrain. In 1968, researchers at Ohio State University proved mathematically that there is an optimal gait for a quadruped that maximizes the longitudinal stability margin. They built a 300 pound hexapod that used force sensors, gyroscopes, proximity sensors, and a camera system to study control algorithms for legged walking machines. Finally, various experiments have been performed on quadruped robots to study walking gaits when one leg is inoperative. In such work, two legs are in-line and the third leg is offset with one of the in-line legs, as in a right-angle triangle orientation, and the two offset legs walk in a predominately bipedal gait with the single in-line leg implementing a hopping motion.

Further developments in legged machines were made to investigate unstable or dynamic legged machines by studying balance of one, two, and four-leg hopping machines. Legged vehicles with less than six legs generally require some degree of dynamic balance to stabilize the body against roll and pitch.

Further developments in legged machines have come about because of advances in high-accuracy, high-pressure servo hydraulics combined with real-time low-level control systems. Such legged actuator systems servo positions and forces at the actuated joints to regulate ground reaction forces, maintain support, position, and traction. For example, Boston Dynamics Company built and demonstrated the BigDog quadruped robot. The BigDog quadruped robot has multi-jointed legs adapted for limited oscillatory movement and exhibits a variety of locomotion behaviors: stand up, squat down, walk with a crawling gait that lifts just one leg at a time, walk with a trotting gait that lifts diagonal legs in pairs, trot with a running gait that includes a flight phase, and bound in a special gallop gait. A high-level control system coordinates behaviors of the legs to regulate the velocity, attitude, and altitude of the body during locomotion. For example, the BigDog control system coordinates the kinematic and ground reaction forces of the robot while responding to basic postural commands. Load is distributed over the stance legs to optimize the load-carrying ability. The vertical loading across limbs is kept as equal as possible while individual legs are encouraged to generate ground reactions towards the hips, thus lowering required joint torques and actuator efforts. A gait coordination algorithm, responsible for inter-leg communication, initiates leg stance transitions to produce a stable gait. A virtual leg model coordinates the legs. The control system adapts to terrain changes through terrain sensing and posture control.

Further developments in legged machines have been realized by improvements in low-power, high computational throughput, self-contained computer systems capable of receiving sensory input, calculating the system and leg kinematics, and controlling each leg joint. For example, a novel tripod robot was designed with omnidirectional legs and body such that the body rotates in the pitch and yaw axis allowing a leg to swing under the body to afford pairs of legs to contact the ground simultaneously.

SUMMARY OF THE INVENTION

A vehicle with legs can go where wheeled or tracked vehicles cannot go. Legged vehicles have improved mobility over rugged terrain with unstable footholds, such as mountain slopes and piles of rubble. Legged vehicles choose discrete, optimal foot placement and vary the length of the leg with respect to the body. Additionally, legged vehicles can bound, leap, or jump over areas of ground that do not have a continuous path of support or closely spaced footholds. Moreover, legged vehicles are able to move in man-made or cultural environments, traversing obstacles such as curbs, stairs, and narrow passageways. With respect to wheeled vehicles, legged vehicles reduce body motion. This characteristic is especially well suited to the comfort of a rider or passenger.

The term *robot* is to be construed broadly and includes any means of vehicular transportation, whether merely of itself or of objects other than itself, relating to a device and method that works autonomously or semi-autonomously whereas the term machine or vehicle, as in the motorcycle or bicycle, relates to an operated device. The robot/vehicle of the present invention takes people places they normally cannot go. It is designed with a narrow profile to walk and maneuver along narrow trails and paths, such as for example horse trails found in parks and wilderness areas. Hopping, bounding, leaping, and jumping enable it to traverse terrain that is too difficult for comparable wheeled machines. Because it has legs like a horse, it does not damage the environment like bicycles, motorcycles, and 4x4 vehicles do. It brings back the thrill of trail riding to improve human health and emotional development. It may also be used as a “pack mule” to carry heavy loads and accompany hikers.

Compared to a quadruped or four-legged mobile robot, the present invention uses 25% fewer actuators, and would thus have higher reliability and cost less to manufacture. Like the quadruped, the single track design is a statically stable design, because the legs can be positioned in a tripod stance. Unlike biped or two-legged mobile robots that must simultaneously maintain balance in both the pitch and roll directions, the robot's/vehicle's balance is controlled in the roll direction. Further, a three-legged design enables the present invention to maintain (or regain) stability of balance at rest and during locomotion, by repeating intervals of dynamic momentum (including the monopod stance) followed by the roll-stable bipedal and/or the fully stable tripod stance.

Like wheeled motorcycles and bicycles, the legged mobile robot of the present invention executes a single-track turn by leaning the body into the turn, thus developing a torque about the roll axis to counteract the outward centripetal force. The single track or in-line legged mobile robot is inherently stable along the length of the body or major axis of motion. The control strategy decouples the leg positioning along the length of the body or major axis of motion and the leg positioning along the width of the body or normal to major axis of motion. That is, legged vehicles heretofore must simultaneously maintain stability of balance in the pitch and roll direction. The single track or in-line legged mobile robot controls stability of balance in the roll direction and (for the most part) not in the pitch direction. Like a quadruped, yaw is controlled by developing torque about any two legs during the stance phase. This device and method drastically simplifies control for many single track or in-line legged gates and modes of operation. Furthermore, the control system senses and prevents turnover of single track legged mobile robots while enabling normal riding techniques in all but out of control situations.

It has not heretofore been possible to realize a multi-legged vehicle, i.e. robot or machine, having a plurality of legs arranged in a minimally narrow profile to place successive footfalls in a predominately single-track or in-line fashion, similar in form and function to motorcycles and bicycles. In off-road environments, such as parks and wilderness areas, single track vehicles, such as motorcycles and bicycles, exhibit superior maneuverability and deployment performance in comparison to double track vehicles, such as automobiles and tanks. Moreover, single track vehicles are typically lighter in weight, have fewer mechanical components, increased reliability, higher energy efficiency, and faster acceleration and deceleration. Further while the aforementioned prior art legged vehicles provide means for implementing various static and dynamic walking gaits, they do not disclose a device or method for single track or in-line multi-legged static and dynamic gaits.

According to the present invention, there is provided a single track or in-line multi-legged mobile robot which achieves the desired form and function of the motorcycle or bicycle but with the added benefit of legs and full or partial robotic control. The term robot relates to a device and method that works autonomously or semi-autonomously whereas the term machine or vehicle, as in the motorcycle or bicycle, relates to an operated device.

Briefly, a single track or in-line multi-legged mobile robot may be constructed in accordance with the teachings of the present invention comprises a device and method:

a body and three legs mounted on the body in-line with the length of the body;

at least three legs comprising a minimally narrow profile so that as a vehicle it can maneuver where prior art vehicles previously could not go, such as walking along a narrow trail or path or through a door;

each leg is connected to a single or multi-segmented body that is generally longer than it is wider;

the body length establishes the major direction of motion, such as forward and backward motion;

each of the at least three legs are spatially arranged at the hip to be generally in-line with the major direction of motion;

each of the at least three legs has at least three degrees of freedom (DOF), such as pitch and roll at the hip and extension and retraction of the foot, to position the foot anywhere within a three dimensional volume;

the at least three legs combine to form three spatial volumes for foot placement that is spatially arranged to be generally in-line with the major direction of motion;

the at least three spatial volumes overlap along the major direction of motion;

the at least three legs have sufficient reach in length, width, and height to afford the three feet to be spatially positioned 1) in a triangular (tripedal) pattern to keep the body in static equilibrium at rest, 2) in any manner of patterns to provide locomotion and dynamic attitude stabilization, and 3) for omnidirectional motion.

A control system is used to coordinate and control the legged vehicle/robot, and may include one or more central processing units (CPU) and one or more memory components. The memory components may include one or more memory modules, such as Random Access Memory (RAM) modules, Read Only Memory (ROM) modules, Dynamic Random Access Memory (DRAM) modules, and any other suitable memory modules. The control system may also include a plurality of input/output (I/O) components that may include a variety of known I/O devices, including network connections, video and graphics cards, disk drives or other computer-readable media drives, displays, or any other suitable I/0 modules. One or more data busses may operatively couple the CPU, the memory component, and the I/O component. The control system may be operatively coupled to a control component having a data display/monitor and a command/control input device (e.g. a keyboard, an audio-visual input device, handlebars, foot pegs, pressure pads, and so on).

In accordance with a first major embodiment of the invention, a legged vehicle includes a frame, wherein the frame includes a major axis corresponding to and generally parallel to a forward/backward direction of travel; a plurality of jointed leg mechanisms attached to the frame, one behind the other, wherein each leg is attached at its proximal end at one or more discrete attachment points, wherein the attachment points are arranged substantially parallel to the major axis of the frame and the forward/backward direction of travel, each of the legs including actuators attached between the legs and the frame and between adjacent leg members, said legs being actuated for movement of a distal end in three dimensions; a control system in communication with the leg mechanisms and receiving sensed data to determine possible future states of the legged vehicle and to coordinate movements of the leg mechanisms and frame, and movement of the legged vehicle in three dimensions over the ground; and a power source connected to and driving the control system components and the plurality of actuators which drive the legs, wherein forward/backward movement of the legged vehicle is according to approximately single track foot placement. The term ‘single track’ shall be interpreted as referring to the general narrowness of the foot-placement patterns along a straight or curved path.

Such an arrangement, wherein the legs are attached to the frame one-behind-the other (in-line), provides numerous advantages in mobility, including the ability to travel through narrow passages, such as doorways, and along narrow paths, such as single-track trails, where traditional vehicles would be unable to go.

According to a first aspect of the invention, the legged vehicle includes three legs. Three in-line legs provide an advantage of inherent stability along the pitch axis, which is generally parallel with the major axis of the body and major direction of travel. Thus most of the stability process can be directed to a roll axis (side-to-side) and perpendicular to the pitch axis.

According to a further aspect of the invention, the legged vehicle includes more than three legs. This arrangement provides greater stability in the pitch axis, and provides multiple options for possible footholds while in motion, and also provides options for not placing a foot down over unstable terrain, and instead relying on dynamic stability and the remaining legs to traverse the terrain.

According to a further aspect of the invention, each of the plurality of legs includes a foot at the distal end. Each of the feet of the legged vehicle may include at least one of, or one or more of, plates, skids, spikes, wheels, skates, skies, slides, floats, hydroplanes, and fingers. Different combinations of the different foot-types may be used to accommodate different types of terrain. Accordingly, different gaits may be used according to the combination of foot-type and terrain. This brings tremendous flexibility to the vehicle.

According to a further aspect of the invention, the legged vehicle includes a single-piece frame. This simplifies the gaits and any necessary programming to traverse terrain.

According to a further aspect of the invention, the legged vehicle includes a frame which is jointed and includes two or more segments, each segment having a major axis corresponding to and generally parallel to a forward/backward direction of travel. The articulated frame provides an advantage in flexibility, which extends the ranges of motion of each of the legs, particularly the front-most and rear-most legs. With proper coordination, a much faster, more natural gait can be used to quickly traverse even the most challenging terrain.

According to a further aspect of the invention, at least one accelerometer and at least one gyroscope mounted on the frame and in communication with the control system, the control system receiving sensed data from the at least one accelerometer and at least one gyroscope to sense velocity, acceleration, attitude, and gravitational forces. The preferred embodiment further comprises the at least one accelerometer and at least one gyroscope mounted on the frame and sensing velocity, acceleration, attitude, and gravitational forces normal to the length of the body and the major axis to sense the roll condition. Additional sensing including the pitch, yaw, x, y, and z axis would be required for omni-directional guidance, navigation and control.

According to a further aspect of the invention, each leg mechanism includes position-measuring components providing feedback to the control system. These position-measuring components provide information regarding relative or absolute leg position to the control system. Such information provides the advantage of more-accurate leg-movement corrections based upon a comparison, within the control system, of commanded or desired leg placement in comparison to actual leg placement.

According to a further aspect of the invention, each leg mechanism includes force-measuring components providing feedback to the control system. These components provide numerous advantages, including accurate determination of the loaded weight of the vehicle, accurate determination of the leg energy required, via one or more actuators, to perform a desired maneuver, such as straight-line walking, and accurate measurements of forces experienced at each leg and through the frame. This permits the control system to compensate according to the desires trajectory.

According to a further aspect of the invention, each leg mechanism includes torque-measuring components providing feedback to the control system. These components provide numerous advantages, including accurate determination of the loaded weight of the vehicle, accurate determination of the leg energy required, via one or more actuators, to perform a desired maneuver, such as straight-line walking, and accurate measurements of torques experienced at each leg and through the frame. This permits the control system to compensate according to the desired trajectory.

According to a further aspect of the invention, the movement range for each of the legs defines a working envelope, each of the feet having sufficient reach and movement range in length, width and height, relative to the frame, (1) to position two feet perpendicular to the major axis of the frame, with one foot positioned to the left of and one to the right of the projected center of gravity of the frame to form a generally bipedal stance along the major axis of the frame to provide a degree of stability in the roll axis, and (2) in addition to the placement of the first two feet, to displace a third foot into a position parallel to the major axis of the frame, either to the front or the rear with respect to the other feet, to form a generally tripedal stance about the projected center of gravity (center of pressure) of the frame to provide a period of stability in both the pitch and roll axes.

According to a further aspect of the invention, the movement range for each of the legs provides range-of-motion overlap in length, width and height of the working envelopes of each adjacent foot, including any foot in front of and behind each foot. This provides a tremendous amount of flexibility in achieving temporary stability while in motion and when utilizing dynamic stability, and permits a great range of possible leg positions which are necessary when traversing difficult terrain.

According to a further aspect of the invention, the feet of two adjacent legs, one in front of and one behind the other, are positionable side-by-side on a center of pressure line generally perpendicular to the frame and perpendicular to the major axis of motion to achieve a bipedal stance. This ability permits the frame to be positioned so as to bring a zero-moment line of the legged vehicle in coincidence with the center of pressure line, which allows the other legs of the legged vehicle to be raised off the ground, at least temporarily.

According to a further aspect of the invention, the control unit has or is in communication with an operator interface, which is in communication with the control system, the control system receiving sensed data from the operator. This arrangement allows the advantage of remotely-directed control of the legged vehicle, and allows a rider/operator to control the legged vehicle.

According to another aspect of the invention, the operator interface components provide at least steering angle, throttle and braking inputs into the control system. In this fashion, the legged vehicle is controlled by an operator in a manner similar to that of controlling a motorcycle, but with the benefit of discrete foot placement.

According to another embodiment of the invention, a method of operating a legged vehicle including a frame, wherein the frame includes a major axis corresponding to and generally parallel to a forward/backward direction of travel; a plurality of jointed leg mechanisms attached to the frame, one behind the other, wherein each leg is attached at its proximal end at one or more discrete attachment points, wherein the attachment points are arranged substantially parallel to the major axis of the frame and the forward/backward direction of travel, each of the legs including actuators attached between the legs and the frame and between adjacent leg members, said legs being actuated for movement of a distal end in three dimensions; a control system in communication with the leg mechanisms and receiving sensed data to determine possible future states of the legged vehicle and to coordinate movements of the leg mechanisms and frame, and movement of the legged vehicle in three dimensions over the ground; and a power source connected to and driving the control system components and the plurality of actuators which drive the legs, wherein forward/backward movement of the legged vehicle is according to approximately single track foot placement, the method comprising the steps of:

- developing reaction forces, torques, and thrusts in a stance phase wherein leg/foot-to-ground interaction is transferred through the leg to stabilize the frame in the pitch, roll, and yaw axes and to propel the frame in the x, y, and z axes, respectively, the foot/distal end of the leg being generally stationary with respect to the ground during the stance phase and moving generally opposite to the major direction of frame motion, of a monopedal stance, a bipedal stance and a tripedal stance, according to the control system;
- unloading reaction forces through the leg/foot in a stance-to-flight phase wherein the foot is lifted off the ground, controlling leg velocities, according to the control system;
- repositioning the leg/foot in a flight phase wherein the distal end of the leg/foot is moved generally in the same direction as the frame and generally at a faster rate, relative to the ground, as the major direction of frame motion, controlling foot placement and leg movement to maintain an upright posture and meet foot placement constraints and desired trajectory requirements for the frame and legged vehicle, according to the control system; and
- placing the leg/foot to the ground and developing reaction forces, torques, and thrusts in a flight-to-stance phase;

wherein movement of each leg includes each of the four phases for each leg.

According to a further aspect of the invention, the method of operating the legged vehicle further comprises:

- during the flight phase for at least one leg, controlling leg movement, torque, extension velocity and retraction to use the mass of the at least one leg to impart forces and torques to the frame in at least one dimension or axis.

According to another aspect of the invention, the method of operating the legged vehicle further includes leaning the vehicle into a desired direction of turn, wherein a projected center of gravity is laterally displaced inwardly from a point within a triangle defined by foot contact with the ground, wherein a torque is developed around the roll axis in the direction of the lean; and displacing one or more feet normal to and spatially distant from the projected center of gravity in the opposite direction of the lean to develop an outward torque about the roll axis to counteract the inward lean, wherein the trajectory becomes a curved line.

According to a further aspect of the invention, the method of operating the legged vehicle further includes developing torque from at least one leg or a combination of two or more legs to rotate the frame along a curved trajectory. This aspect is key to the "lean into the turn maneuver" and may precede the turn, occur continuously or discretely during the turn, and/or provides a means for exiting the turn to pursue a different trajectory.

According to a further aspect of the invention, the method of operating the legged vehicle further includes sensing with at least one of a gyroscope and accelerometer an induced roll condition from an external force; and leaning the vehicle into the direction from which the external force is applied, wherein the roll condition is neutralized, according to the control system. Examples of external forces include, but are not limited to wind forces, impulse forces, centripetal forces, and gravitational forces (due to loss of traction causing the frame to fall over). Leaning the vehicle may be accomplished in one of several ways including but not limited to developing a foot-to-ground reaction torque about the ankle and/or placing one or more feet in the same direction as the applied external force, beyond the projected center of gravity plus a distance equal to or greater than is required to counter the estimated dynamic momentum at the time the foot is repositioned. Furthermore, the external force may be desired, to initiate a lean into a turn maneuver, for example, but ultimately the roll condition must be neutralized to maintain an upright vehicle posture.

According to a further aspect of the invention, the method of operating the legged vehicle further comprises:

- leaning into a turn by balancing the centripetal forces of the frame, as exemplified through the displacement of the center of pressure from foot placement with an acceleration force of the legs. The method of turning the legged vehicle may include the steps of: leaning the vehicle into a desired direction of turn, wherein a projected center of gravity is laterally displaced inwardly from a point within a triangle defined by foot contact with the ground, wherein a torque is developed around the roll axis in the direction of the lean; and displacing one or more feet normal to and spatially distant from the projected center of gravity in the opposite direction of the lean to develop an outward torque about the roll axis to counteract the inward lean, wherein the trajectory becomes a curved line.

The outward and inward torques may be adjusted as necessary to conform to a desired radius of turn. Of course by leaning into the turn, an inward torque, toward the radius of the turn, is created by gravity due to the unstable positioning of the projected center of pressure. It is necessary to create a sufficient outward (centripetal) force from several leg movements to balance the inward force. The legs movements move the legged vehicle along the desired curved line, or around the desired radius of turn. The turn may be stopped or changed as desired through leg movements arranged to adjust the position of the projected center of pressure.

This arrangement provides a distinct advantage in that the legged vehicle may be ridden like a bicycle or motorcycle, and combining the narrow profile of a two-wheeled vehicle with the sure-footed flexibility of a legged vehicle.

According to a further aspect of the invention, the leg mechanisms, such as the actuators, are controlled by the control system to selectively induce roll, pitch and/or yaw torques between each foot and the ground.

According to a further aspect of the invention, the body is jointed and includes two or more segments being joined by a plurality of actuators, position-sensors and elastic components. Such an arrangement provides superior flexibility and adaptability to a wide range of terrains, and enables the legged vehicle to traverse a wide range of terrains quickly.

According to a further aspect of the invention, at least one leg of the legged vehicle includes at least three degrees of freedom (DOF).

According to a further aspect of the invention, the three degrees of freedom may be defined by pitch and roll movement at a hip joint and may include extension and retraction of the leg by knee and ankle joints which define a spatial volume for possible leg placement.

According to a further aspect of the invention, the movement range for each of the legs defines a working envelope, each of the feet having sufficient reach and movement range in length, width and height, relative to the body, to be placed in a plurality of predetermined locomotion and dynamic attitude stabilization patterns.

According to a further aspect of the invention, the movement range for each of the legs defines a working envelope, each of the feet having sufficient reach and movement range in length, width and height, relative to the body, to be placed in at least one omni-directional locomotion pattern. Motion along the major axis of the frame, is only one of the possible directions of travel. The movement ranges for the legs, and the actuator/control system interface permit the legged vehicle to move in any direction along the ground. Motion normal to the major axis may be in a side-step pattern, which will be described below.

According to a further aspect of the invention, the body includes two or more segments and is jointed in at least one axis between adjacent legs such that the feet have sufficient range of movement in length, width and height to provide overlap of the working envelopes of at least two legs at any one time. This arrangement provides flexibility to place the legged vehicle into a stable bipedal or tripedal state whenever desirable.

According to a further aspect of the invention, the body is jointed in at least one axis between adjacent legs wherein the body is conformably flexible to the curvature of a single track turn maneuver. This arrangement provides a minimally narrow profile relative to the major axis of motion whereby the legged vehicle can engage in proper single-track operations, such as along a narrow trail or through a doorway.

According to a further aspect of the invention, the body is jointed in at least one axis between adjacent legs wherein the body is conformably flexible to ground undulations and uneven ground. This arrangement provides a minimally narrow profile relative to the major axis of motion wherein the legged vehicle can be engaged in proper single-track activities, such as walking along a narrow trail and walking through a doorway.

According to a further aspect of the invention, the body includes elastic energy storage and release components between body segments, wherein the elastic components operate in at least one axis, wherein the elastic components store and release kinetic energy for transfer between adjacent body segments and adjacent legs. The elastic members may be used to accept and release energy in a predictable manner. This energy may be used by the control system to supplement the leg and/or body actuators in placing legs/feet at desired footholds rapidly and accurately.

According to a further aspect of the invention, the legged vehicle includes three legs attached to the frame in an in-line fashion, wherein the second or middle leg is capable of supporting the entire weight of the vehicle, rider and any cargo and the first (front) and third (rear) legs are capable of at least partially supporting the entire weight of the vehicle, rider, and cargo.

According to another embodiment of the invention, the method of executing straight-line walking with an in-line legged vehicle utilizes a four-phase cycle for each leg, the four phases including:

- a stance or support phase wherein foot-to-ground interaction is developed to produce reaction forces and torques that are transferred from the foot through the leg to stabilize the body in the pitch, roll, and yaw axes and to propel the body in the x, y, and z axes, the stance foot being generally stationary with respect to the ground and moving generally opposite in direction to the major direction of body motion,
- a stance-to-flight phase wherein the reaction forces between the foot and the ground are unloaded and the foot is lifted off the ground,
- a flight phase wherein the leg is moved to reposition its foot by moving the foot in the same general direction and generally at a faster (negative) rate as the major direction of body motion, and

- a flight-to-stance phase wherein the foot is placed on the ground and reaction forces and torques are developed between the foot and the ground.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle includes the steps of:

- tracking and synchronizing each phase for each leg, according to a selected predetermined gait model, with a state machine.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle,

wherein a foot is positioned to the right or to the left of the projected center of gravity on to the ground to develop during a stance phase:

1) additional ground reaction forces that are normal to the major direction of motion and 2) ground reaction torques in the pitch, roll, and/or yaw axes.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle,

wherein the leg length during a stance phase is different between feet positioned to the right or to the left of the projected center of gravity of the body on to the ground in order to level the body attitude, within the working range of the legs and their feet.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle,

wherein retraction of the legs during flight phase is inwards towards the body and along the major direction of motion such that no torque is imparted to the body in the roll axis.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle,

wherein the leg is swept/swung outward during a flight phase without reducing its length to impart a torque in the pitch, roll and/or yaw axes to aid in stabilizing the body.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle, further comprising the steps:

- sweeping/swinging a leg outward from the body and away from the ground;
- reducing the length of the leg, such as by bending the leg at the knee;
- sweeping the shortened leg back inward towards the ground during a flight phase to impart a torque in the pitch, roll and/or yaw axes to aid in stabilizing the body.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle, wherein two feet are positioned one to the left and one to the right of the projected center of gravity of the body onto the ground in a generally bipedal stance with respect to the length of the body and major direction of motion to provide a period of stability in the roll axis.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle, wherein three feet are positioned in a tripod stance to provide a period of stability in the x, y, and z axes and pitch, roll, and yaw axes.

According to another aspect of the invention, the method of executing straight-line walking with an in-line legged vehicle, wherein the combined ground reaction forces of said three feet positioned in a tripod stance impart a torque in the pitch, roll and/or yaw axes to aid in stabilizing the body.

According to a further embodiment of the invention, a method of executing a single-track walking turn with an in-line legged vehicle, wherein a yaw torque about the center of gravity is developed by the interaction of two or more legs with the ground, according to control system control of leg actuators.

According to a further embodiment of the invention, a method of executing a single-track walking turn with an in-line legged vehicle, wherein a yaw torque about the center of gravity is developed by the interaction of one foot with the ground.

OBJECTS, FEATURES AND ADVANTAGES

It has long been known that it would be advantageous to develop a vehicle that uses legs rather than one with wheels because a vehicle with legs can go where wheeled or treaded vehicles cannot go. Legged vehicles have improved mobility over rugged terrain with unstable footholds, such as mountain slopes and piles of rubble, because the legged vehicles may choose optimal foot placement and vary the length of the leg with respect to the body. Additionally, legged vehicles can bound, leap, or jump over areas of ground that do not have a continuous path of support or closely spaced footholds. Moreover, legged vehicles are able to move in man-made or cultural environments, traversing obstacles such as curbs, stairs, and narrow passageways. With respect to wheeled vehicles, legged vehicles reduce body motion. This characteristic is especially well suited to the comfort of a rider or passenger.

It is therefore an object of the present invention to solve the problems associated with providing a single track or in-line multi-legged mobile robot similar in form or function to the motorcycle or bicycle but with the added benefit of legs and full or partial robotic control. For example, unlike the wheeled motorcycle or bicycle, a feature and advantage of the single track or in-line multi-legged mobile robot is that it can move sideways. It is a feature of this invention to solve these problems by providing a walking machine in which the legs are in-line or co-linear with respect to the body and primary direction of motion. Unlike the wheeled motorcycle or bicycle, the single track or in-line multi-legged mobile robot uses discrete footholds over the duration of the stance period, which is an advantage or feature in rugged, natural terrain where footholds are unevenly spaced. For example in the case where all three legs are in contact with the ground, the ability to shift one of the legs laterally to affect balance is an advantage or feature. Further, unlike the outrigger wheels of the prior art, the feet of the single track or in-line multi-legged mobile robot are stationary with respect to footholds during the support period, thus eliminating the drawback of the prior art when used in rugged terrain.

Still other objects, features and attendant advantages of the present invention will become apparent to those skilled in the art from reading of the following detailed description of the preferred embodiment constructed in accordance therewith and taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 illustrates a perspective skeletal view of a single track or in-line three legged mobile robot;

FIG. 2 illustrates a perspective skeletal view of a single track, in-line three-legged mobile robot/vehicle having a jointed, articulated body/frame;

FIG. 3 illustrates a side skeletal view of a single track or in-line three legged mobile robot illustrating the range of motion of the legs along the major direction of travel;

FIG. 4 illustrates a perspective skeletal view of a single track or in-line three legged mobile robot illustrating one possible configuration of the legs, typically used in a stationary stance;

FIG. 5 illustrates a top schematic view illustrating center of gravity, placement of the feet, and resulting area of support for the single track or in-line three legged mobile robot illustrated in FIG. 4;

FIG. 6 illustrates a side skeletal view of a single track or in-line three legged mobile robot illustrating overlap and crossover of the first and second legs, typically used while moving;

FIG. 7 illustrates a top schematic view illustrating center of gravity, placement of the feet, and resulting area of support for the single track or in-line three legged mobile robot illustrated in FIG. 6;

FIG. 8 illustrates a perspective skeletal view of a single track or in-line three legged mobile robot executing a single-track leaning turn;

FIG. 9 illustrates a schematic skeletal view of a single leg of illustrating the fundamental feedback and control system of a single track or in-line multi legged mobile robot; and

FIG. 10 illustrates a front view of a single track or in-line three legged mobile robot extending a leg in the direction of roll to catch its fall.

DETAILED DESCRIPTION OF THE INVENTION

The invention will now be explained with reference to a single track or in-line three legged mobile robot as a specific embodiment of the single track multi-legged mobile robot. Referring now to the drawings and, more particularly, to FIGS. 1-2 thereof, there is shown a single track or in-line legged mobile robot, generally designated 41, including a body or frame, generally designated 42, a control unit 86, a power supply 13, and three identical leg mechanisms, generally designated 43, attached one behind the other, substantially parallel to the major axis of the frame 42, defining a forward/backward direction of travel along planes 44 and 55. By convention, the left side of the page is the front side and forward direction, the right side of the page is the rear side, into the page is the right side, and out of the page is the left side of the robot 41. The construction of each leg mechanism 43 is not directly relevant to the present invention, the present invention being directed to the method and manner in which the leg mechanisms 43 may be combined and attached to the body 42 for forming a complete legged mobile robot and control thereof. However, leg mechanisms 43 will be described briefly, because the teachings of which are necessary for an understanding of the present invention. Since each leg mechanism 43a, 43b, and 43c is identical, a description of one will suffice to describe all.

It will be readily apparent by those skilled in the art, that a pantograph leg mechanism would include a plurality of elongated links arranged in a parallelogram to form a pantograph mechanism whereby forces applied at selected points on individual parts of the links can be transmitted to another link which forms the movable foot 45a-45c of the mechanism, or a movable distal end of a leg 43a-43c. Pantograph legs reduce the complexity of actuation, increasing reliability, and decreasing computational requirements. However, the popularity of biologically inspired jointed legs, found in prior art and in commercial off-the-shelf robotic kits is believed to improve the clarity of understanding the teachings.

An overall skeletal view of the tri-legged walking machine is shown in FIGs. 1-2. The articulated structure of the legged walking machine 41 includes three jointed legs mounted in-line, one behind the other, along the length of the body 42 such that the three legs establish a plane 44 (X-Z axis). Each leg mechanism is associated with six articulations or joints (axes) to enable each foot 45a, 45b, and 45c to be positioned in six dimensions (X-Y-Z and roll-pitch-yaw axis, respectively) with respect to the body 42. Since each leg mechanism 43a, 43b, and 43c is identical, a description of the first leg 43a will suffice to describe all and the other legs are unlabeled for clarity. The joints (axes) of the leg include a yaw rotational joint (yaw axis) 46a for turning the leg and foot 45a with respect to the body 42, a roll rotational joint (roll axis) 47a for moving the foot to the side (Y axis) of the body 42, a pitch rotational joint (pitch axis) 48a on a thigh link 49a for moving the foot forward and backward (X axis), a rotational joint (axis) 50a in the knee and at the distal end of the thigh link 49a and on a shank link 51a for moving the foot forward and backward (X axis), a rotational joint (axis) 52a at the distal end of the shank link 51a for moving the foot in the pitch direction, and a rotational joint (axis) 53a for moving the foot in the roll direction. Axes 52 and 53 are parallel to the pitch and roll axes, respectively. The foot 45a is mounted to a small shank (not labeled for clarity) connected to rotational joint 53a on the lower end of the leg 43a. The joints (axes) 46, 47, and 48 jointly constitute a hip joint assembly, joint 50 constitute a knee assembly, and the joints 52 and 53 jointly constitute a foot joint assembly. The foot 45 is moved forward or backward with respect to the length of the body 42 or parallel to the plane 44 by rotating joints 48, 50, and 52 and/or rotating joints 23. The foot 45 is moved to the right or left side with respect to the length of the body 42 or perpendicular to the plane 44 by rotating joints 47 and 53 and/or rotating joints 21. The foot 45 is rotated clockwise or counterclockwise with respect to the length of the body 42 by rotating joints 46 and/or rotating joints 22. The roll axis 54 of the walking machine 41 is about ankle joints 53. Note that for legs with a point-contact foot, that is without ankle joints 53, the roll axis 54 is at the point of contact of the at least two single track feet 45 and the ground 55 for the condition where there is negligible foot slip. It may be desirable for legs 43, connecting joints 21-23 and/or feet 45 to be mechanically compliant to comprise a spring-mass-damper system to afford a gentler ride of body 42.

Still referring to FIGs. 1-2, body 42 includes three main support plates to mount the legs 43 to frames 56 and 57 on body 42 to afford roll, pitch, and yaw hip rotations along the axis of motion such that the foot may be positioned laterally or radially outward with respect to the body 42 and measured thusly. On each of the thigh and the ankle of each leg, the pitch joints 48 and roll joints 47 are disposed perpendicularly to each other, and have respective axes intersecting with each other at one point. The joints 48, 50, and 52 in the hip joint assembly, the knee joint, and the foot joint assemblies, respectively, extend parallel to each other in plane 44. Irrespective of movements caused by other degrees of freedom, particularly, movements of the joints 46 to change the direction of the legs, the joints 48, 50, and 52 remain parallel to each other, with respect to a single leg. In the hip joint assemblies, the joints 46 and the pitch and roll joints 47, and 52 extend perpendicularly to each other, so that the three axes of rotation, representing three degrees of freedom, extend perpendicularly to each other. More specifically, the axis 46 may be considered to define a first axis of the hip joint assembly, the axis 47 to define a second axis of the hip joint assembly, and the axis 48 to define a third axis of the hip joint assembly. The axes 46, 47 and 48 each provide respective degrees of freedom about which the leg of the robot may be moved, for example, the axis 48 provides a first degree of freedom for angularly moving the leg forwardly in the pitch direction, the axis 47 provides a second degree of freedom for moving the leg laterally in the roll direction, and the axis 46 provides a third degree of freedom in the yaw direction for rotating the leg with respect to the body 42. It should be understood, however, that the designations "first," "second" and "third" are arbitrary, and are used merely to facilitate a description of the invention. The legs 43 thus have six degrees of freedom each, so that during locomotion the legs as a whole can be caused to execute the desired motion by driving the $6 \times 3 = 18$ joints (axes) to appropriate angle. Irrespective of the position or posture of the body 42, the feet 45 can be placed in any position, at any angle, and in any direction. The robot is thus capable of walking freely within three dimensional space. The joint actuations may be provided by any means such as electric motors and reduction gear mechanism for increasing motor torque or high pressure servo hydraulics. A power supply 13 and a control unit 86 are mounted on the legged vehicle. The power supply is in communication with each component of the legged vehicle which requires power, including the control unit 86 and all its distributed components, and the numerous actuators. The control unit 86, also called a control system in a larger sense, includes numerous parts, as described above, including numerous sensors which may be distributed throughout the vehicle.

Still referring to FIG. 1-2, body 42 has physical mass and thus a center of gravity 58 and its projection to the ground 55, called the center of pressure 59. The center of gravity 58 and center of pressure 59 are well known physical properties, especially with respect to single track vehicles, such as motorcycles and bicycles, legged mobile robots, and the like, described in the prior art.

Referring now to FIGS. 3-7, several views of possible configurations of the legs and the method in which operation of the individual legs move are illustrated, whereby foot placement along the length of the body 42 and in the major direction of motion shall now be discussed. According to the preferred embodiment of the present invention, each leg 43 can be rotated about hip, knee, and ankle joints in three dimensions. FIG. 4 illustrates the side skeletal view of one possible configuration of the legs, wherein the x and z axes with the side or y axis into and out of the page. By convention, the left side is the forward direction. The first leg 43a is shown with its foot 45a extended forward with respect to its hip joints 46a, 47a, and 48a. Hereinafter, the terms forward or rearward shall be with respect to the hip joints 46, 47, and 48 along the length of the body 42. The second or middle foot 45b is shown in a middle or neutral position, and the third foot 45c is shown in a rearward extended position. From left to right, the first dashed cardioid 61a envelops and illustrates the total range of motion for the center bottom of foot 45a (hereinafter the center bottom of each foot is referred to as the foot), and a second rectangular dashed box 62a inscribed inside the first dashed cardioid 61a and illustrates the working range of motion for foot 45a. Two more dashed cardioids 61b and 62c and two more dashed boxes 62b and 62c illustrate the total range of motion and working range of motion for feet 45b and 45c, respectively. In operation, FIG. 4 shows the range of motion for each foot 45 of each leg 43 wherein there is a maximum working envelope 61 and a typical working range 62 for legged locomotion. Both the maximum working envelope 61 and typical working range 62 are three-dimensional volumes, but are shown as two-dimensional areas for clarity. Because the leg system shown uses hip, knee, and ankle joints, as previously described, the maximum working envelopes 61 is unique for that leg geometry.

Specific to this invention is the overlap of the typical working range 62a, 62b, and 62c, shown as a dashed rectangular boxes within the maximum working envelope 61a, 61b, and 61c, shown as dashed cardioids, because it is highly desirable to have a legged mobile robot which can operate on uneven surfaces, such as along narrow trails and paths, for example those found in parks and wilderness areas. That is, at a minimum the maximum working envelope 61a overlaps with 61b, and 61b overlaps with 61c, and at a minimum the typical working range 62a overlaps with 62b, and 62b overlaps with 62c. In other words, the typical working range of the front leg overlaps with the middle leg and the middle leg overlaps with the rear leg to enable in three dimensions the front foot 45a to be positioned alongside the middle foot 45b and the middle foot 45b to be positioned alongside the rear foot 45c without mechanical interference. FIG. 4 schematically shows a three-dimensional perspective view of a leg configuration wherein each foot is displaced to left or right side of the projected center of gravity such that feet 45a and 45c traverse a centerline 64 that is spatially displaced but parallel to the centerline 65 of foot 45b. FIG. 5 schematically shows the top view of FIG. 4 wherein the centers of feet 45 are shown as dots, displaced about the center of gravity 58 and its ground projection center of pressure 59 (not shown for clarity) of body 42. FIG. 4 schematically shows one possible configuration of the legs 43 of the legged mobile robot 41 in a resting stance configuration, such as when the robot is turned off, of the foot 45 placement and leg 43 geometry such that the legs are in a tripod configuration and the legged mobile robot does not fall over.

FIG. 6 schematically shows a side view where the front leg 43a is fully extended rearward and the middle leg 43b is fully extended forward. FIG. 7 schematically shows the top view of FIG. 6 wherein the centers of feet 45 are shown as dots, displaced about the center of gravity 58 and its ground projection center of pressure 59 (not shown for clarity) of body 42. The legs 43 and feet 45 may be configured in infinite variety such that the projected center of gravity 58, the center of pressure 59, is contained within the foot extent. In terms of the zero moment point (ZMP), the feet 45 are positioned such that the net moment or torque about the projected center of gravity 58, the center of pressure 59, is zero and the robot does not fall down. The advantage of such a range of motion can be seen in FIG. 8, wherein the extreme rearward position of the front leg 43a and the extreme forward position of middle leg 43b overlap such that the feet 45a and 45b are positioned similar to that of a biped. This design and method is highly important so that a legged machine can achieve the desired stability of balance, leap and jump, land, and so on, and in addition to the legs 43 being capable of operation in such a manner that it has a very narrow profile so that it can maneuver in a space where walking machines previously could not go, such as along a narrow path or trail or through a door.

Referring now to FIG. 8 and as was previously mentioned, dynamic momentum plays an important role in maintaining the stability of balance of dynamic or moving systems. Like wheeled motorcycles and bicycles, FIG. 8 shows the legged mobile robot 41 executing a single-track turn whereby the body 42 is spatially and angularly displaced from the normal plane of operation 44, called “leaning into the turn”, such that the center of gravity 58 and projected center of pressure 59 is moved towards the center of curvature 70 thus developing a torque about the roll axis 54 (not shown for clarity but refer to the feet 45) that counteracts the outward centripetal inertial force acting on the center of gravity 58 of the body 42. In leaning into a turn, the feet 45 are following a single track or in-line curve 71 of radius 72 about the center point 70 normal to the ground 55, and the body 42 is leaning with angle theta 73 between the normal reference plane 44 and the projected plane 74 tangent to the single track or in-line curve 71 on the ground 55 and through the center of gravity 58 and parallel to the body 42 length. The top of the body thus follows a second curve 75 of smaller radius 76 about the projected center point 70 normal to the ground such that the resulting plane of motion 77 is a truncated cone. The legged mobile robot 41 is able to lean into a turn like wheeled motorcycles and bicycles but with the advantage of a narrow profile along the direction of motion and the ability to choose discrete foot holds for the feet 45. This design and method is highly important so that a legged machine can achieve a high-speed turn and dynamic turns over rugged terrain not heretofore accomplished by legged mobile robots.

Referring again to FIG. 8, forward motion is achieved by any number of gaits, such as for example a wave gait, whereby each foot 45 is repositioned along the desired single track or in-line curve 71 with minor variation in radius 72 to achieve stability of balance and to develop torque to rotate the frame along a curved trajectory. A more aggressive gait, such as for example the leg crossover motion used by ice skaters where curve 71 is a piece-wise combination of curves of different radius and center point to achieve the overall desired motion of body 42. Such aggressive gaits would find use on lose ground or slippery surfaces, because for each piece-wise curve each leg 43 would not only develop an outward torque in the direction of slip that would further counteract the outward centripetal inertial force acting on the center of gravity 58 of the body 42 but would incrementally push the body 42 in the desired direction of motion. Furthermore, if bottoms of each of the feet 45 were ice skating blades, a piece-wise curve would develop force in the forward direction to propel the legged mobile robot 41 in the forward direction.

Referring now to FIGS. 9 and 10, the individual ankles 52 and 53 of the leg 43 of the legged mobile robot 41 are shown with a six dimensional force and torque sensor 81 of conventional design. By measuring the x, y and z force components Fx, Fy and Fz transmitted to the legged mobile robot 41 through the feet 45 and also measuring the moment components Mx, My and Mz around the three axes, the six-dimensional force and torque sensor 81 detects whether or not the associated foot 45 has landed and the magnitude and direction of the forces acting on the supporting leg 43. The body 42 may be provided with a three-dimensional inclination sensor 82, called an inertial measurement unit or IMU, rigidly connected by mount 83 that is ultimately connected to leg mounts 56 and 57, not shown for clarity. The IMU is sometimes also referred to as an inertial navigation system or INS. An INS combines the IMU with complementary filters and kinematic proprioceptive information (body height, center of pressure, zero moment point, etc.) to provide more accurate dynamic information. The IMU 82 measures the robot's three-dimensional (roll, pitch, and yaw) angle, angular velocity, and angular acceleration relative to z axis in the x-z reference plane 44, y-z plane, and ground (x-y) plane 55, not shown for clarity.

Still referring to FIG. 9, each actuator at the individual joints 46, 47, 48, 50, 52, and 53 is provided with an encoder disposed adjacent to the respective motors for generating sensed kinematic data for actuation control, proposition and posture. As illustrated in FIG. 9, the legged mobile robot 41 is provided with a zero reference switch 84, such as an oil-damped pendulum, for calibrating the output of the IMU 83 and a limit switch 85 for a failsafe to stop motion in the case of overturn. The outputs of the sensors 81, 82, 83, and 85 are sent to the control system 86. The control system 86, which may be synonymous with the control system, is a computer comprising the at least one central processing unit or CPU 87, read only memory or ROM 88, random access memory or RAM 89, data storage 90, such as for example a solid state drive, and input output devices including but not limited to digital to analog converter or D/A 91, digital counter 92, digital interface 93, such as for example a universal serial bus or USB port, analog to digital converter or A/D 94, and network interface 95, such as for example an Ethernet port. All aforementioned devices are connected together by the at least one bus 96. The angle, angle rate or velocity, and angle acceleration 97, from the inclination sensor 83 is communicated to the control unit 87 via the digital interface 93. The D/A output 91 is amplified 98 to control joint actuators 46, 47, 48, 50, 52, and 53 with resulting encoders provide joint angle feedback 99 converted into digital signals by counter 92. Feedback 100 from six dimensional force and torque sensor 81 is input to the A/D 94. The resulting digital values are sent via a bus 96 to RAM 89 for storage.

When a large disturbance is applied, one or more legs 43 may be repositioned to counteract the force. The pitch angle and angular velocity of the body 42 is measured using the IMU 83 combined with complementary filters and kinematic proprioceptive information (body height, center of pressure, zero moment point, etc.). The angular sideways velocity and angular sideways displacement of the leg 43 may be measured with rotary encoder 99. Using said feedback, the control input, u, may be modeled.

The body 42 leans in the direction from which the external force is applied. Full-state feedback may be used to control the stabilization of the upright equilibrium or balance, and a reduced-order disturbance observer estimates the external force. Through the use of estimated external forces, the hip torque and/or leg/foot repositioning occurs. Further refinement of control considers the steering angle and the driving torque. Insofar as a model which faithfully simulates the dynamics of the actual robot is created and the difference between the ground reaction force of the actual robot and that of the robot model is controlled, the same principle can be applied with the same effect irrespective of the number of single track or in-line legs.

FIG. 10 is a front skeletal view illustrating the principles of the present invention. The legged mobile robot 41 is shown with at least one leg 43 and foot 45 in contact with ground 55 after the feet 45 have started to lose traction. Uncontrolled foot slip is measured by the IMU 82 and foot force and torque sensor 81. The IMU 82 senses changes in the rate of body 42 roll and the foot force and torque sensor 81 senses changes in the foot traction. As foot slip continues to increase, traction will approach zero and rate of roll will increase measurably. The control unit 86 receives continuous measurement data from the sensors and determines via an algorithm if data inputs of slip and rate of roll are higher than achievable when feet have lateral traction with the ground. A desired counteracting moment can be produced by controlling the joint actuations so as to produce a moment in the direction of attitude restoration. In other words, a restoring force acts to bring the inclination of the legged mobile robot closer to that of the model. The restoring force is produced by deliberately shifting a foot away from that of the target walking pattern to shift the ground reaction forces to regain stability of balance.

It is known that as the traction of the feet 45 approaches zero (due to a slippery roadway or loose road surface, for example) the roll axis 54 moves to the center of mass 58 of the body 42 as shown in FIG. 34. The reasons that traction approaches zero (rate of roll increases) are: 1) as the feet lose traction, the leg frictional force 115 with the ground 55 is now based on the coefficient of kinetic friction instead of the coefficient of static friction; 2) friction is reduced as feet lose lateral traction uncontrollably because some of the vehicle weight is in a free state; and 3) the polar moment of inertia moves to the center of mass 103. As the legged mobile robot is rolling from an upright position to an attitude deviating from the vertical, the normal force 114 on the feet decreases to zero. In other words, traction approaches zero as the load transfers from the feet 45 to the free-falling center of mass 103 (roll axes). It is also known that the polar moment of inertia is simultaneously reduced as the roll axis moves towards the center of mass 58, allowing the legged mobile robot 41 to roll at an increased rate.

The initial condition is when the center of gravity 58 is above the supporting point of the foot. The actuator encoders 99 measure kinematic proprioception and the IMU 82 measures body 42 displacements from the vertical reference plane 44, are compared by the control unit to make a more precise determination as to criticality of rate of roll. FIG. 21 is a simplified front view skeletal diagram illustrating the movement of body roll axis as foot traction approaches zero. In particular, the legged mobile robot 41 is shown in a tilted position. When uncontrolled slip is detected, a leg in flight or near flight phase or the leg contributing least to the expected stability of the body is repositioned to catch the fall. That is in order to stabilize the legged vehicle and prevent turnover, the trajectory of the body 42 as an inverted pendulum is computed and the at least one leg, called the swing leg, is extended in the direction of the fall. Planning of this swing leg involves controlling two parameters. First, FIG. 10 shows that the center of gravity 58 trajectory is expressed as an inverted pendulum whose leg length is constant and thus defines an arc of radius R2. The center of gravity 58 moves in a circular orbit about the supporting foot 45, and the projected center of pressure 59 and zero moment point shifts in the direction of the fall. Second, the expected moment of inertia of the body 42 is calculated for the future time of when the fall would be caught, and a torque is computed to counteract the fall, which then computes the distance, d, required from the projected center of pressure and the swing leg arc of radius R1. The control unit 86 adjusts the placement of the at least one foot so as to position the foot beyond the projected center of gravity and in the direction of the roll. As a result, a counteracting moment can be induced to obtain a large attitude restoring force, to catch the fall and prevent vehicle overturn. Simultaneously, the control unit 86 re-adjusts the gait pattern of the other legs such that in mid-step or in following footstep, the walking gait is restored. It should be noted that the system of the present invention can operate on the basis of the IMU data 97 alone or the kinematic proprioception data 99 and 100 alone.

As the outstretched foot touches ground 55 and body roll is stopped, the IMU data 97 and kinematic proprioception data 99 and 100 is feed back to the control unit 86. While the outstretched leg and foot keeps the legged mobile robot 41 from overturning or lying down on its side, it does not immediately force the body 42 into an upright position. Rather, the at least one rider or passenger may regain control of the vehicle while it is held at an attitude very close to that at which control was originally lost. After a predetermined pause to allow the at least one rider or passenger to regain control, the legs 43 and feet 45 are repositioned through the recovery gait to raise the legged mobile robot 41 to the fully upright position. Depending on the circumstances (e.g., based on input from kinematic proprioception and high-level commands), the control unit 86 is additionally programmed to slow or stop all motion and transition the legs 43 to a stable tripod stance, such that all three feet 45 are in contact with ground 55, but not necessarily with equal force. If the legged mobile robot 41 has come to incline greatly with respect to the maximum leg reach given the actuation time and time of fall, it is not possible to obtain a righting force to restore balance. Thus a cautious rider may never lose lateral traction in which case the system of the present invention would not become operative.

While the invention has thus been shown and described with reference to the specific embodiments, it will be apparent to those skilled in the art that various changes, modifications, and improvements may be made without departing from the scope and spirit of the invention. Accordingly it is to be understood that the invention is not limited by the scope of the illustrative embodiment or to the details of the described arrangements. For example, the present invention has been shown and described as being a three legged robot. However, the design and method of the present invention is also applicable to an articulated body structure for a multi-legged walking robot having two, three, four or more in-line legs. In another example, the single track or in-line legs may be adapted for movement on the surface of or through water. In another example, while many of the embodiments were shown and described with reference to straight line motion, the invention also enables trajectories for various curved motion and situations, including curved trajectory stair climbing and descent. In another example, while many of the embodiments were shown and described with reference to a foot-based sensor for determining the foot and leg forces and torques and motor encoders for leg position and orientation, the invention is not limited to this type of control and sensing. In another example, while many of the embodiments were shown and described with respect to application of models and other *a priori* data set in advance, this is not limitative and the invention can also be applied in cases where the control values during locomotion are calculated completely in real time. Moreover, while invention was shown and described with reference to a legged mobile robot, the invention can not only be applied to other types of mobile robots, but can also be applied to various stationary industrial robots. Furthermore, the invention can also be applied to movable objects other than robots.

CLAIMS:

What is claimed is:

1. A legged vehicle comprises:

a frame, wherein the frame includes a major axis corresponding to and generally parallel to a forward/backward direction of travel;

a plurality of jointed leg mechanisms attached to the frame, one behind the other, wherein each leg is attached at its proximal end at one or more discrete attachment points, wherein the attachment points are arranged substantially parallel to the major axis of the frame and the forward/backward direction of travel, each of the legs including actuators attached between the legs and the frame and between adjacent leg members, said legs being actuated for movement of a distal end in three dimensions, wherein forward/backward movement of the legged vehicle is according to approximately single track foot placement;

a control system in communication with the leg mechanisms and receiving sensed data to determine possible future states of the legged vehicle and to coordinate movements of the leg mechanisms and frame, and movement of the legged vehicle in three dimensions over the ground; and

a power source connected to and driving the control system components and the plurality of actuators which drive the legs.

2. The legged vehicle of claim 1, wherein the number of legs is three.

3. The legged vehicle of claim 1, wherein the number of legs is more than three.

4. The legged vehicle of claim 1, wherein each of the plurality of legs includes a foot at the distal end.

5. The legged vehicle of claim 1, wherein the feet include at least one of plates, skids, spikes, wheels, skates, skies, slides, floats, hydroplanes, and fingers.

6. The legged vehicle of claim 1, wherein the frame is a single piece unit.

7. The legged vehicle of claim 1, wherein the frame is jointed and includes two or more segments, each having a major axis corresponding to and generally parallel to a forward/backward direction of travel.

8. The legged vehicle of claim 1, wherein the control system further comprises

at least one accelerometer and at least one gyroscope mounted on the frame and and in communication with the control system, the control system receiving sensed data from the at least one accelerometer and at least one gyroscope to sense velocity, acceleration, attitude, and gravitational forces.

9. The legged vehicle of claim 1, wherein each leg mechanism includes position-measuring components providing feedback to the control system.

10. The legged vehicle of claim 1, wherein each leg mechanism includes force-measuring components providing feedback to the control system.

11. The legged vehicle of claim 1, wherein each leg mechanism includes torque-measuring components providing feedback to the control system.

12. The legged vehicle of claim 1, wherein the movement range for each of the legs defines a working envelope, each of the feet having sufficient reach and movement range in length, width and height, relative to the frame to position two feet generally perpendicular to the major axis of the frame, with one foot positioned to the left of and one to the right of the projected center of gravity of the frame to provide stability in the roll axis.

13. The legged vehicle of claim 1, wherein the movement range for each of the legs defines a working envelope, each of the feet having sufficient reach and movement range in length, width and height, relative to the frame to position the first, second and third feet in a triangular tripedal stance, wherein the projected center of gravity of the frame is located within the tripedal stance, providing stability in both the pitch and roll axes.

14. The legged vehicle of claim 1, wherein the movement range for each of the legs provides range-of-motion overlap in length, width and height of the working envelopes of each adjacent foot, one in front of and one behind the other.

15. The legged vehicle of claim 1, wherein the feet of two adjacent legs, one in front of and one behind the other, are positionable side-by-side to form a generally bipedal stance along a center of pressure line generally normal to the frame and normal to the line of motion to achieve a bipedal stance.

16. The legged vehicle of claim 1, further comprising:

a control unit having an operator interface, in communication with the control system, the control system receiving sensed data from the operator.

17. The legged vehicle of claim 16, wherein the operator interface components provide at least steering angle, throttle and braking inputs into the control system.

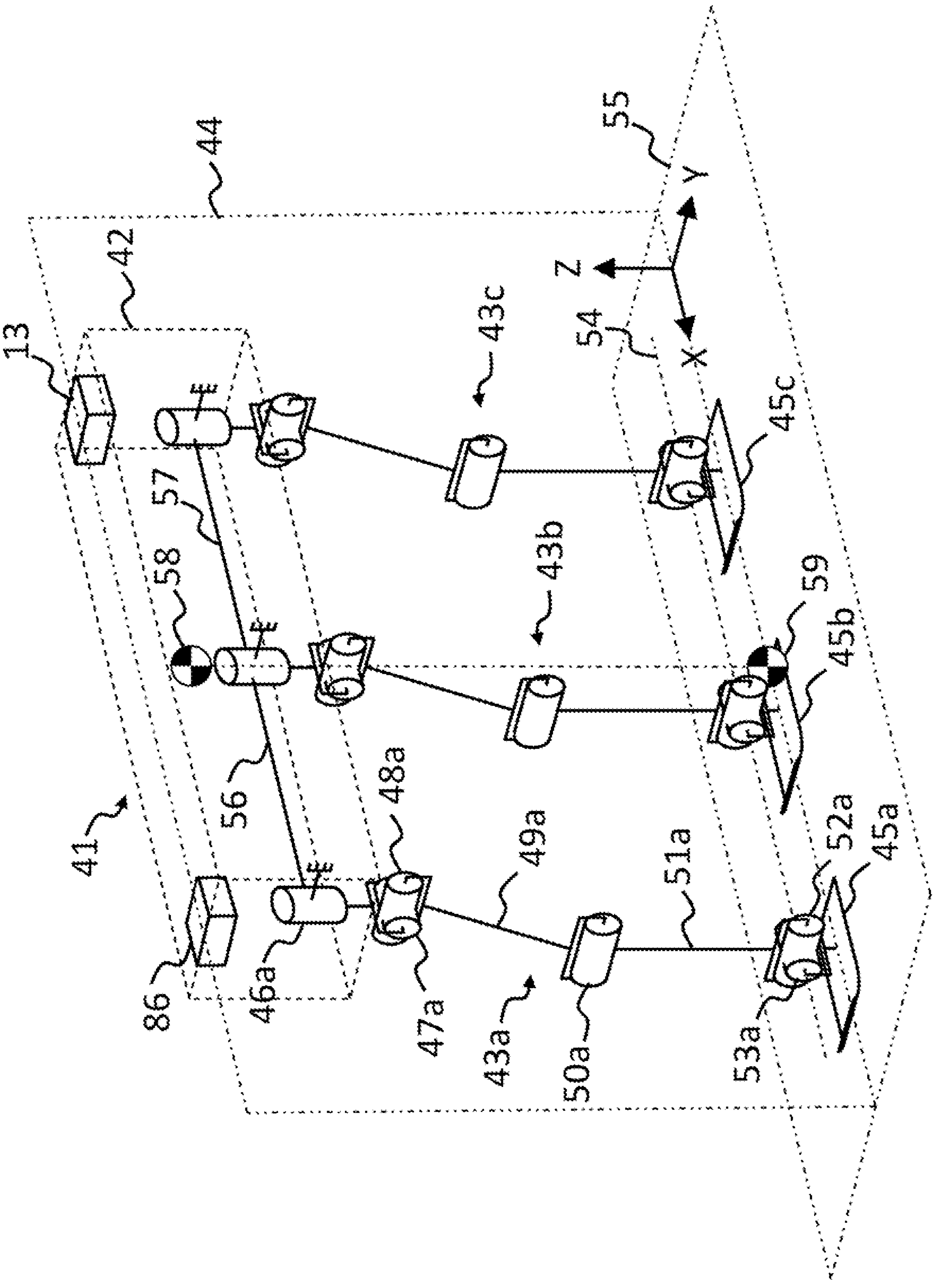
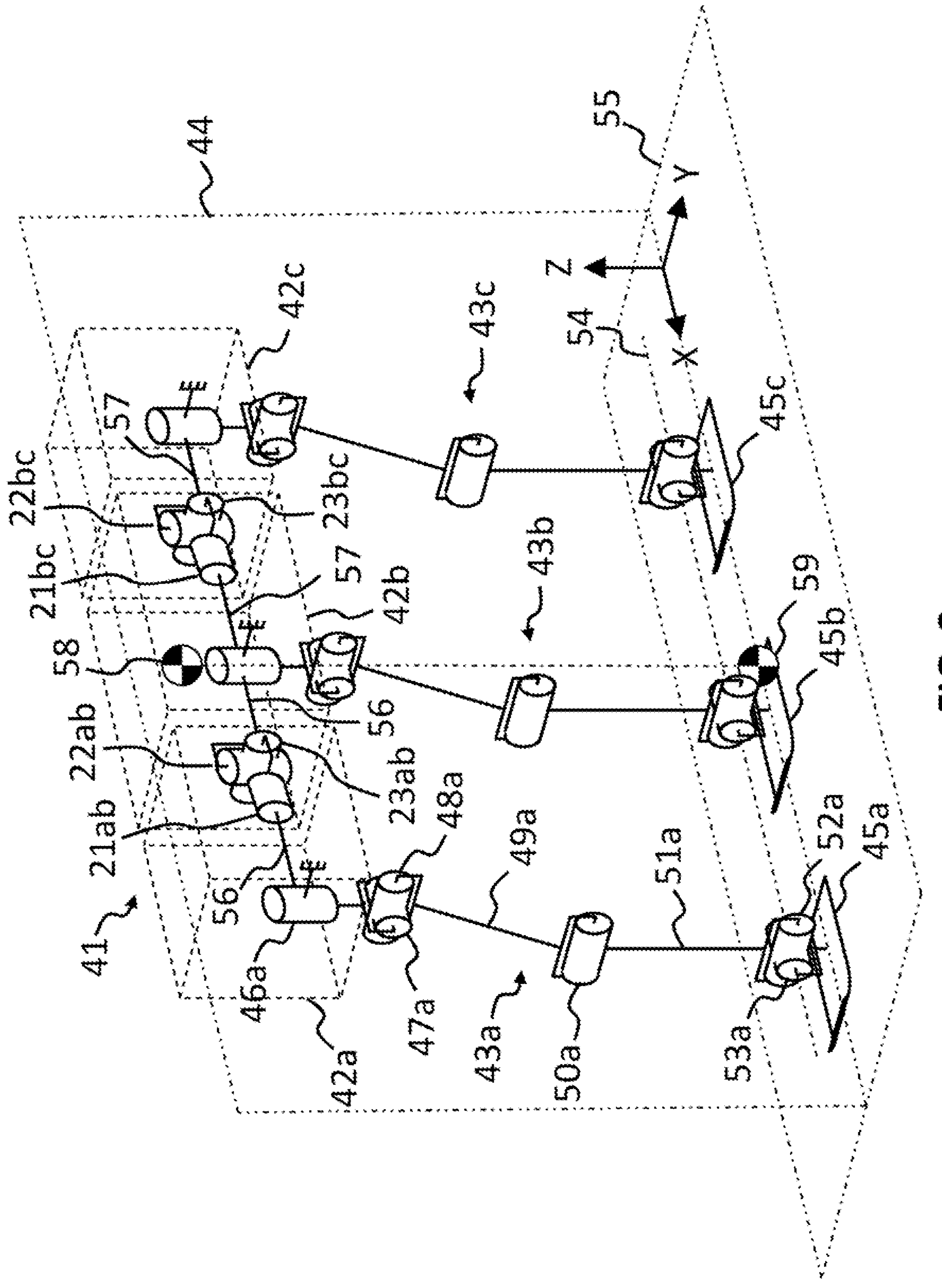

13
42
44
43c
55
Z
Y
X
54
45c
57
58
43b
59
45b
41
56
48a
49a
51a
52a
45a
86
46a
47a
43a
50a
53a

FIG. 1


44
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Y
Z
X
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42c
43c
57
22bc
23bc
21bc
57
42b
43b
59
45c
45b
58
56
22ab
23ab
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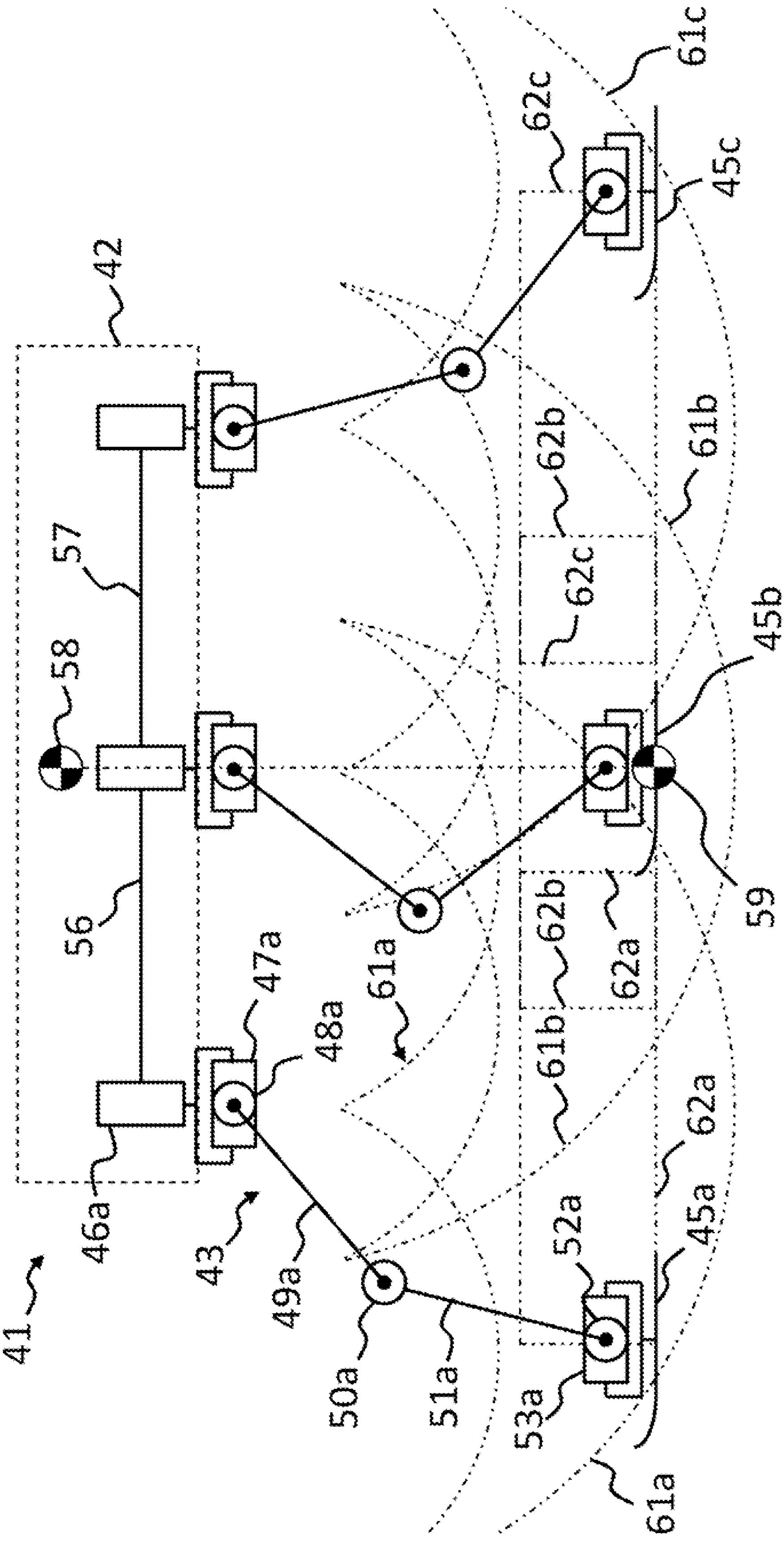
49a
51a
52a
45a
21ab
41
56
46a
42a
47a
43a
50a
53a

FIG. 2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43
46a
47a
48a
49a
50a
51a
52a
53a
45a
45b
45c
56
57
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61c
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62a
62b
62b
62c
62c

FIG. 3

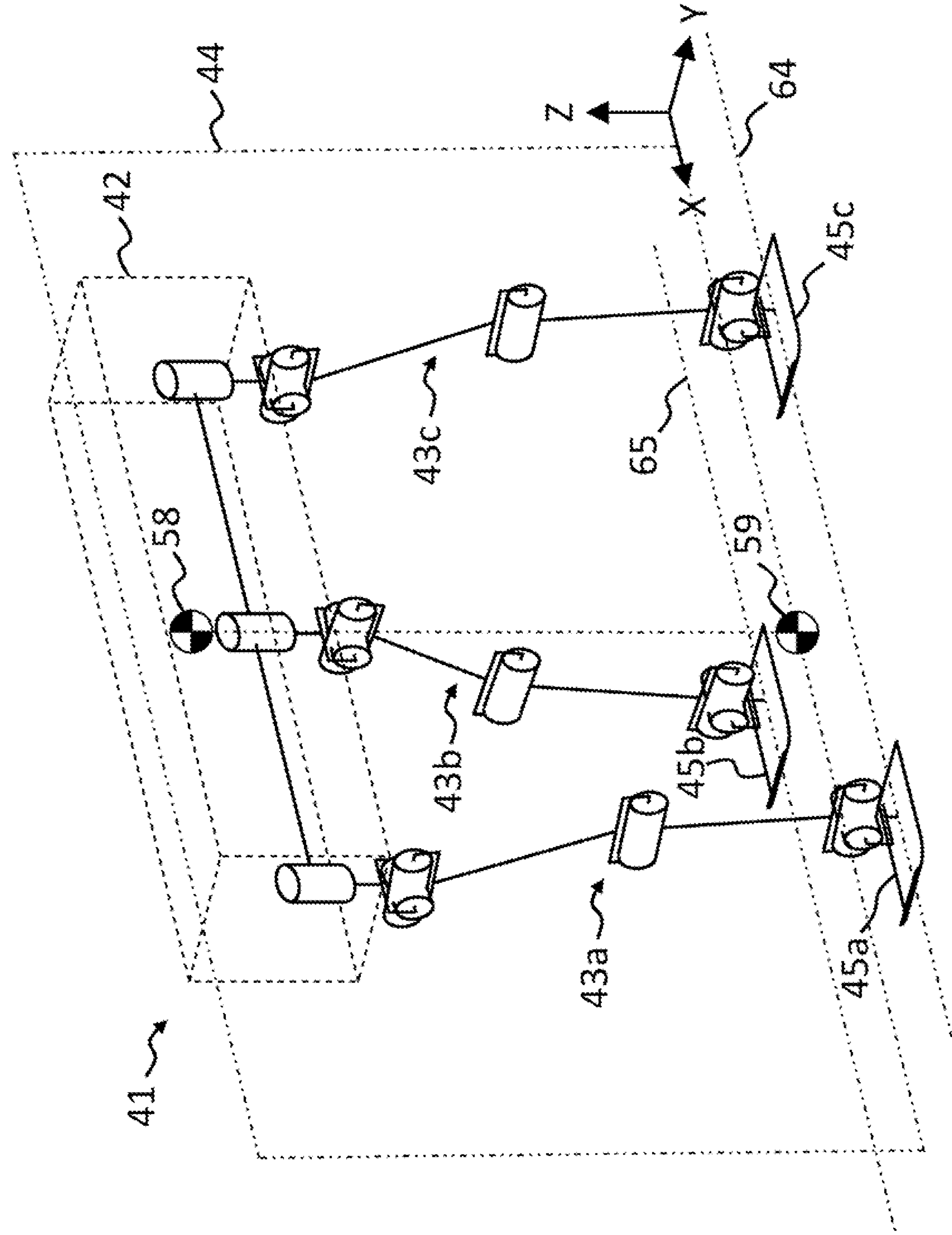


FIG. 4

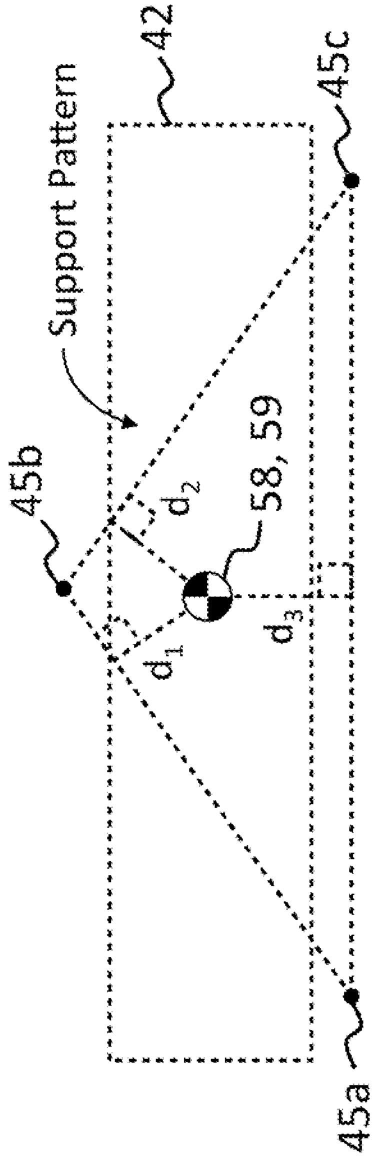


FIG. 5

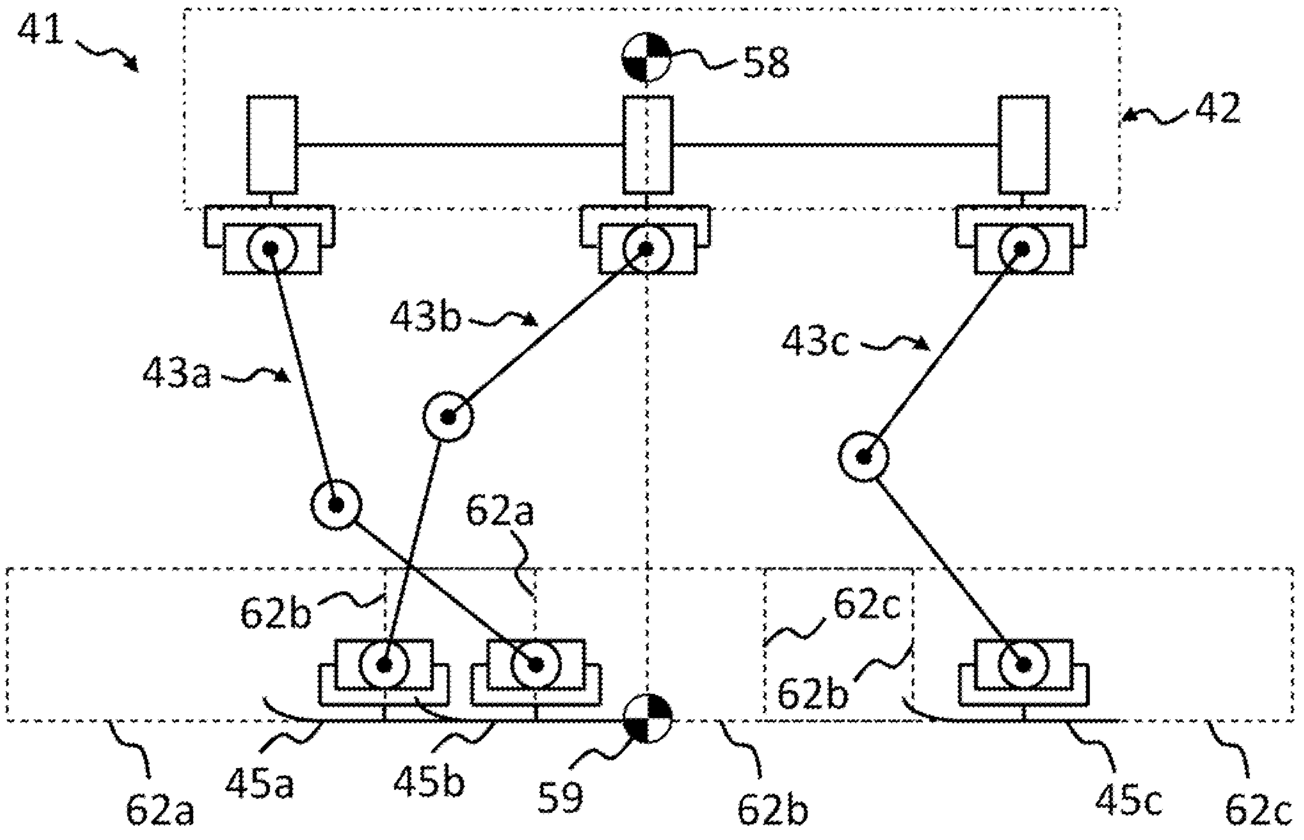


FIG. 6

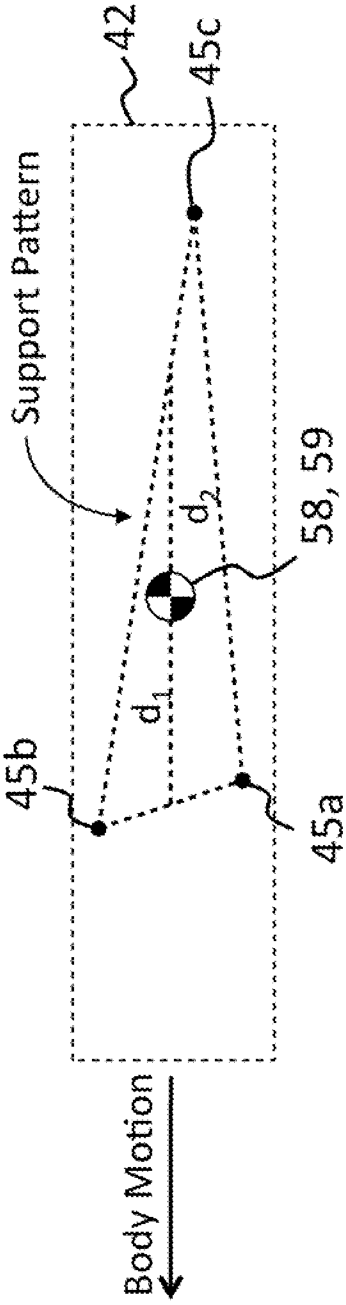


FIG. 7

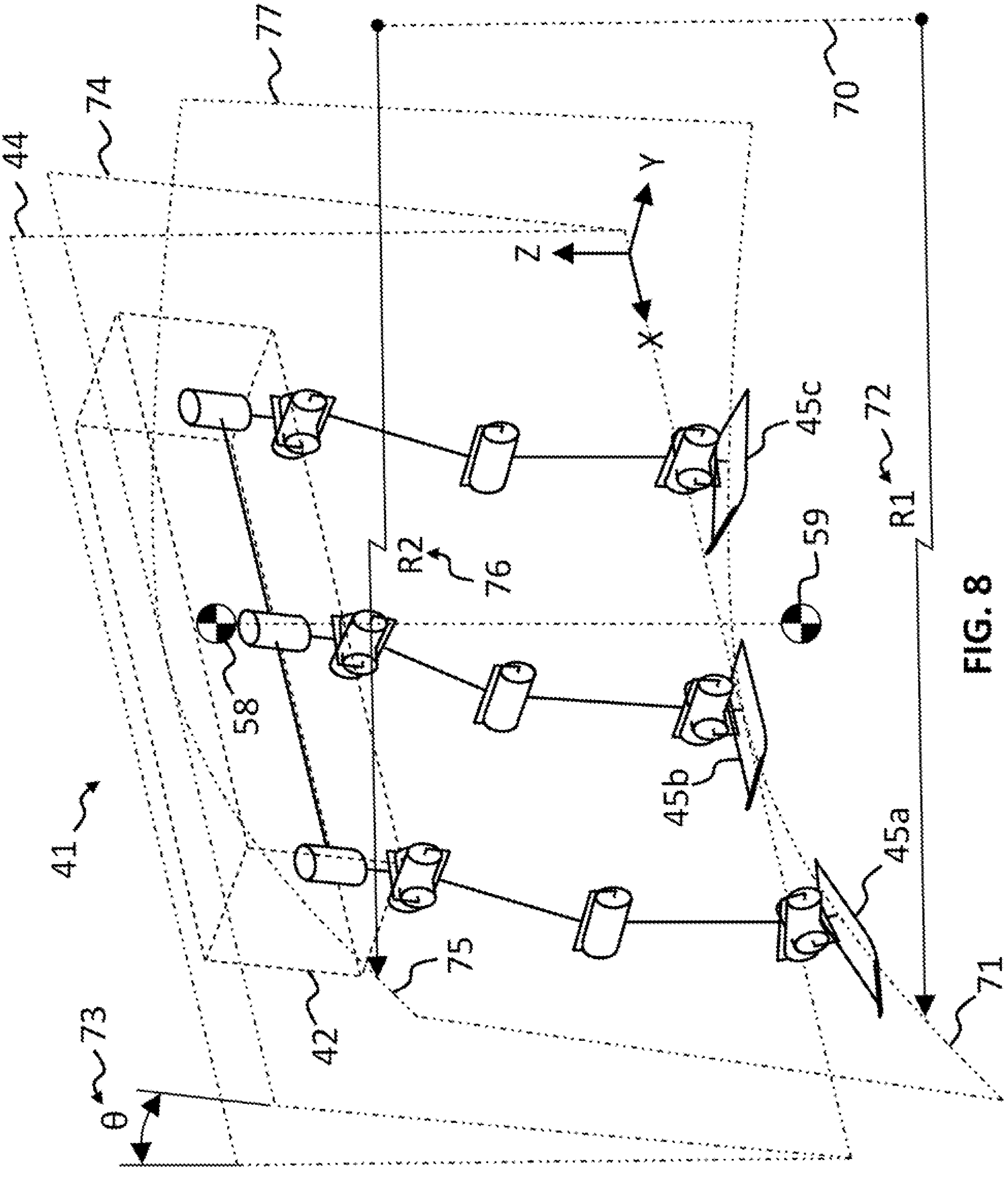
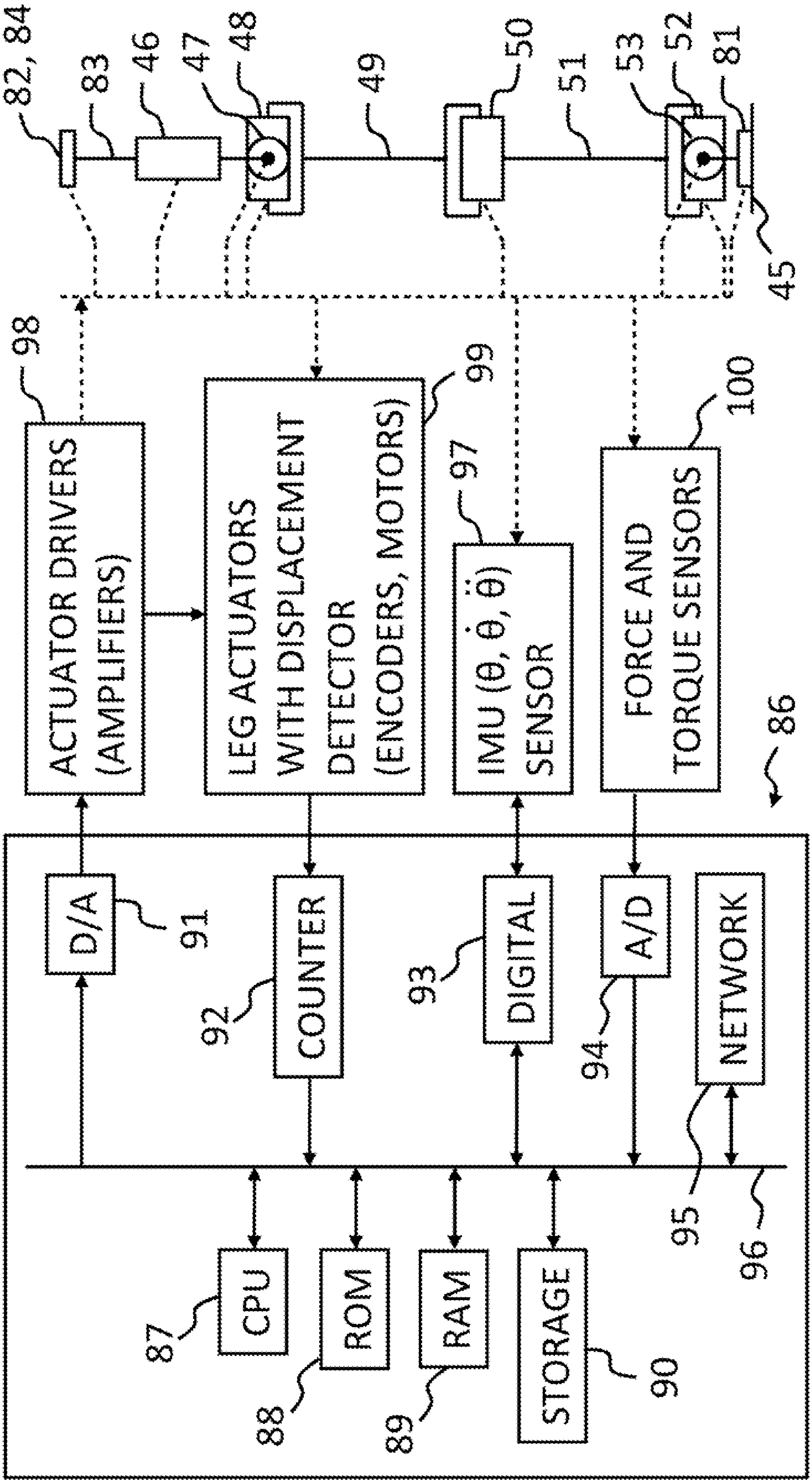


FIG. 8


82, 84
83
46
47
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53
52
81
45
98
ACTUATOR DRIVERS (AMPLIFIERS)
99
LEG ACTUATORS WITH DISPLACEMENT DETECTOR (ENCODERS, MOTORS)
97
IMU (θ, $\dot{\theta}$, $\ddot{\theta}$) SENSOR
100
FORCE AND TORQUE SENSORS
86
D/A
91
COUNTER
92
DIGITAL
93
A/D
94
NETWORK
95
96
CPU
87
ROM
88
RAM
89
STORAGE
90

FIG. 9

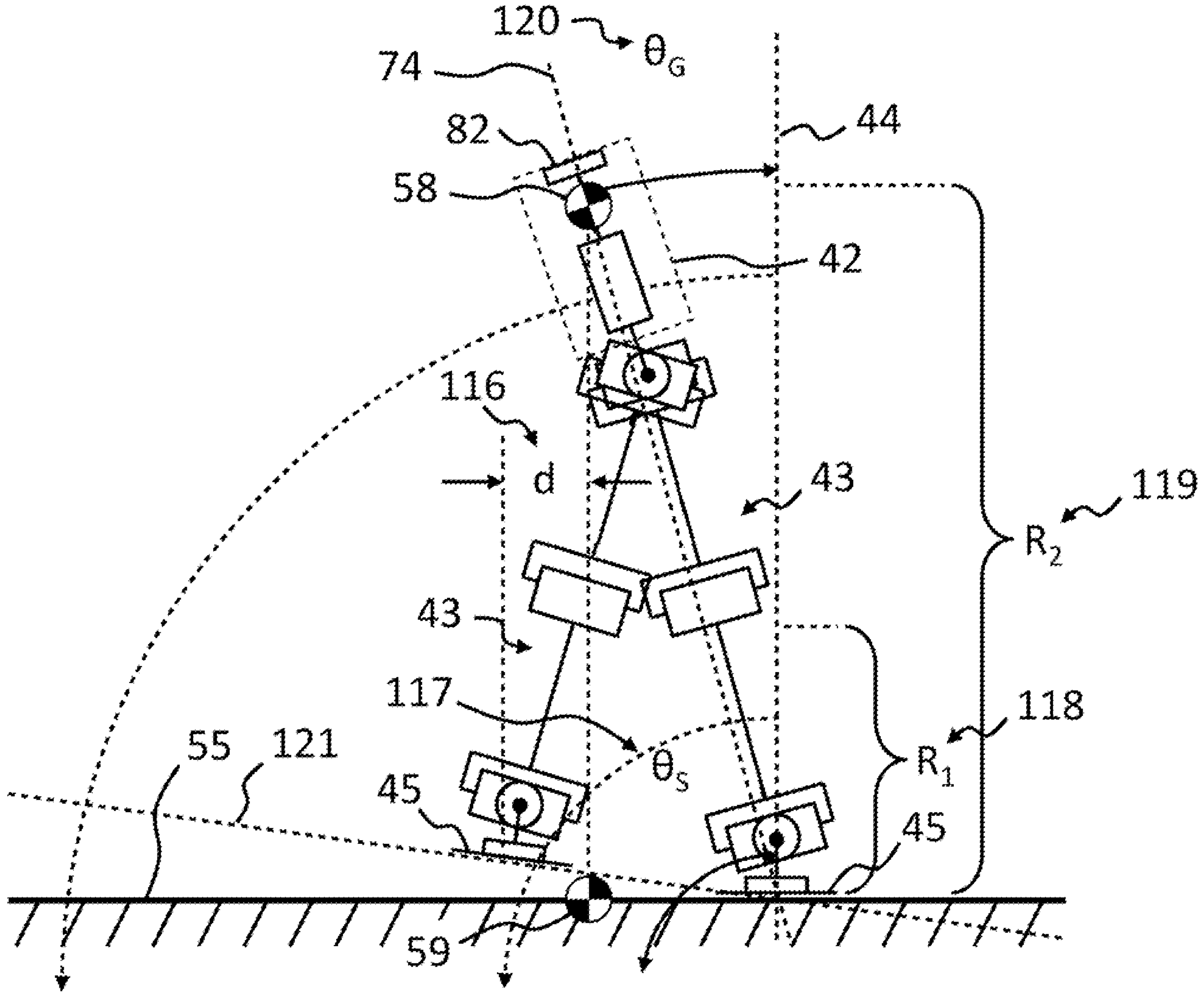

FIG. 10