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2	Application Data Sheet	US0032_ADS.pdf	1028165 c847a860597b9d5e27185c7435d744f8d079629f	no	6
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5	Non Patent Literature	Brown_Stabilized_robots_1996.pdf	695044 9e5ef3a2b7144e71cff9ae066a38124970ceadb8	no	6
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6	Non Patent Literature	Nandy_Gyoscopic_wheel_IEEE1998.pdf	482262 633175d210ffaaa8aecdf45be8cd328f8d88fad6	no	6
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12	Non Patent Literature	Srivastava_Spherical_Rotation_JAppMath_2009USPTO.pdf	2585173 9c74f527c959e8f84c0d61c2af9b210a112a4a9a	no	13
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15	Non Patent Literature	Xu_Dynamically_stabilized_robot_1999USPTO.pdf	3301694 421e19214bff2deaa75994cc7fda69b98f3ade26	no	11
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16	Non Patent Literature	Ylikorpi_Ball_shaped_Robots_Oct2007USPTO.pdf	9191162 db133a06e998d1c316b53a6b8c0eb25b263676ab	no	22
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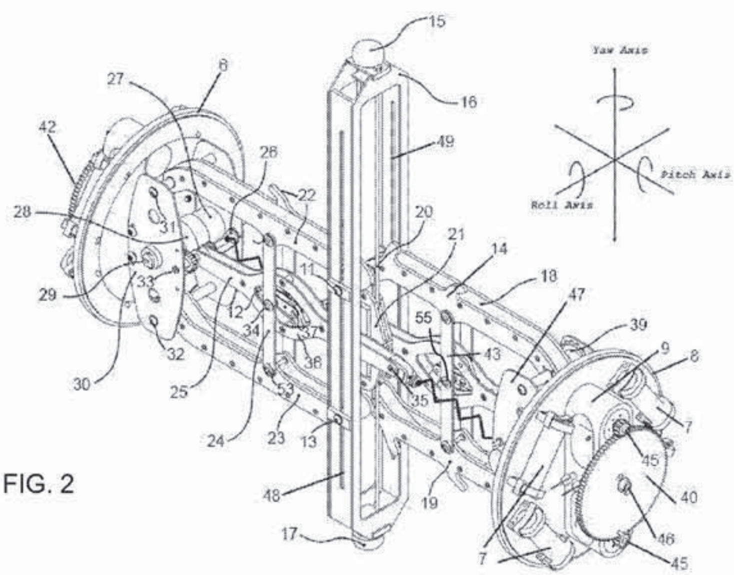

FIG. 2

(57) **Abstract**: Robotic systems according to the invention include a frame or body with two or more wheels rotatably mounted on the frame or body and a motor for independently driving each wheel. A system controller generates a signal for actuating each motor based on information provided by one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, throwing and catching. A power source is included for providing power to operate the drive motors, system controller and the one or more sensors.

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MULTIMODAL DYNAMIC ROBOTIC SYSTEMS

RELATED APPLICATIONS

This application claims the priority of U.S. Provisional Applications No. 61/231,672, filed August 6, 2009, and No. 61/324,258, filed April 14, 2010, which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to robotic mechanisms that exhibit multimodal capability including rolling, hopping, balancing, climbing, and picking up and throwing objects. More particularly, the invention relates to multimodal dynamic robotic systems that can move and function efficiently on complex terrain and/or in harsh operating environments.

BACKGROUND OF THE INVENTION

Robots have been developed for applications ranging from material transportation in factory environments to space exploration. One area in which mobile robots have been widely adopted is in the automobile industry, where robots transport components from manufacturing work stations to the assembly lines. These automated guided vehicles (AGVs) follow a track on the ground and have the ability to avoid collisions with obstacles in their path. Autonomous mobile robots designed for planetary exploration and sample collection during space missions, such as NASA's Mars Exploration Rover, have also received significant attention in recent years. This attention has resulted in advancement of mobile robot technology and a corresponding increase in the effectiveness of mobile robots in a wide range of applications.

Mobile robot technology has primarily focused on robot designs having a body with wheels for mobility. This has led to advancements in motion planning and control of the rolling wheel. Notwithstanding these developments, wheeled mobile robots have significant deficiencies that have not been adequately overcome. For example, wheeled robots frequently have difficulty traversing rough terrain. While this problem may be reduced by increasing the size of the wheels of the robot, increases in wheel size cause various undesirable consequences including an increase in the overall size and weight of the robot. Further, increases in wheel sizes do not necessarily result in corresponding increases in operational features such as payload capacity. Also, wheeled robots can be adversely affected by harsh operating environments such as heat, chemicals, and the like.

A variation of a wheeled robot that addresses certain difficulties found in harsh environments is described in U.S. Patent Publication No. 2008/0230285 A1, which shares partial inventorship with the present application. The cited application, which is incorporated herein by reference, describes the first vehicle of its kind which combines efficient wheeled locomotion with a hopping capability. The multimodal robot adds hopping and climbing capability to a wheeled robot by attaching the axle to a central leg so that relative movement of the leg and axle can lift axle. A hopping action can be produced by applying sudden downward force to drive the leg against the support surface. Stair climbing is provided by applying a steady force against the support surface to allow the wheels to climb up the vertical riser. The leg also provides additional stabilization for movement across uneven terrain. In one embodiment, the multimodal robot's wheels are mounted on independently-moving axes that have independent parallelogram linkages to permit the wheels to change relative orientations and tilt.

One alternative to the wheeled robot is the rolling robot. A rolling robot is one that rolls on its entire outer surface rather than on external wheels or treads. They tend to be spherical or cylindrical in form and have a single axle, if any axle at all, and an outer surface that is fully involved in the robot's movement. State-of-the-art rolling robots are all based on the principle of moving the center of gravity of a wheel or sphere, which causes the wheel or sphere to fall in the direction of movement and thus roll along. Rolling robots have a number of advantages over wheeled robots including that the components of the robot are enclosed within a shell, so there are no extremities to hang-up on obstacles, they don't fall over, they can travel on soft surfaces, including water, and they can move in any direction and turn in place.

Improvements in methods of locomotion are needed to allow robotic systems to move within environments that are difficult or impossible for currently-used robot locomotion designs to traverse. The following description discloses such improvements.

BRIEF SUMMARY OF THE INVENTION

It is an advantage of the present invention to provide a multimodal robot that can move and function efficiently on complex terrain and/or in harsh operating environments.

In an exemplary embodiment, the robotic systems according to the invention include a frame or body with two or more wheels rotatably mounted on the frame or body and a motor for independently driving each wheel. A system controller generates a signal for actuating each motor based on information provided by one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, and throwing. A power source is included for providing power to operate the drive motors, system controller and the one or more sensors.

In one aspect of the invention, a robotic system according includes a frame with two or more wheels rotatably mounted thereon and a motor for independently driving each wheel. A system controller generates a signal for actuating each motor based on information provided by one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, and throwing. A power source is included for providing power to operate the drive motors, system controller and the one or more sensors. The frame includes two arms, each having a distal end on which a wheel is mounted and a proximal end and a leg centrally disposed between the two arms with the proximal end of each arm rotatably attached to the leg. An arm motor is disposed on each arm for independently driving rotation of the arm relative to the leg, so that when the leg is disposed in a vertical orientation with an end of the leg in contact with a support surface, (i) downward symmetrical rotation of the arms positions the wheels in contact with the support surface for wheeled locomotion on the support surface, (ii) rapid upward symmetrical rotation of the arms lifts the leg off of the support surface to produce a hopping motion; and (iii) antisymmetrical rotation of the arms balances the frame on the end of the leg.

In another aspect of the invention, a robotic system according includes a body with two or more wheels rotatably mounted thereon and a motor for independently driving each wheel. A system controller generates a signal for actuating each motor based on information provided by one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, and throwing. A power source is included for providing power to operate the drive motors, system controller and the one or more sensors. The body comprises a chassis having two drive wheels rotatably mounted on opposite sides thereof, each drive wheel disposed on an axle that is rotated by a corresponding drive motor for rotating the drive wheel. A pair of elongated arms is rotatably mounted on opposite sides of and perpendicular to the chassis, each arm having a proximal end disposed on a corresponding axle, and a distal end, on which a second wheel is mounted in a common plane with the corresponding drive wheel. A second motor is associated with each arm, and a linkage between the second motor and the axle for each arm causes the second motor, when activated, to rotate one of the chassis and the corresponding arm relative to the other. Independent activation of the second motor of both arms to rotate the arms symmetrically relative to the chassis shifts a center of gravity for balancing on one of the distal end or proximal end of the arms. The linkage between the second motor and the axle for each arm and a linkage between the drive motor and the drive wheel can be incorporated into a two-degree of freedom joint. In one embodiment, each arm supports a track.

In still another aspect of the invention, a robotic system according includes a body with two or more wheels rotatably mounted thereon and a motor for independently driving each wheel. A system controller generates a signal for actuating each motor based on information provided by one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, and throwing. A power source is included for providing power to operate the drive motors, system controller and the one or more sensors. The body comprises a chassis having two drive wheels rotatably mounted on opposite sides thereof, attached to a corresponding drive motor for rotating the drive wheel. A pair of elongated drive arms is rotatably mounted on opposite sides of and perpendicular to the chassis, with each drive arm having a proximal end disposed on a corresponding axle, and a distal end which supports a second wheel in a common plane with the corresponding drive wheel. A boom arm comprising a weighted portion attached to connector arms that are pivotably mounted on each side of the chassis so that the weighted portion is disposed parallel to the chassis. At least one second motor is connected to the connector arms by a linkage such that activation of the at least one second motor rotates one of the chassis and the boom arm relative to the other. Independent activation of the at least one second motor shifts a center of gravity for balancing on one of the distal end or proximal end of the drive arms. The system controller controls the drive motors and the at least one second motor to reactively shift the center of gravity for stability. In one embodiment, each arm supports a track.

In another aspect of the invention, a robotic system according includes a frame with two or more wheels rotatably mounted thereon and a motor for independently driving each wheel. A system controller generates a signal for actuating each motor based on information provided by one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, and throwing. A power source is included for providing power to operate the drive motors, system controller and the one or more sensors. The two or more wheels comprise a plurality of reaction wheels and the motor for driving each reaction wheel is disposed within a housing to define a plurality of momentum exchange elements mounted on one or more axes attached to the frame. The frame comprises a geometrical structure which allows the plurality of momentum exchange elements to be distributed about the frame to individually or simultaneously generate angular momentum in a plurality of different directions. In one variation, the one or more axes comprise a single gimbal axis, each having a corresponding gimbal motor. In another variation, the one or more axes comprise a double gimbal axis, each having two corresponding gimbal motors. A shell may be provided to enclose the frame and momentum exchange elements.

In yet another aspect of the invention, a robotic system includes a body with two or more wheels rotatably mounted thereon and a motor for independently driving each wheel. A system controller generates a signal for actuating each motor based on information provided by one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, and throwing. A power source is included for providing power to operate the drive motors, system controller and the one or more sensors. The body is configured as a cylinder having a rotational axis, the cylinder having two ends, each end defining a hub having an axle aligned with the rotational axis for rotatably retaining a wheel, the body having a cavity therein defining a storage volume for retaining an object having an object diameter. An elongated arm extends away from the body perpendicular to the rotational axis so that a base portion of the elongated arm is in communication with the storage volume. A lower body portion opposite the elongated arm is symmetrical along a plane bisecting the cylinder. A curved channel is located on each side of the bisecting plane with an exit end in communication with the storage volume and an entrance end defined by the hub, the lower body portion and an inner surface of the wheel. Each channel has a dimension for receiving the object to produce a frictional contact between the inner surface of the wheel, the hub and the lower body portion, so that rotation of the wheel draws the object into the channel and into the storage volume. The drive motors are adapted for rotating the body relative to the wheels so that the elongated arm can be oriented in a horizontal position. With the elongated arm oriented in a horizontal position, rapid activation of the motors rotates the corresponding wheels in a first direction causing the body to rotate around the rotational axis in an opposite direction to rapidly accelerate the horizontal arm toward a vertical position. An object disposed on the base portion of the elongated arm rolls toward a distal end of the arm as the elongated arm accelerates toward the vertical position, causing the object to be thrown when the object reaches the distal end of the arm.

In a first exemplary embodiment, enhanced mobility within a harsh environment, which may include rough terrain or hazards, is provided in a modification of a wheeled robot which combines a hopping ability with a leaning maneuver. The inventive robot includes end-over-end stair climbing capability, which involves raising its center of mass above the obstacle while balancing the vehicle on its toe and shifting the mass of the drive wheels side-to side for balance.

The robot of the first embodiment comprises two independently driven wheels mounted on the ends of two independently driven arm assemblies which pivot about a central leg to produce both symmetric and anti-symmetric rotation, depending on the motion desired. The arm assemblies are adapted to linearly travel along the length of the leg via a non-backdriveable motorized lead screw. This gradual linear motion allows the vehicle to transition between an upright roving configuration and a toe-balancing configuration.

The independently-actuated arms can function both as a hopping mechanism when rotated symmetrically about the central leg, and as an actively-controlled roll-axis stabilizer when rotated anti-symmetrically relative to the central leg. Appropriate superposition of these two motions allows the robot to simultaneously stabilize and hop in the roll axis plane.

The multimodal robot of the present invention improves upon previous designs by leveraging a highly-efficient leaning maneuver while retaining the hopping capabilities necessary to overcome other obstacles, including jumping onto a raised platform or across a gap, or quickly traversing flames or other hazards that could damage a slower-moving robot.

Applications for the multimodal robot of the first embodiment include reconnaissance in burning or chemical-contaminated environments, monitoring hazardous materials (e.g. nuclear waste stockpiles), providing mobile platforms for weapons, planetary exploration, and for incorporation in toys.

A second embodiment of a multimodal robot combines rolling, balancing and climbing capabilities in a wheeled or treaded vehicle by changing the vehicle's center of gravity relative to its chassis. These multiple modes of operation allow the vehicle to perform and stabilize "wheelies" and "reverse wheelies" (also known as "stoppies"). In an exemplary embodiment, the robot is capable of overcoming obstacles nearly as tall as the vehicle is long (in its folded configuration) by reconfiguring itself to adjust its center of gravity. A platform or frame is preferably connected to the chassis to carry a payload, sensors, cameras or other electronic devices. In a preferred configuration, motors that drive the treads or wheels are capable of independent rotation with respect to the chassis, so that the treads or wheels may be used in both the rolling and balancing functions. This allows the robot to dynamically adjust its center of gravity. MEMS accelerometers and gyroscopes, coupled with advanced filtering techniques, allow the robot to estimate its angle with respect to gravity. With the tread assemblies unfolded away from the body, the robot can balance upright on its treaded ``toes" and stand up in order to expand the view of an onboard camera (or other sensors) and overcome obstacles that would otherwise be insurmountable with a treaded robot that is of the same height as the robot in its conventional treaded mode. This design is also capable of both crossing chasms nearly as wide as the vehicle is long, and using the front-mounted pivot of the chassis to actively dampen vibrations when driving quickly over rough terrain. The reconfigurability of the tread assemblies permits several modes of locomotion, which can be selected to adapt the robot to the type of terrain encountered. The unique mechanical design of this multimodal robot coupled with feedback control algorithms enables it to overcome complex terrain (e.g. stairs, rubble) while retaining a small form factor to navigate in confined spaces and to reduce cost and weight.

In an alternative configuration, an actuated boom is included to facilitate balancing and climbing. The boom has significant mass, approximately equal to the mass of the chassis. Motors are configured on the robot to drive the treads (or wheels) and to change the angle of the boom with respect to the chassis. Sensors are integrated to detect the robot's configuration, including one or more level sensors along each axis, which provide signals to a system controller. Feedback may be applied to enable the vehicle to balance on its front or rear treaded toes (or wheels). The vehicle can also climb obstacles (including stairs) by extending the mass of the boom over the obstacle and rotating the chassis up and over. This maneuver may be done in a statically stable manner or in a dynamically balanced manner. The boom arm may be extensible and/or may be configured with its own wheels or treads,

The shifting of the robot's center of gravity allows it to overcome obstacles nearly as tall as the vehicle is long (in its folded configuration) by repositioning its boom arm.

Applications of this multimodal robot include building, cave, and mine exploration; search and rescue; monitoring hazardous materials (e.g. nuclear waste stockpiles); improvised explosive device (IED) detection and disposal; weapons platform; toy; planetary exploration; HVAC system monitoring.

In a third embodiment, motion in harsh operating environments and uneven terrain is provided by a spherical robot that incorporates momentum exchange devices to achieve rapid acceleration or deceleration in any direction.

The inventive spherical robot can efficiently traverse a wide variety of terrain including, but not limited to: carpet, pavement, sand, gravel, and mud. In addition, it can incorporate an amphibious capability which allows it to traverse mud, swamp, and open water. Unlike existing spherical robots, the internal frame of the present embodiment is fixed to the external sphere and the center of mass of the robot remains fixed to the center of the sphere. In an exemplary embodiment, single-gimbaled control moment gyroscopes (CMGs) are used for momentum exchange. This design is especially agile, as the momentum needed to maneuver is stored within the CMGs and, thus, does not need to be generated by high-torque (and large electrical power-consuming) motors like a standard direct drive system.

In one embodiment, a cubical frame is populated with four single-gimbal CMGs, with each gimbal axis at an angle on each face. A plurality of other momentum exchange devices such as reaction wheels, dual-gimbal CMGs, or momentum wheels may be incorporated as alternatives to the single-gimbal CMGs.

The robot is not limited to spheres as an outer structure, but to all generalized amorphous ellipsoidal configurations as well.

In military applications, the inventive spherical robot can be used in covert reconnaissance or munitions delivery. For the general commercial applications, the robots can be a toy or a therapeutic device.

The fourth embodiment of the multimodal robot is a wirelessly-controlled or autonomous vehicle which is an all-in-one system of ball retrieval, storage and throwing. The design includes an integrated ball pick up mechanism and the jai alai style throwing arm design.

To enable ball pick up, the body and wheels of the robot are spaced to provide automatic pickup and loading of the target balls. This method allows the operator to drive the robot toward the target, with the curvature of the robot directing the ball into the space between the wheel and the body. The rotation of the wheel brings the ball up to be stored within a basket or other storage receptacle.

For throwing, the robot is stabilized by a feedback control circuit to balance upright as an inverted pendulum. The great rotational inertia of the wheels allows the robot to rotate the body quickly from a lay-down mode to an upright mode. The rapid rotation results in the effective toss of a light weight ball. The ball is imparted with a spin as it rolls off the throwing arm track. The result is a more stable and longer throw.

The potential applications of the present robot embodiment include remote controlled toy cars, an automatic tennis ball retrieval system, and a grenade launcher, among others.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1a is a diagrammatic front view of a first embodiment of the multimodal hopping robot; FIG 1b is a detail view of the circled area in FIG. 1a.

FIG. 2 is a diagrammatic perspective view of the hopping robot of FIG. 1.

FIG. 3 is a diagrammatic perspective view of the arm assemblies of the hopping robot.

FIG. 4 is a series of cartoons illustrating the modes of operation of the robot of FIG. 1.

FIGs. 5a and 5b illustrate configuration of the arm assemblies during motion, where FIG. 5a shows a hopping motion; FIG. 5b shows asymmetric arm motion for stabilization about the roll axis.

FIG. 6 is a diagrammatic front view of the multimodal hopping robot in an upright roving configuration.

FIG. 7 diagrammatically illustrates a self-locking arm suspension mechanism.

FIG. 8 diagrammatically illustrates an alternative embodiment of the arm suspension mechanism.

FIG. 9 is a series of plots of effective spring resistance due to symmetric rotation, showing angular displacement as a function of spring stretch, resultant torque and effective torsional spring rate.

FIG. 10 is a series of plots of effective spring resistance due to antisymmetric rotation, showing angular displacement as a function of spring stretch, resultant torque and effective torsional spring rate.

FIG. 11 is a plot of critical zero-torque arm angle (symmetric rotation) as a function of linkage parameters.

FIG. 12 is a perspective view of the arm mechanism of the hopping robot during conventional operation.

FIG. 13 is a perspective view of the hopping robot in a horizontal roving configuration.

FIG. 14a is a diagrammatic perspective view of a multimodal robot according to a second embodiment; FIG. 14b is a diagrammatic side view of an exemplary tread assembly.

FIGs. 15a-15c illustrate different modes of locomotion of the embodiment of FIG. 14, where FIG. 15a shows the robot in a heel-balancing position, FIG. 15b shows the robot in a toe-balancing position, and FIG. 15c showing the robot with its treads extended for reaching across and spanning a gap, or for climbing.

FIGs. 16a-16c illustrate an alternative configuration of the multimodal robot of FIG. 14, in which an actuated boom is used to shift the robot's center of gravity.

FIG. 17 illustrates an alternative configuration of the multimodal robot of FIG. 14 in which the treads are replaced with wheels.

FIG. 18 illustrates an alternative configuration of the multimodal robot of FIG. 16a.

FIG. 19 is a diagrammatic view of the components of a hip joint of the second multimodal robot embodiment.

FIGs. 20a – 20e are perspective views of the treaded robot, where FIG. 20a shows the robot in a horizontal skid steer configuration; FIG. 20b shows the robot in a "chasm-crossing" configuration; FIG. 20c shows the robot in a vertical "C-balancing" configuration; and FIG. 20d shows the robot in a vertical "V-balancing" configuration.

FIGs. 21a and 21b illustrate examples of functions performed by the multimodal robot of FIG. 14, where FIG. 21a is a perspective view of the robot maneuvering within a duct, and FIG. 21b is a perspective view of the robot perching on the edge of a stair step.

FIG. 22 illustrates a sequence of steps in a climbing operation performed by the robot of FIG. 14.

FIG. 23 is a diagrammatic perspective view of a spherical robot according to the third multimodal robot embodiment.

FIGs. 24a-24c are diagrammatic views of three different prior art momentum exchange devices that may be used in the spherical robot, where FIG. 24a illustrates a reaction wheel assembly; FIG. 24b shows a single gimbal control moment gyro; and FIG. 24c illustrates a double gimbal control moment gyro.

FIG. 25 is shows four exemplary geometric configurations for a frame for supporting the momentum exchange elements.

FIG. 26 is a three-dimensional computer drawing of a first exemplary construction of the spherical robot.

FIG. 27a is a perspective drawing of a second exemplary construction of the spherical robot; FIG. 27b is an exploded view of the construction; FIG. 27c is an exploded view of one SGCMG element.

FIG. 28 is a block diagram showing the sequence of control operations for the spherical robot.

FIGs. 29a-29c illustrate examples of possible functions that can be performed using the spherical robot, where FIGs. 29a and 29b show examples of motion of the robot in a free-surface case and a near-a-surface case, respectively; and FIG. 29c is a series of cartoons showing the steps of a process for coordinating multiple spherical robots to overcome an obstacle.

FIG. 30 is a perspective view of a fourth multimodal robot embodiment.

FIGs. 31a and 31b are a front view and a rear view, respectively, of the body portion of the multimodal robot of FIG. 30.

FIGs. 32a and 32b are side views of the body portion with the wheel removed showing steps in a sequence for picking up a round object.

FIG. 33 is a perspective view of latch for preventing the object from rolling backward in the channel.

FIGs. 34a and 34b are side and perspective views, respectively, of a ball release mechanism.

FIGs. 35a-35c are cross-sectional views of the robot body showing the ball release sequence.

FIGs. 36a-36d are side views of the robot showing the throwing sequence, where FIG. 36a shows the ball at the lower portion of the throwing arm; FIG. 36b shows the beginning of the body rotation to move the ball to a mid-point of the throwing arm; FIG. 36c shows the ball at the upper portion of the throwing arm; and FIG. 36d shows the ball after release.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The following description of four embodiments of multimodal robots provide details of functions including locomotion via rotation of wheels or tracks and spherical rotation, hopping, climbing, and throwing. While the different embodiments may use different locomotion means, the common feature among all embodiments is their use of feedback to control angular momentum to enable active balancing and effect changes in orientation and movement of the robots, resulting in vehicles that can be used in a wide range of applications from military and industrial applications to toys.

First multimodal robot embodiment

Referring initially to FIGs. 1-3 and 6, the robot 10 of the first embodiment (which may also be referred to herein as a "vehicle") includes two independently driven wheels 6, 8 mounted on the ends of two independently driven arm assemblies 12, 14 which pivot about central leg/shaft 16. The arm assemblies 12, 14 travel linearly along the length of leg 16 by way of a non-backdriveable motorized leadscrew 20. The gradual motion provided by the screw 20 allows the vehicle 10 to transition between an upright roving configuration and a toe-balancing configuration. FIG. 2 illustrates the three rotational axes around which the inventive robot moves, with leg 16 corresponding to the yaw-axis, the axles of the drive wheels corresponding to the pitch-axis, and the arm carrier 21, to the extent that it defines the midpoint in the arm assembly, corresponding to the roll-axis.

Referring to FIG. 2, arm assemblies 12, 14 are linked to a central arm carrier 21 via joints 11 and 13, which extend through leg guide channels 48 and 49. The arm carrier 21 is driven linearly along the leg 16 via a leadscrew powered by motors within the arm carrier to move joints 11 and 13 along the lengths of the guide channels.

Left arm assembly 12 includes a parallelogram linkage, which has the basic "frame" elements of a top left arm 22, bottom left arm 23, left arm end link 30 and left arm mid-link 25. Similarly, right arm assembly 14 includes the frame element of top right arm 18, bottom right arm 19, right arm mid-link 50 and right arm end link 47. The frame elements of the arms are preferably formed from a lightweight but relatively rigid metal, such as aluminum or titanium. Alternatively, the frame elements may be formed from a strong, rigid plastic or other polymer. The joints and drive mechanisms that connect and allow manipulation of the frame basic elements are described in more detail below.

The top left arm 22 attaches to the arm carrier 21 via joint 11, which attaches to the left arm end-link 30 via joint 31. The bottom left arm 23 is attached to left arm end-link 30 via joint 32 and to the arm carrier 21 via joint 13. The left arm mid-link

24 attaches to the top left arm 22 via joint 4, and to the bottom left arm via joint 3. In all cases, the joints described herein are revolute joints.

The left spring lever 25 is attached to the left arm assembly via joints 33 and 34. As illustrated, joint 34 is horizontally offset from the midpoint of a line connecting joints 31 and 32. The attachment between the spring lever 25 and joint 34 consists of a standard revolute joint coaxial with joint 34. Joint 34 attaches to either a linear bearing (free to travel along the line connecting the endpoints of the spring lever 25) affixed to the spring lever, or to a straight-line "Watts" linkage 70, details of which are shown in FIG. 1b, consisting of the links 60, 61 and 62 and connecting joints 36, 37, 38 and 59. The arm assembly 12 will not move if the spring lever 25 attaches directly to joint 34 without some form of linear bearing/prismatic joint or straight-line linkage. Left spring lever 53 is attached to the right arm assembly via joints 55 and 56 in conjunction with a similar Watts linkage.

The left arm assembly 12 is actuated via torque applied to left chain drive sprocket 41 at joint 32. Sprocket 41 engages the output shaft 29 of the arm motor 27, which is centrally mounted within the left arm end-link 30. The right arm assembly 14 is similarly actuated, with right chain drive sprocket 39 engaging the output shaft (not shown) of right arm motor 51, which is mounted within right arm end link 47.

Two extension springs 5, 52 connect the two arm assemblies. Left spring 52 connects the proximal end of the left arm spring lever 25 at joint 35 to the right spring pre-tension pulley 54 (visible in FIG. 3) of the right assembly. Similarly, right spring 5 extends between the proximal end of the right arm spring lever 53 and the left spring pre-tension pulley 26. Spring tension may be adjusted by rotating the spring pretension pulleys 26, 54 in the appropriate direction. Such adjustment can be accomplished by applying torque via the arm motors 28, 51 while their respective arm motor clutches 28, 44 are disengaged. Since the arm motor output shaft 29 (right shaft not shown) has a finite range of travel, this will eventually result in rotation of the arm motor body 28, 51, which engages the respective spring pre-tension pulley 26, 54 via a single-stage spur gear transmission.

FIG. 4 illustrates possible modes of operation of the inventive robot. Using the combination of the independently-driven wheels 6, 8, the leadscrew 20 and the independently actuated arms12, 14, the robot can use one or a combination of motions to perform useful functions during operation of the vehicle. Horizontal roving (a) is effected when the left and right drive wheels are rotated in the same direction to tilt the leg forward. The wheels continue driving in the same direction to move the vehicle forward with the end of the leg on the support surface. To steer, the wheels may be operated in opposition to each other. The independent operation of the wheels allows the robot to be turned quickly on a point, or with a very small turning radius. As can be seen in the perspective view of FIG. 13, horizontal roving mode gives the vehicle a low vertical profile, allowing it to pass easily beneath low obstacles, such as fences, wires, or low shrubs, and to avoid optical sensors that may be positioned several inches or more above the floor or support surface.

An uprighting maneuver (b) from the horizontal roving mode involves applying a sudden strong torque to the wheels in the appropriate direction. When reaction wheels are torqued in one direction, the vehicle experiences an equal-and-opposite reaction torque. As illustrated, a strong clockwise torque induces a counter-clockwise rotation of the leg to rotate the leg into a vertical position. The motion of the reaction wheel itself can later be bled back off, either with reaction control thrusters, or merely when the vehicle comes back in contact with the support surface. The instantaneous torque available when using reaction wheels is limited to that provided by the motor used to drive the reaction wheels themselves. In the upright mode, the robot drives only on the reaction wheel wheels, with the leg pointed upward to providing a raised support frame for mounting vision systems or other sensors to expand the sensor's range for surveying the surroundings.

For upright balancing and roving (c) in the fore-aft direction, toe-balancing (e) and hopping (d), reaction-wheel stabilization may be used. The reaction wheels can be used as counterweights in the left-right direction (akin to a tight-rope walker's balance bar). Finally, the reaction wheels may act as counterweights for the stiff elastomer spring to work against in order to achieve the actual hopping motion of the vehicle in either conventional monopedal locomotion (f) or cartwheeling monopedal locomotion (g).

The mass of the wheels should be significant in order for the last three of these functions (e, f and g) to be viable. In the exemplary embodiment, the mass of each of the wheels is provided by the vehicle batteries 7, which are distributed symmetrically around the outer hub of each wheel, and the motors 45 (within their corresponding motor housings 9) that are used to drive the wheels 6, 8. By exploiting the weights of these relatively heavy components as opposed to adding dead weight to the wheels, the overall mass of the robot can be minimized.

The independently-actuated arms 12, 14 can function both as a hopping mechanism when rotated symmetrically about the central leg 16 (around the roll-axis) and as an actively-controlled roll-axis stabilizer when rotated anti-symmetrically about the central leg. A hopping motion, shown in FIG. 5a, is created by, starting from a configuration with the arms angled downward (indicated by grey lines in FIG. 5a), rapidly rotating the arms 12, 14 symmetrically upward relative to the leg 16, abruptly stopping as they reach a horizontal orientation. One or more level sensors (not shown), which may be located on the arm assemblies 12, 14 and/or on the leg 16, may be used to generate electrical signals that are communicated to the vehicle's controller (not shown). In an exemplary embodiment, the controller may be incorporated in one or more custom and/or commercial off the shelf (COTS) printed circuit boards (PCBs), such as the C200 MCU available from Texas Instruments. The PCBs will preferably be enclosed within a protective housing that can be attached to the leg 16 in a way that does not interfere with operation of the leadscrew. Feedback from the level sensors may be used to control the anti-symmetric arm motion for balancing. As illustrated by FIG. 5b, anti-symmetric arm motion generates an equal and opposite torque about the leg 16, enabling feedback stabilization about the roll-axis. Appropriate superposition of these two motions allows the robot to simultaneously stabilize and hop in the roll-axis plane. The majority of the vehicle's mass should be concentrated at the ends of the arms in order for the arms to effectively hop and balance the vehicle.

In the preferred embodiment, the leg 16 should be formed from a material that is light while maintaining sufficient stiffness to avoid buckling or introducing excessive structural flexibility. Lightweight steel, aluminum and titanium are examples of appropriate materials.

When out of ground contact, the wheels 6, 8 provide pitch-axis stability by actively applying torque, using the same principle as the anti-symmetric action of the arms. The arm assemblies 12, 14 are configured in a parallelogram linkage so as to maintain constant angular alignment of the wheels 6, 8 relative to the central leg 16 throughout the arm's range of motion. This simplifies the overall dynamics by preventing strong coupling between the pitch- and roll-axis dynamics. In this configuration, the top and bottom arms 18, 22 and 19, 23, respectively, preferably have an outward curvature at their lengthwise centers, as shown, in order to prevent interference between coplanar components. In other words, the ends of the arm sections curve inward relative to their midpoints. A simpler configuration in which the wheels are directly attached to a single link would function similarly for small angular deflections (+/- 15 degrees) of the arms.

In the preferred embodiment, the left and right arm motors 28, 51 are high-speed/low-torque in order to optimize hopping performance. The arms are spring-loaded by extension springs 5, 52 to support the weight of the arms and to recover energy during hopping. While this spring mechanism should strongly resist motion of one arm relative to the other in order to support the weight of the wheels during hopping, it should not substantially resist rotation of either arm relative to the central leg 16. This arrangement allows the anti-symmetric rotation necessary for active roll-axis stabilization.

While placing a torsion spring across the arms fulfills these basic requirements, additional functionality can be realized via a more intricate linkage mechanism. Specifically, since each arm is actuated by torque applied at one of the outward joints by the corresponding high-speed / low-torque motor 28, 51, a digressive stiffness (decreasing with increasing deflection) is desirable in order to provide a more constant resistance to symmetric motion; i.e., provide high support at small deflections, without overwhelming the motors at large deflections. Secondly, in order to facilitate multimodal operation, the effective spring rate is preferably adjustable on-the-fly, without introducing torsional bias/asymmetry. Lastly, in order to store energy for large jumps (and to keep the vehicle in a folded configuration during roving), the arms should preferably self-lock into a fully-tensioned state without requiring additional actuators. Furthermore, the angular deflection at which locking occurs must be less than 90 degrees in order to prevent collision between coplanar mechanism links.

In the preferred embodiment, the self-locking feature is achieved by incorporating a pair of non-coplanar springs 5, 52 attached to spring levers 25, 53 within the parallelogram linkage. The relationship between the springs 5, 52 and levers 25, 53 is illustrated in FIG. 7, which shows how the top plane and bottom plane function separately and combined (right). The top plane, shown on the left in FIG. 7, includes right spring 5, left spring lever 25, and joint 34′, which includes joint 34 and Watts linkage 70. The bottom plane, shown in the center of the figure, includes left spring 52, right spring lever 53, and the joint corresponding to left joint 34′, which includes joint 55 and its associated Watts linkage (or other appropriate linkage.) The black dots in the line drawing correspond to the respective joints identified in FIGs. 1-3. FIG. 8 illustrates the kinematic equivalent realizations of the arm suspension mechanism shown in FIG. 7.

As illustrated by the curves plotted in FIG. 9, the resistance to symmetric motion decreases with increasing deflection from horizontal, (arms outstretched, as in FIG. 1), measured as angular displacement ($\alpha_L = -\alpha_R$ [deg]), and eventually changes sign past a certain critical angle ("0" in the plots). This causes the arms to lock into a fully tensioned state, provided that the arms are constrained to deflect at most slightly past this critical zero-torque angle. In FIG. 9, angular displacement is plotted relative to percentage spring stretch, resultant torque (in Newton meter), and effective torsional spring rate (in Newton meter/radian), respectively, at four different levels of spring pre-tension. FIG. 10 illustrates the resistance to anti-symmetric rotation under varying levels of spring pre-tension using the same comparisons used in FIG. 9. FIG. 11 is a plot of the critical zero-torque arm (locking) angle as a function of varying link lengths for symmetric rotation, where B/L = 0.125, C/L = 1.094, and D/L = 0.438.

Note that the symmetric configuration enables bi-directional series-elastic actuation using the extension spring. Referring to FIG. 12, during conventional operation, the main body of left arm motor 28 is held stationary by a small actuated clamp 62. Loosening clamp 62 allows the motor 28 body to rotate. This, in turn, drives left spring pre-tension pulley 27 around which the one end of extension spring 25 is wound. Similarly, right arm motor 51 may be rotated by loosening its corresponding clamp (not visible in the figures) to drive right pre-tension pulley 54 to adjust the tension on spring 5. These features allow the springs to be pre-tensioned while the arms 12, 14 are locked at the maximum extent of travel by loosening the clamps 62, and driving the motors 28, 51 in the direction that causes downward arm motion (in order to prevent unlocking). Note that, since the springs 5, 25 are always in tension, they may be tightened by driving the corresponding pulley 27, 54 in either direction. Additionally, the motors 28, 51 may actuate in series with the springs 5, 25 by loosening the clamps. This is sometimes referred to a "series elastic actuation" and may be useful for buffering mechanical energy, and isolating the motors 28, 51 from mechanical shock.

As described above, each drive wheel 6, 8 has two wheel motors that propel and steer (via differential drive) the vehicle when in contact with the support surface. Referring to FIGs. 1 and 2, on right drive wheel 8, two wheel motors 45 are fixed on the wheel hub via housing 9. The drive gears of motors 45 engage spur gear 40, which is mounted on axle 46. As previously mentioned, the batteries 7 are located on each wheel hub to provide the added weight needed for balancing, hopping and monopedal motion. On the left side, drive wheel 6 has two motors 45 that drive spur gear 42 to rotate the wheel around its corresponding axis.

In an alternative embodiment, the drive wheels may be replaced by a second set of arms mounted in an orthogonal arrangement with the arm assemblies 12, 14. This provides a pitch-axis arm pair and a roll-axis arm pair. In this embodiment, level sensors may be provided within both the pitch- and roll-axes to provide the feedback needed to control anti-symmetric arm motion within both axes. The resulting structure can provide highly stable monopedal locomotion that can balance in multiple axes. Since the weights of the wheels and their corresponding drive motors are eliminated in this embodiment, additional weight may need to be added to the end of each arm assembly to provide the mass needed for hopping and toe balancing.

The multimodal robot of the first embodiment can be fitted with optical, audio, thermal, chemical and other environmental sensors, or a combination of different sensors, which can be used to provide input into an adaptive system controller, e.g., artificial intelligence to allow the vehicle to develop a situational awareness that will permit predictive path planning in complex environments. Alternatively, or in addition, the vehicle can have incorporated into its electronics a transceiver for receiving remote commands and for transmitting information collected by its sensors.

The robotic system described herein is useful for maneuvering within complex structures or rugged terrain via different combinations of hopping, pole climbing, toe balancing, horizontal roving and uprighting, all in a controlled fashion. For example, the robotic system can climb stairs using a combination of pole climbing and toe balancing to climb stairs.

Second multimodal robot embodiment

A second multimodal robot 100, illustrated in FIGs. 14, 15 and 20, is a treaded vehicle that can perform stable both heel and toe standing, i.e., “wheelies” and “stoppies”, and can balance on the edge of a step or similar change in elevation. As shown in FIG. 14a, multimodal robot 100 includes a pair of arms 110 and 120 which comprise independent tread assemblies that are attached to chassis 102 by way of tread shaft 108. In the exemplary embodiment, a single chassis holds the actuators, sensors, electronics, and batteries required for operation and communication with the robot. Rotation of the shaft 108 causes the tread links to advance for translational movement; rotation about the shaft causes the entire tread assembly to rotate with respect to the chassis. This unique “hip joint” is described in more detail below. An optional platform 104 may be attached to chassis 102 to provide a support for attaching sensors, cameras, or other equipment or instruments to be transported on the robot. Where no platform is provided, a housing may be provided to enclose the chassis and any associated electronics, batteries or actuators. If a platform 104 is included, the chassis housing and platform can be the same structure (as illustrated, chassis 102 is separated from platform by a dashed line), or the chassis housing can be fully or partially enclosed within the platform. It should be noted that platform 104 is not limited to a rigid structure – it may be a rigid or a deformable body which may be passively or actively deformed to adapt the robot as required for a particular task. Further, the platform need not be a solid, enclosed structure, but can be an open frame or a combination of open and closed portions.

One or more sprockets may be driven with an actuator such as a motor, engine, or pneumatic or hydraulic turbine. As illustrated in FIG 14b, which is a simple diagram showing the components of a tread assembly with a side cover removed, each tread assembly includes two or more tread sprockets 114, 116 rotatably mounted in the same plane on a vertical side plate or frame 111 to engage tread 112. One or more tread guides 115 may also be rotatably mounted on frame 111. Tread sprocket 114 is mounted coaxially with shaft 108. One or both sprockets 114 may be mounted with a sensor to measure position, speed, and/or torque. A force or pressure sensor may optionally be provided underneath a span of the tread 112 to detect where the tread assembly is in contact with the ground or other surface. Mechanisms as are known in the art for adjusting the tension of the tread may also be included. Control electronics, batteries, and communications electronics may be mounted within the tread arm 110, or may be housed within chassis 102 or platform 104, if appropriate.

Referring briefly to FIGs. 20b and 20c, wheels 124 may be rotatably mounted near the edge of platform 104, opposite the chassis, to further expand the robot's functionality. For example, in FIG. 21a, the robot is shown maneuvering within a duct 128 or other narrow passageway by effectively wedging itself between opposite sides of the duct. The wheels 124 allow the robot to apply pressure perpendicular to the side of the duct as the robot moves forward along the length of the duct. Sensors within the treads or attached to the tread shaft are preferably included to provide feedback to allow the robot's controller to adjust the relative angles of the chassis and treads to maintain the pressure needed to allow the robot to progress through the duct or passageway. The wheels 124 may be attached to freely rotate around their axles, or they may be attached to the drive shaft of one or more additional motors for providing an additional degree of control.

A variation on the embodiment of FIG. 14a is illustrated in FIG. 17, where the tread assemblies are replaced with a corresponding wheel assembly, which includes two or more wheels 117, 118 rotatably mounted in a planar relationship on the arms

119. In this embodiment, a drive chain or other linkage should be provided to drive wheels 117 and 118 together in order to perform toe balancing or other maneuvers that require force to be applied at the distal or toe end of the arm 119. Axle 108 extends from chassis 102 as above to drive wheels 118. The following descriptions of the robot's "hip joint" and maneuvers enabled thereby are equally applicable to the treaded version of FIG. 14a and the wheeled configuration of FIG. 17.

Referring to FIG. 19, in the preferred embodiment, a two degree of freedom joint is used in the mobile robot of FIG. 14a to connect each arm 110, 120 (or 119 in the wheeled version), to the chassis 102 and transmits two decoupled, yet coaxial, torques. The torque to advance the treads 112, 122 (or rotate the wheels) is transmitted by coupling the tread shaft 108 on one end to a motor 140 and on the other to the drive sprocket 114 (or wheel). This shaft passes through, and spins freely relative to, a tread gear 130, which is rigidly mounted to the arms 110, 120 (or 119). A pinion gear 132 mounted to a second shaft 136, parallel to the tread shaft 134, causes the pinion gear 132, and arms 110, 120 (or 119), to rotate with respect to the chassis 102 when driven by the second motor 142, which may also be referred to as the boom motor. This assembly provides for the adjustment of the center of gravity, as will be discussed in more detail below. A slip ring 144 (with one or more channels) may be located coaxially with the first shaft 108 in order to transmit and receive power and/or electrical signals between the chassis 102 and arms 110, 120 (or 119) throughout a continuous range of rotation. Optical encoders 134 may be included to measure the angle of the chassis with respect to arms 110, 120 (or 119) to provide feedback to the control system. In an alternative configuration, the components of the hip joint, i.e., all motors, gears and sensors, may be located in the arms, such that the chassis can simply be an axle that joins the shafts 108 of two arms 110, 120 or 119 together.

The embodiments of FIG. 14 and FIG. 17 are capable of independently rotating the arms 110, 120 (or 119) with respect to the chassis 102 in addition to driving the treads 112, 122 (or wheels 118). This allows the robot to dynamically adjust its center of gravity. Commercially-available MEMS accelerometers and gyroscopes, coupled with advanced filtering techniques, allow the robot to estimate its angle with respect to gravity. With the arms 110, 120 unfolded away from the body, the inventive multimodal robot can balance upright on the distal (with respect to the tread shaft 108) end of the arms, as illustrated in FIG. 15b and 20c, making it possible to significantly expand the range of an on-board sensor or instrument, such as a camera. An exemplary robot with tread assemblies on the order of 10-15 cm high and 30-50 cm long may be able to stand up to 65 cm tall and overcome obstacles that would otherwise be insurmountable with a 10-15 cm tall treaded robot. The inventive design is also capable of both crossing chasms nearly as wide as the vehicle by extending the arms in opposite directions, as illustrated in FIGs. 15c and 20b. Further, the front-mounted pivot of the chassis may be used to actively dampen vibrations when driving quickly over rough terrain. The reconfigurability of the arms permits several modes of locomotion, which the inventive robot can switch between based on the type of terrain encountered. As illustrated in FIG. 15a and FIG. 20d, the robot can balance on the proximal (with respect to the tread shaft 108) end of the arms, i.e., perform a wheelie, with the proximal end of the arms 110, 120 in contact with the ground and neither the chassis 102 nor the distal end of the arms in contact with the ground. This can be referred to as the "V-mode". The angle between the chassis 102 and the arms 110, 120 may be changed by actuating the boom motor where the tread motor will be actuated as needed to keep the changing center of gravity over the contact point to keep the robot from falling over. This change in angle may be the result of a reference command sent by an operator or performed automatically by the robot in response to an external stimulus or as part of a programmed sequence. This maneuver can be used to initiate a climbing sequence, for example. In FIG. 15b and 20c, the robot is illustrated in a toe balance, or a "stoppie", which is performed by placing the distal end of the arms 110, 120 in contact with the ground and neither the chassis 102 nor the proximal ends of the arms in contact with the ground. This can be referred to as the "C-balancing mode." The angle between the chassis 102 and the arms 110, 120 may be changed by actuating the boom motor where the tread motor will be actuated as needed to keep the changing center of gravity over the contact point. This change in angle may be the result of a reference command sent by an operator or performed automatically by the robot in response to an external stimulus or as part of a programmed sequence. The multiple modes of locomotion according to the inventive mechanical design coupled with feedback control algorithms will enable the robot to overcome complex terrain, such as stairs, rubble, and other obstacles while retaining a small form factor to navigate in confined spaces and to reduce cost and weight. In a preferred embodiment, the on-board electronics includes wireless communication circuitry, as is known in the art, to enable bidirectional communication over WiFi. In an especially preferred embodiment, the robot includes appropriate electronics and programming to enable the robot to communicate with one or more computers, other robots, and mobile devices, such as a cellular telephone by using, for instance, the IEEE 802.11g standard.

Examples of complex tasks that can be performed by the treaded/wheeled robot are illustrated in FIGs. 21a, which was discussed above, and FIG. 21b, which illustrates a portion of a stair climbing maneuver as well as showing how the treaded robot is capable of "perching" on small surfaces, such as the edge of a stair (126), a branch, or a telephone or power line. In this configuration, the treads of the robot are in contact with the surface at one point and the robot maintains its balance by adjusting the chassis and/or boom to keep its center of gravity in line with the contact point. Inertial sensors (e.g., accelerometers and gyroscopes) may be used in conjunction with contact sensors (e.g., force sensitive resistors) inside the tread assemblies to determine the contact point. Active balancing provided by the combination of the tread and balancing motors and continuous feedback from the sensors to control the motors maintains the robot's center of gravity to stabilize it sufficiently to hold its position. The center of gravity is shifted in the desired direction when the robot is made to climb up or climb down the stairs 126 so that the center of gravity is kept directly above the contact point using a combination of modes of movement.

FIG. 22 illustrates one example of operations that may be performed by the above-described multimodal robot for climbing an obstacle such as a staircase. In step (1), the robot approaches the step while balancing on the distal end of the arms (in "C-balancing" mode, as illustrated in figures 15b and 20c). In steps (2) and (3), upon arriving at the step, the position of the chassis is adjusted such that the center of mass is directly above the edge of the first step. In steps (4) through (7), via a coordinated combination of tread actuation and appropriate variation of the angle between the treads and the chassis, the robot balances on the edge of the step while gradually edging up the step.

In one realization of this maneuver, the angle between the treads and the chassis is actuated as a function of time based on what is required, nominally, to keep the center of mass over the edge of the step while maintaining the desired angle between the chassis and horizontal, while the contact point between the treads and the edge of the step moves (relatively slowly) along the arm; balancing is then achieved via feedback control applied (relatively quickly) via tread actuation. In a second realization of this maneuver, feedback control is applied via a coordinated application of both tread actuation and small adjustments to the angle between the treads and the chassis.

Upon reaching the top of the step, there are two possible scenarios: The first is that vehicle has either reached the top of the stairs, or the angle of the edges of successive steps from horizontal is less than the angle of the chassis from horizontal (that is, the angle of the steps is relatively shallow). In either situation, the vehicle simply returns to C-balancing mode upon reaching the top of the step and continues its forward movement. If it reaches another step, the situation is equivalent to that depicted in step (1).

The second scenario is that the vehicle has not reached the top of the stairs, nor is the angle of the edges of successive steps from horizontal relatively shallow. In this case, the angle of the chassis from horizontal as the vehicle nears the top of the current step may be planned to be nearly the same as the angle of the edges of successive steps from horizontal. By planning the maneuver in this manner, the proximal end of the vehicle will reach the edge of the next step while still in contact with the edge of the previous step, as in step (8). The center of mass may then be adjusted to be over the edge of the next steps (9) and (10), and the process described in steps (4) through (7) is repeated, as illustrated in steps (11) through (15).

Various combinations of the above steps can be used to maneuver the robot into positions for performing a desired task. The inventive robot is able to perform this and similar tasks because it operates, or can be operated, to shift its center of gravity to balance on a small point by changing the angle between the arms and the chassis, and by using the treads or wheels to "catch itself" before it falls.

The multi-modal robot of the second embodiment is capable of performing a wide variety of maneuvers with the minimal set of actuators, thus saving cost and weight. Additional sensors can be mounted internally or externally, such as contaminant sensors, Global Positioning System (GPS) receivers, wind sensors, analog or digital cameras, optical or radiation sensors, among many other possible uses. End effectors may be mounted on the mobile robot platform 104 or arms 110, 120 or 119, such as linkage mechanisms with a gripper, solid or liquid collection systems, lighting systems, or weapons systems, among many others.

An alternative configuration of the second multimodal robot embodiment is illustrated in FIGs. 16a-c. In this configuration, shifting of the center of gravity is still used, however the manner in which the shifting is effected is different.

In this embodiment, the robot includes a chassis 148 and an actuated boom 150. The chassis 148 is driven by a pair of treads 152, 154 (or conventional wheels 156 may be substituted, as shown in FIG. 18). The boom 150 has significant mass. In the exemplary embodiment, the mass of the boom is approximately equal to the mass of the chassis. As in the previous embodiment, motors are configured on the robot to drive the treads (or wheels) and to change the angle of the boom 150 with respect to the chassis 148.

The hip joint described above with reference to FIG. 19 may also be incorporated in the configuration that uses a boom for shifting the center of gravity. In this case, the boom motor (which corresponds to the balancing motor) will activate rotation of the boom arm.

The second multimodal robot embodiment includes sensors to detect the robot's configuration. Feedback control is applied to enable the vehicle to balance on its front or rear cogs (or wheels). The vehicle can also climb obstacles (including stairs) by extending the mass of the boom 150 over the obstacle and rotating the chassis up and over. This maneuver may be done in a statically stable manner or in a dynamically balanced manner. The boom arm may be extensible and/or may itself be configured with wheels or treads, in a manner similar to the wheels 126 in the previous configuration.

As in the first multimodal robot embodiment, the configuration with the boom 150 takes advantage of the weight of the batteries for use as a functional mass. An electrical connection is made between the boom and the chassis to transmit the power from the batteries to the motors housed within the chassis. In the exemplary embodiment, this connection is made with slip rings, steel shafts riding in bronze bushings, as in the hip joint describe above. The slip rings allow the boom to be rotated about the chassis with no angular limitation.

In this configuration, the treads of the robot are in contact with the surface at one point and the robot maintains its balance by adjusting the boom to keep its center of gravity in line with the contact point. Inertial sensors (e.g. accelerometers and gyroscopes) may be used in conjunction with contact sensors (e.g. force sensitive resistors) inside the tread assemblies to determine the contact point.

The second multimodal robot embodiment uses multiple commercial off-the-shelf (COTS) sensors (MEMS-based accelerometers and gyroscopes, and optical encoders 134 (shown in FIG. 19) to estimate the angle of the chassis with respect to gravity (in the configuration of FIG. 14) and the angle of the boom arm with respect to the chassis (in the configuration of FIG. 16). The programming of the robot includes a control system (which may include a Kalman filter) to actuate the motors to dynamically balance the robot. The current prototype also accepts manual input via a COTS radio frequency remote.

In one application of the second multimodal robot embodiment, an "army" of the robots was deployed in an open, paved area (a parking lot) around which plumes of colored smoke were released. Each robot was equipped with a sensor pack and electronics to measure smoke concentrations and wind velocities. The measurements were transmitted in real time (via WiFi and 3G cellular data links) to an off-site supercomputer running advanced weather-forecasting type algorithms. These algorithms, in turn, synchronized a numerical simulation of the smoke plume with the actual measurements taken in the field in real time (a problem known as data assimilation), then told the vehicles where to move next in order to minimize the uncertainty of the forecast. The goal of the system, which was successfully realized in the experiment, was to forecast where the smoke was going to go, as precisely as possible, before it got there, while coordinating the vehicles in real time to collect the most valuable information possible for the particular wind conditions present during that test. The research has important social relevance related to new technology and algorithms for tracking a wide variety of environmental plumes of interest, from gulf-coast oil, to Icelandic volcanic ash, to possible chemical/radioactive/biological plumes in homeland security settings.

Third Multimodal Robot Embodiment

In a third embodiment, a spherical robot incorporates momentum exchange devices to achieve rapid acceleration or deceleration in any direction.

As illustrated in FIG. 23, an exemplary embodiment of the spherical robot according to the present invention includes a frame 202 for supporting a plurality of momentum-exchange elements 204 so that the elements are distributed relative to the surface of a spherical shell 210 that encloses the frame 202, elements 204, and all control electronics, actuators and batteries that are required to power and control the robot. Sensors may also be included to provide feedback to optimize balancing and locomotion under different conditions. The control electronics may include wireless communication devices for communication with a remote computer, mobile phone or other wireless device. Alternatively, the spherical robot may be tethered to a controller, such as a joystick, track ball or the similar external control device.

The basic elements of three different momentum exchange elements that may be used in the spherical robot are shown in FIGs. 24a-24c. The reaction wheel assembly (RWA) shown in FIG. 24a includes a single motor for spinning the wheel. A single gimbal control moment gyro (SGCMG) is shown in FIG. 24b. This assembly includes two motors, one for spinning the wheel, the other for rotation of the gimbal, allowing the direction of the wheel angular momentum to be varied. In FIG. 24c, a double gimbal control moment gyro (DGCMG) is shown, with three motors, including the two used in the SGCMG plus a third motor to vary the plane on which the SCGMG sits.

In the configuration of the fourth embodiment that is shown in FIGs. 23 and 26, a cubical frame 202 is populated with four single-gimbal CMGs 204a – 204d, with each gimbal axis 206a-206d at an angle extending across each of four faces 208a – 208d. This makes the inventive robot particularly agile, as the momentum needed to maneuver is stored within the SGCMGs and, thus, does not need to be generated by high-torque, large electrical power-consuming motors as in standard direct drive systems of the prior art. The SGCMGs may be operated individually or simultaneously to effect the desired function, such as rolling, steering, stationary rotation around the contact point or balancing in position. While frame 202 is shown in a cubical configuration, it may be constructed with virtually any geometric shape that fits within a spherical shell, including pyramidal, conical, symmetric, skewed, linear arrangements combined with 3-D structures, and various other combinations of such shapes. FIG. 25 illustrates a few of a large variety of possible arrangements of momentum exchange elements, including a pyramid, skewed cone, symmetrical octahedron, and roof-type with linear combinations of elements. Virtually any geometrical shape can be used that will allow momentum to be generated in a plurality of different directions for steering, rolling, balancing, etc. Further, the robot is not limited to spheres as an outer structure, but may include generalized amorphous ellipsoidal configurations as well.

The shell 210 that is used to enclose the frame, momentum exchange elements, the actuators and control electronics may be formed from a wide range of materials, selection of which will depend on the intended application and will be within the level of skill in the art. In general, the outer surface of the shell should be capable of generating sufficient friction with the surface on which the robot will be moving to efficiently convert the action of the momentum exchange elements into motion in the desired direction. The material may be a rigid, preferably impact-resistant plastic or polymer, which may include carbon-fiber or fiberglass, among others. In some applications in harsh environments, metals, metal-composites, or specialized materials such as KEVLAR® composites, may be appropriate for particularly hazardous applications. In other applications, it may be appropriate to use a layered structure that includes padding for shock absorption, thermal insulation or other protective covering, such as NOMEX® or other fire-retardant material that can be incorporated in or underneath a hard exterior shell.

FIG. 26 provides a three-dimensional drawing of an exemplary implementation of the inventive spherical robot. As illustrated, the frame 202 should fit snuggly within the spherical shell 210. For the example of a cubic frame, the corners of the frame may be chamfered, as shown, to provide a broader, angled and somewhat rounded surface to contact the inner surface of the shell (as opposed to having sharp corners on the frame). This provides uniform structural support for the shell 210 while ensuring that the frame 202 and the components mounted thereon are stably supported, i.e., so that the frame does not move relative to the shell.

As illustrated, each SGCMG 204a-d incorporates the spin motor (the shaft of the spin motor 220 can be seen in FIG. 26) and reaction wheel within a small, flat cylindrical housing, which is fixedly mounted on the corresponding gimbal axis 206a-206d. Power for driving the spin motor is provided through wires running through the corresponding gimbal axis. One end of each gimbal axis is attached the shaft of a gimbal motor 222, while the other end of the axis is supported within a pivot so that the axis and reaction wheel rotate when driven by their corresponding gimbal motor.

All electronic components for operating, communicating with, and collecting data, if appropriate, including all wiring and connectors, will be housed within shell 210, preferably centered within frame 210 to place the weight at the center of the sphere. The components, which may include one or more printed circuit boards with associated battery casings or other holders, may be supported on a bar or plate that extends between opposite corners of the cube or between the upper face 208e and lower face 208f of the cube as illustrated, so as not to interfere with movement of the elements 204. Some of the components, e.g., the batteries, may alternatively be mounted within the inside edges of the frame if the frame is hollow. In an alternative embodiment, elements 204 may be mounted on all 6 faces of the cube, or on all faces of a selected geometric structure, as long as sufficient space is provided to avoid interference between movement of momentum exchange elements and other components of the system.

FIGs. 27a and 27b illustrate an alternative construction of the spherical robot with the outer shell removed. In this case, the frame 232 is formed by the intersection of four open-centered disks 234a-d that correspond to faces 208a-d of FIGs. 23 and 26. The rounded faces provide additional structural support for the spherical shell. The top housing 236, which encloses the control electronics is attached to the top of frame 232.

Referring to FIG. 27b, which shows an exploded view of the full assembly with one SGCMG also in exploded view, the frame is defined by the assembly of faces 234a – 234d with top plate 244 and bottom plate 245, which are attached by brackets 242. In addition to the top housing 236, attached to the upper surface of top plate 244 are a number of battery holders 240 for retaining batteries 238. As illustrated, the batteries are button style lithium batteries. Additional battery holders 240 and batteries 238 are located on the outer surface of bottom plate 245 along with the gimbal motor controllers 246.

FIG. 27c shows an exploded view of SGCMG 250 shown in FIG. 27b. The rotor 268 is attached to the rotor shaft 270. The rotor provides the inertia for the momentum storage of a SGCMG. The rotor and rotor shaft 268, 270 are held in place relative to the outer housing formed from the combination of 256, 259, 260, 267, 272 and 278, by a journal 252, 277 and thrust bearing 258, 271 combination. The shaft of the spin motor 254 is attached to the rotor shaft 270 and the spin motor 254 is attached to the c-ring 252, which is also attached to the bottom plate 256 of the housing. The spin motor 254 rotates the rotor 268 at a constant rate (in the SGCMG case) or varies the angular rate (in the VSSGCMG case) via feedback from the optical encoder 280 and spin motor electronics 282. The rotor speed is measured by the optical encoder 280, which is attached to the top plate 276 of the housing. The spin control electronics 282 are mounted to mounting posts 279, which are also attached to the top plate 276 of the housing. The housing assembly 256, 259, 260, 267, 276, 278 is attached to gimbal shafts 269,273. One gimbal shaft 269 is attached to a spur gear 262, which is free to rotate relative to the right gimbal mounting bracket 264 via a thrust/journal bearing combination. This spur gear 262 is kinematically constrained to a second spur gear 263 which is attached to the gimbal motor 261 and is also free to rotate relative to the right gimbal mounting bracket. The second gimbal shaft 273 is rigidly attached to the slip ring assembly 274 and is free to rotate relative to the left gimbal mounting bracket 276 via a thrust/journal bearing combination. The slip ring assembly 274 provides power (in spite of the continuous rotation of the gimbal) to the spin motor controller 282. The angular rotation of the gimbal shaft 273 is measured by a potentiometer 275 whose movable part is attached to the gimbal shaft and immovable part is attached to the left gimbal mounting bracket (28). The left 276 and right 264 gimbal mounting brackets are attached to the sidewall 234a.

In one embodiment, the spherical robot may have pressure bladders attached on the inner surface of the shell 210 or on non-interfering locations on the frame 202. (A single exemplary pressure bladder 214 is diagrammatically illustrated in FIG. 23). The bladders will preferably be uniformly distributed around the inner surface of the shell, e.g., on the edges of two opposite faces of the cube, to control buoyancy, thereby allowing the robot to float on the surface of a liquid, e.g., a natural or artificial body of water, or to move fully- or partially submerged below the surface. Operation of the momentum exchange elements will allow the buoyant robot to move within or over the surface of the body of water as the robot spins, thus providing an amphibious vehicle. In one implementation, the bladders may be pre-filled to the desired buoyancy prior to deployment of the robot via a valve accessible through the shell. In another approach, small compressed gas canisters, as are known in the art for use in life vests and buoyancy compensators, may be mounted on the frame in communication with a feedback system that will determine the conditions in the body of water, e.g., temperature, surface turbulence and weather conditions, and control the amount of gas released into the bladders to achieve the desired buoyancy and friction with the water's surface to maneuver effectively and efficiently. Bleed valves on the bladders may also be provided to actively adjust the buoyancy as needed under changing conditions. The gas canisters may be replaced with new canisters after one or more uses.

Alternatively, the robot can be made passively buoyant through material selection. For example, the frame can be constructed using a lightweight material such as plastic, wood or fiberglass, or using lightweight metals such titanium or aluminum when the strength and durability of metal is required. The material used for the frame can also be hollow or partially-hollow, e.g., honeycomb structures or extruded channel. The shell, which would need to be a continuous surface without any openings to make it watertight, could be a formed from a buoyant plastic or polymer, such as polystyrene, neoprene or closed cell foam. The buoyant foam structure could be covered with an impervious outer skin or coating, such as a lightweight metal, for applications where metal is preferred, or an epoxy resin or other polymer, using a construction similar to that used in typical surfboards. Openings (ports or doors) in the shell for accessing the interior components of the robot would need to be sealable to produce a watertight closure.

FIG. 28 provides a block diagram of an exemplary control architecture that can be used with the spherical robot. As will be recognized by those in the art, other control architectures can be use. The path generation block can be achieved by the relationship between the velocity of the body and the angular rate. The ACS control law block, pseudoinverse CMG steering law block, and gimbal angular rate controller block can be derived using procedures and algorithms that are known in the art.

Locomotion within a body of liquid can be achieved by activating the momentum exchange elements to rotate the robot's body in the direction of desired motion, the same as would be used on land. FIGs. 29a-c illustrate different applications of the spherical robot. Using a series of cartoons depicting an exemplary robot with a single RWA, FIGs. 29a and 29b illustrate a free-surface case and a near-a-surface case, respectively. In FIG. 29a, in a fluid, when the RWA spins one direction (counter-clockwise as shown), the sphere spins in the opposite direction (clockwise as shown). The fluid's interaction between the rotating sphere and the free-surface causes the sphere to move in translation to the left, as dictated by known analytical solutions to the Navier-Stokes equations, which prove that a rotating sphere in an incompressible viscous fluid near a wall (or free surface) can move in a translational direction orthogonal to the angular rate and parallel to the wall (or free surface). See. e.g., J. Happel and H. Brenner, *Low Reynolds Number Hydrodynamics: with special applications to particulate media*, Springer 1983, which is incorporated herein by reference. In FIG. 29b, which represents movement on top of a surface, when the RWA spins one direction (clockwise as shown), the sphere spins in the opposite direction (counter-clockwise as shown), propelling the sphere to the left.

A plurality of spherical robots can work in cooperation to facilitate locomotion and overcoming various obstacles. As illustrated in FIG. 29c, a sequence of steps is shown for stacking a number of spherical robots to increase the height of one or more robots, thus giving the uppermost robot(s) an increased perspective to for collection of visual information or for other tasks that may require an obstacle to be overcome. In step 1, three spherical robots, designated as A, B and C, start off positioned side-by-side on a support surface. Robots A and C move toward robot B to squeeze B upward in step 2. In step 3, A and C come together with B balanced on top. In step 4, robots D and E are added to the mix, with C and E being moved toward each other to squeeze D upward. A will move along with C to keep B on top. In step 5, B and D are on top after C and E come together. Added spherical robots F and G combine with E in step 6 to force F upward, after which B, D and F are supported on top of A, C, E and G. In step 7, B and F move toward each other to squeeze D upward. In step 8, D moves up and to the right to climb up on F while B moves back to the left. In step 9, the dynamic balancing ability provided by the multiple momentum exchange elements of each robot allows D to balance on top of F which in turn balances on top of E, as shown in step 9. Stacking the spherical robots makes it possible to position a robot with a camera or other sensor to look over an obstacle. Thus, the spherical robot, while taking advantage of a low profile to approach a target by passing under a variety of obstacles, a still able to cooperate with other similar robots to enable climbing to overcome obstacles.

In an exemplary application, multiple spherical robots can be deployed, with each robot carrying a different instrument or payload. The deployed robots can cooperate to enable the robot carrying a particular instrument to position itself optimally for completing its task. In military or law enforcement applications, the above-described spherical robot can be used in covert reconnaissance or munitions delivery. Commercial applications of the robot include incorporate of the robot a toy or a therapeutic device.

Fourth multimodal robot embodiment

FIGs. 30 – 36 illustrate a fourth embodiment of the multimodal robot, which is a wirelessly-controlled vehicle that can perform the tasks of object retrieval, storage and throwing. The design includes an integrated ball pick up mechanism and a throwing arm. Although described in the example as a ball-handling robot, the fourth embodiment is not limited to balls, but may be adapted to pick up and throw other objects that are sufficiently symmetric to allow the pick-up mechanism to work. Similarly, the throwing arm, described in the example as "jai alai-style", is not limited to a jai alai shape, but may be of different shapes depending on the desired speed, trajectory and spin of the object being thrown.

To enable ball pick up, the body and wheels of the robot are spaced to provide automatic pickup and loading of the target balls. This feature allows the operator to drive the robot toward the target, with the curvature of the robot directing the ball into the space between the wheel and the body. The rotation of the wheel brings the ball up to be stored within a basket or other storage receptacle.

For throwing, the robot is stabilized by a feedback control circuit to balance upright as an inverted pendulum. The rotational inertia produced by the motors that drive the wheels allows the robot to rotate the body rapidly from a lay-down mode to an upright mode. This rapid rotation results in the effective toss of a lightweight ball. The exemplary shape of the throwing arm imparts a spin to the ball as it rolls off the throwing arm track, resulting in a more stable and longer throw.

As illustrated in FIGs. 30 and 31, the fourth robot embodiment 300 includes a molded body 302 that is roughly cylindrical in shape (circular as viewed from the side) with a diameter and a width (between the wheels) that is approximately three times the diameter of the target object. In the exemplary embodiment, the target object is a ping pong ball with a diameter of about 40 mm. Two coaxial wheels 306 are mounted on a rotational axis 303. Each wheel 306 is independently driven by a motor (not shown) that is responsive to active feedback controls to provide the robot with a self- balancing function. Control electronics for receiving feedback and actuating the motors are mounted on a printed circuit board (not shown) that is housed under a removable back cover 309. One or more batteries (not shown) for providing power to the motors and electronics are preferably enclosed within the lower portion of body 302, below the rotational axis 303, and are also accessible through back cover 303. The center of gravity of the robot is above the rotational axis so that when the motors are disconnected from its power source, i.e., switched off, the robot falls over.

The vertical arm 304 is configured as a track for launching the object as well as being a mass the enables backward and forward motions through leaning. In the exemplary embodiment, the track has a slight curvature that is similar in design to a jai alai cesta (basket). When the robot leans forward, it moves forward to restore vertical balancing. Turning is facilitated by rotating the wheels in opposite directions.

The feedback controls that enable self-balancing rely on a comparison of the signals of two MEMS (micro electro-mechanical systems) accelerometers, which are well known in the art. One such accelerometer 324 is located on a platform 322 near the upper end 318 of the vertical arm 304. The feedback from this sensor may be turned off or ignored to allow a horizontal orientation of the robot with the arm 304 (actually, the bottom surface of platform 322) dragging on the support surface, as shown in FIG. 36a. Orientation in the horizontal mode is necessary to initiate the throwing process. The second accelerometer is located coplanar with, and at a fixed distance from, the first. In the exemplary embodiment, the second accelerometer is located on the printed circuit board under removable back cover 309, near the axis of rotation 303 of the wheels 306. Comparing the signals from the two accelerometers yields decoupled rotational and translational acceleration measurements.

Referring to FIGs. 31a and b, the pick-up mechanism comprises a circular channel 312 formed on each side of a central plane bisecting the robot between the lower portion of body 302 and the inner surface of the wheel 306. The body has a peaked leading edge 310 that is coincident with the central plane. The leading edge 310 acts as a guide, similar to the bow of a ship, to direct the target object (ball) to one side of the centerline and toward one of the channels 312. The scooped contour of the hub sections 308, in combination with the inner surface of the wheels and the guide 310, define channels 312, which direct the ball into position for pick-up. The inner surface of each wheel has a compressible foam insert 307 to generate friction against the ball, causing it to be captured within the channel to be drawn along with the wheel as it rotates. Other methods for generating sufficient friction to capture the ball between the hub and the inner surface of the wheel may be used, including spring-loaded tracks, other compressible/resilient surfaces, or rough textures molded into or applied to the inner surfaces of the wheels to generate sufficient friction to pull the ball into the channel.

Referring to FIGs. 32a and 32b, as the wheel 306 rotates forward relative to the body, the ball rolls within the channel 312 into a storage volume 316 located at the center of a hollow portion of body 302, between hubs 308. (For clarity, the body is shown with the wheel removed.) Since the robot is able to turn on a point due to the independent operation of the wheels, similar to a treaded vehicle, ball pickup is possible even when the robot spins in place, as long as the wheel in contact with the ball is moving forward with respect to the body 302 to draw the ball into the channel.

Referring again to FIGS. 31a and 31b, in the upper portion of body 302, channels 312 continue into a curved passageway defined by channel covers 314, which help guide the ball into the storage volume 316 within the body 302. At the opening defined by the edge of each channel cover 314 is a spring loaded flipper 330. A detailed view of the flipper 330 can be seen in FIG. 33. The flipper 330 is depressed by the ball as it enters the channel cover 314 and approaches the storage volume, then resiles once the ball is past to extend up into the channel 312 to prevent the ball from leaving the storage volume through the channel. Once the ball is in the storage volume 316, it is ready to be thrown.

The ball release mechanism 340, illustrated in FIGs. 34a and 34b, is mounted within the center of body 302 within the storage volume 316. (The location of mechanism 340 can be seen in FIGs. 35a-35c.) The ball release mechanism consists of a gate 342 which is connected to a servo motor 344 by a push rod 346 and a cylindrical sliding collar 347. The push rod 346 slides freely along the axis of the cylindrical sliding collar 347 and is displaced in the direction normal to the cylindrical sliding collar. The servo motor 344 may be radio-controlled or activated by a system controller (not shown). The gate 342 has a curved surface that is shaped to match the exterior dimensions or the ball. The arc length and/or angle of the gate is preferably large enough to prevent passage of multiple balls while being small enough to minimize servo movement and release time.

FIGs. 35a-35c are cross-sectional views of the robot body illustrating a sequence of steps within the ball release function. In FIG. 35a, the robot 300 is in an upright orientation, which is the appropriate orientation for collecting the balls for storage within the storage volume 316. The ball release mechanism 340 is in its normally closed position to prevent balls from escaping from the storage volume unintentionally. The shape of the gate 342 allows a single ball to sit at the base 348 of the throwing arm 304 while the robot is upright. The bottom of storage volume 316 is sloped toward the rear of the body to encourage the ball toward the throwing arm base 348.

FIG. 35b shows the robot after rotation of the body and throwing arm to a horizontal orientation. The gate 342 of ball release mechanism 340 remains closed to prevent balls 320 from rolling out of the storage volume.

In FIG. 35c, when the throwing function is to be executed, the servo motor 344 of ball release mechanism 340 is triggered to open the gate briefly to allow one ball 320 onto the track of throwing arm 304.

FIGs. 36a-36d illustrate a sequence of steps of the throwing or launching function. By conservation of angular momentum around the robot's center of gravity, the throw can be performed by rapid reverse acceleration of the wheels 306 in a direction away from the throwing arm. This causes the body 302 to suddenly rotate in the opposite direction, so that the throwing arm 304 quickly rotates up and forward. As seen in FIGs. 36b-36d, the throwing motion imparts a forward velocity on the ball relative to the support surface. Because the ball rolls along the track rather than sliding up to the release end 318, the track impacts a backspin on the ball 320, which improves flight stability and effective range.

The fourth embodiment of the multimodal robot may be controlled remotely by wireless communication with a simple joystick and/or push button controller, or it may possess sensors (optical, audio, temperature, chemical, etc.) and internal circuitry including a computer controller capable of effecting autonomous behavior with adaptive response to the sensor feedback of environmental conditions. Using vision, motion, heat or other object detection technology, the robot may be capable of tracking and seeking a target object to pick up, store and throw to a user or another robot. Another potential embodiment may consist of just object pick up and storage for the purpose of object retrieval and transport. Adaptive behavior would, for example, allow the robot to be operated in horizontal mode to pass under obstacles or to maintain a low profile to avoid detection, shifting to the vertical orientation as needed to pick up an object and return to horizontal mode to initiate a launching sequence. Additionally, the robot may be configured for catching as well by means of a modified track. The appeal of a catching robot is the active responsiveness of the robot's self-balancing. The combined abilities of the fourth multimodal robot embodiment to catch, throw, seek and pick up objects autonomously would allow for "team" sports or robotics competitions.

The above-described multimodal robots all incorporate a number of design features that are important to their successful operation. These features include (1) multifunctional wheels, which are used for main-drive, differential-steering wheels, upright actuators, reaction wheels, counterweights and ball pick-up mechanisms; (2) multifunctional motors used to produce completely different effects when driven clockwise or counterclockwise by virtue or creative use of latching mechanisms; (3) sensors that provide feedback to a system controller for reactive actuation of motors for balancing and locomotion; and (4) custom printed circuit boards used to connect exactly the right electronics together with a minimum footprint and mass, in addition to high-performance COTS boards such as the Texas Instruments C2000 MCU (used in the first embodiment), the National Instruments sbRIO 9602 (used in the second embodiment) and the Technologic Systems TS-7250 (used in the third embodiment), with both low-level coding in C as well as high-level control design leveraging MathWork's MATLAB® SIMULINK® software and National Instrument's LabVIEW™ CD&Sim™ modules, respectively, to program the Texas Instruments and National Instruments boards.

The above-described robots by may be combined to perform a variety of different tasks that may be useful in areas including defense, counterterrorism, surveillance and law enforcement, industrial applications, such as transport of payloads and environmental monitoring in areas that are hazardous or otherwise difficult to access, space exploration, entertainment, along with many other possible uses. For example, features of the tracked robot of the second embodiment could be combined with the throwing function of the fourth embodiment to allow a robot to travel over rough terrain and/or climb over obstacles, the deliver an object by launching it using the throwing functions of the fourth embodiment.

While the foregoing written description contains many specifics, these should not be construed as limitations on the scope of the invention or of what may be claimed, but rather as descriptions of features specific to particular embodiments of the invention. Certain features that are described in this specification in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable sub-combination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a sub-combination or variation of a sub-combination.

CLAIMS:

1. A robotic system comprising:

a frame or body;

two or more wheels rotatably mounted on the frame or body;

a motor for independently driving each wheel of the two or more wheels;

a system controller for generating a signal for actuating each motor;

one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, throwing and catching; and

a power source for providing power to operate the motors, the system controller and the one or more sensors.

2. The robotic system of claim 1, wherein the frame comprises:

two arms, each having a distal end on which a wheel is mounted and a proximal end; and

a leg centrally disposed between the two arms with the proximal end of each arm rotatably attached to the leg;

and further comprising:

an arm motor disposed on each arm for independently driving rotation of the arm relative to the leg;

wherein, when the leg is disposed in a vertical orientation with an end of the leg in contact with a support surface,

(i) downward symmetrical rotation of the arms positions the wheels in contact with the support surface for wheeled locomotion on the support surface;

(ii) rapid upward symmetrical rotation of the arms lifts the leg off of the support surface to produce a hopping motion; and

(iii) antisymmetrical rotation of the arms balances the frame on the end of the leg.

3. The robotic system of claim 2, wherein the leg further comprises an arm carrier disposed on a leadscrew for moving the proximal ends of the arms along a length of the leg.

4. The robotic system of claim 2, wherein, when the wheels are in contact with the support surface, rotation of the wheels in same direction moves the leg into a horizontal orientation in the direction of the rotation so that the leg is in front of the arms for horizontal roving.

5. The robotic system of claim 4, wherein sudden rotation of the wheels in a forward direction rotates the leg in an opposite direction from the horizontal orientation to the vertical orientation.

6. The robotic system of claim 2, wherein each arm comprises a parallelogram linkage.

7. The robotic system of claim 6, each arm further comprises:

a spring having a distal end and a proximal end;

an arm motor disposed on the parallelogram linkage near the distal ends of the arm;

a spring lever having a proximal end connected to the proximal end of the spring and a distal end connected to the arm motor near the distal end of the arm;

wherein the distal end of the spring is linked to the distal end of the other arm.

8. The robotic system of claim 7, further comprising a spring pre-tensioning means disposed at the distal end of the spring.

9. The robotic system of claim 7, wherein the distal end of the spring lever is connected to the parallelogram linkage by way of a prismatic joint.

10. The robotic system of claim 7, wherein the arms are lockable when in a fully tensioned state.

11. The robotic system of claim 2, wherein the drive motor and the power source are mounted on the corresponding wheel.

12. The robotic system of claim 1, wherein frame or body comprises a chassis having two drive wheels rotatably mounted on opposite sides thereof, each drive wheel disposed on an axle that is rotated by a corresponding drive motor for rotating the drive wheel, and further comprising:

a pair of elongated arms rotatably mounted on opposite sides of and perpendicular to the chassis, each arm having a proximal end disposed on a corresponding axle, and a distal end;

a second wheel disposed on the distal end of each arm in a common plane with the corresponding drive wheel;

a second motor associated with each arm;

a linkage between the second motor and the axle for each arm, wherein activation of the second motor rotates one of the chassis and the corresponding arm relative to the other;

wherein independent activation of the second motor of both arms to rotate the arms symmetrically relative to the chassis shifts a center of gravity for balancing on one of the distal end or proximal end of the arms.

13. The robotic system of claim 12, wherein the linkage between the second motor and the axle for each arm and a linkage between the drive motor and the drive wheel are incorporated in a two-degree of freedom joint.

14. The robotic system of claim 12, wherein the system controller controls the drive motors and the second motors to reactively shift the center of gravity for stability.

15. The robotic system of claim 12, wherein independent activation of the second motor of both arms to rotate the arms antisymmetrically relative to the chassis extends an effective width of the robot for spanning an opening in a support surface.

16. The robotic system of claim 12, wherein the drive wheels and the second wheels each comprise sprockets and the elongated arms have treads mounted are driven by the sprockets.

17. The robotic system of claim 12, further comprising a platform connected to the chassis.

18. The robotic system of claim 17, wherein the platform is adapted for mounting a payload or instrument.

19. The robotic system of claim 17, further comprising a plurality of wheels disposed on an end of the platform opposite the chassis.

20. The robotic system of claim 1, wherein frame or body comprises a chassis having two drive wheels rotatably mounted on opposite sides thereof, each drive wheel disposed on an axle that is rotated by a corresponding drive motor for rotating the drive wheel, and further comprising:

a pair of elongated drive arms rotatably mounted on opposite sides of and perpendicular to the chassis, each drive arm having a proximal end disposed on a corresponding axle, and a distal end;

a second wheel disposed on the distal end of each drive arm in a common plane with the corresponding drive wheel;

a boom arm pivotably mounted on the chassis, the boom arm comprising a weighted portion and connector arms, wherein one connector arm is mounted on each side of the chassis so that the weighted portion is disposed parallel to the chassis;

at least one second motor connected to the connector arms;

a linkage between the at least one second motor and the connector arms, wherein activation of the at least one second motor rotates one of the chassis and the boom arm relative to the other;

wherein independent activation of the at least one second motor shifts a center of gravity for balancing on one of the distal end or proximal end of the drive arms.

21. The robotic system of claim 20, wherein the system controller controls the drive motors and the at least one second motor to reactively shift the center of gravity for stability.

22. The robotic system of claim 20, wherein the linkage between the at least one second motor and the connector arm and a linkage between the drive motor and the drive wheel are incorporated into a two-degree of freedom joint.

23. The robotic system of claim 20, wherein the drive wheels and the second wheels each comprise sprockets and the elongated arms have treads mounted thereon that are driven by the sprockets.

24. The robotic system of claim 20, further comprising a platform connected to the chassis.

25. The robotic system of claim 20, wherein the platform is adapted for mounting a payload or instrument.

26. The robotic system of claim 1, wherein the two or more wheels comprise a plurality of reaction wheels and the drive motor for driving each reaction wheel is disposed within a housing to define a plurality of momentum exchange elements mounted on one or more axes attached to the frame, and wherein the frame comprises a geometrical structure so that the plurality of momentum exchange elements are distributed about the frame to individually or simultaneously generate angular momentum in a plurality of different directions.

27. The robotic system of claim 26, wherein the one or more axes comprises a single gimbal axis, each having a corresponding gimbal motor.

28. The robotic system of claim 26, wherein the one or more axes comprises a double gimbal axis, each having two corresponding gimbal motors.

29. The robotic system of claim 26, further comprising a shell enclosing the frame and momentum exchange elements.

29. The robotic system of claim 29, wherein the shell is spherical or ellipsoidal.

30. The robotic system of claim 26, further comprising a buoyancy compensating means.

31. The robotic system of claim 26, wherein the frame has a cubic configuration and the plurality of momentum exchange elements comprises four single gimbal control moment gyroscopes.

32. The robotic system of claim 1, wherein the body comprises a cylinder having a rotational axis, the cylinder having two ends, each end defining a hub having an axle aligned with the rotational axis for rotatably retaining a wheel, the body having a cavity therein defining a storage volume for retaining an object having an object diameter, and further comprising:

an elongated arm extending away from the body perpendicular to the rotational axis, the elongated arm having a base portion in communication with the storage volume;

a lower body portion disposed on the body opposite the elongated arm, wherein the lower body portion is symmetrical along a plane bisecting the cylinder; and a curved channel disposed on each side of the bisecting plane having an exit end in communication with the storage volume and an entrance end defined by the hub, the lower body portion and an inner surface of the wheel and having a dimension for receiving the object to produce a frictional contact between the inner surface of the wheel, the hub and the lower body portion, wherein rotation of the wheel draws the object into the channel and into the storage volume.

33. The robotic system of claim 32, wherein at least one motor drives a corresponding wheel in a forward direction to draw the object into the channel.

34. The robotic system of claim 32, wherein the motors are adapted for rotating the body relative to the wheels so that the elongated arm is oriented in a horizontal position.

35. The robotic system of claim 32, further comprising a release gate disposed between the storage volume and the base portion of the elongated arm, wherein activation of the release gate releases an object to pass from one of the storage volume and the base portion to the other.

36. The robotic system of claim 35, wherein when the elongated arm is oriented in a horizontal position, activation of the release gate releases the object to the base portion.

37. The robotic system of claim 32, wherein the elongated arm comprises a curved track upon which the object rolls.

36. The robotic system of claim 32, wherein, when the elongated arm is in a horizontal position, rapid activation of the motors rotates the corresponding wheels in a first direction causing the body to rotate around the rotational axis in an opposite direction to rapidly accelerate the horizontal arm toward a vertical position.

37. The robotic system of claim 36, wherein an object disposed on the base portion of the elongated arm rolls toward a distal end of the arm as the elongated arm accelerates toward the vertical position, wherein the object is thrown when the object reaches the distal end of the arm.

38. The robotic system of claim 32, wherein the one or more sensors comprise at least two accelerometers for measuring rotational and translational acceleration,

and wherein the system controller compares measured acceleration to control the motors for self-balancing.

39. The robotic system of claim 32, wherein the system controller is responsive to a wireless remote control signal.

40. The robotic system of claim 32, wherein the one or more sensors comprise sensors for detecting location of an object or another robot.

41. The robotic system of claim 40, wherein the system controller responds autonomously to feedback from the sensors.

42. A robotic system comprising:

a frame;

two or more wheels rotatably mounted on the frame, wherein the frame comprises:

two arms, each having a distal end on which a wheel is mounted and a proximal end; and

a leg centrally disposed between the two arms with the proximal end of each arm rotatably attached to the leg;

a drive motor attached to the frame for independently driving each wheel of the two or more wheels;

an arm motor disposed on each arm for independently driving rotation of the arm relative to the leg;

a system controller for generating a signal for actuating each motor;

one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, throwing and catching; and

a power source for providing power to operate the motors, the system controller and the one or more sensors;

wherein, when the leg is disposed in a vertical orientation with an end of the leg in contact with a support surface,

(i) downward symmetrical rotation of the arms positions the wheels in contact with the support surface for wheeled locomotion on the support surface;

(ii) rapid upward symmetrical rotation of the arms lifts the leg off of the support surface to produce a hopping motion; and

(iii) antisymmetrical rotation of the arms balances the frame on the end of the leg.

43. The robotic system of claim 42, wherein the leg further comprises an arm carrier disposed on a leadscrew for moving the proximal ends of the arms along a length of the leg.

44. The robotic system of claim 42, wherein, when the wheels are in contact with the support surface, rotation of the wheels in same direction moves the leg into a horizontal orientation in the direction of the rotation so that the leg is in front of the arms for horizontal roving.

45. The robotic system of claim 44, wherein sudden rotation of the wheels in a forward direction rotates the leg in an opposite direction from the horizontal orientation to the vertical orientation.

46. The robotic system of claim 42, wherein each arm comprises a parallelogram linkage.

47. A robotic system comprising:

a body comprising a chassis;

two drive wheels rotatably mounted on axles disposed on opposite sides of the body;

a motor for independently driving each drive wheel;

a pair of elongated arms rotatably mounted on opposite sides of and perpendicular to the chassis, each arm having a proximal end disposed on a corresponding axle, and a distal end;

a second wheel disposed on the distal end of each arm in a common plane with the corresponding drive wheel;

a second motor associated with each arm;

a linkage between the second motor and the axle for each arm, wherein activation of the second motor rotates one of the chassis and the corresponding arm relative to the other;

wherein independent activation of the second motor of both arms to rotate the arms symmetrically relative to the chassis shifts a center of gravity for balancing on one of the distal end or proximal end of the arms;

a system controller for generating a signal for actuating each motor;

one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, throwing and catching; and

a power source for providing power to operate the motors, the system controller and the one or more sensors.

48. The robotic system of claim 47, wherein the linkage between the second motor and the axle for each arm and a linkage between the drive motor and the drive wheel are incorporated in a two-degree of freedom joint.

49. The robotic system of claim 47, wherein the system controller controls the drive motors and the second motors to reactively shift the center of gravity for stability.

50. The robotic system of claim 47, wherein independent activation of the second motor of both arms to rotate the arms antisymmetrically relative to the chassis extends an effective width of the robot for spanning an opening in a support surface.

51. The robotic system of claim 47, wherein the drive wheels and the second wheels each comprise sprockets and the elongated arms have treads mounted are driven by the sprockets.

52. The robotic system of claim 47, further comprising a platform connected to the chassis.

53. A method for maneuvering a robotic system having a chassis and a pair of elongated arms disposed on opposite sides of the chassis, wherein each arm supports a distal end wheel and a proximal end wheel in a planar relationship, the proximal end

wheel being rotatably disposed on an axle coaxial with the chassis, the method comprising:

providing a first motor for rotating the wheels of each arm;

providing a second motor for rotating the chassis relative to each arm;

activating the second motors to rotate the chassis at a non-parallel angle relative to a support surface;

activating the first motors to lift one of the distal end wheel and the proximal end wheel away from the support surface so that the other wheel is positioned at a contact point on the support surface;

activating the second motors to position the chassis at a balance angle relative to the arms to shift a center of gravity of the robot over the contact point; and

activating the first motors in short bursts to maintain the center of gravity over the contact point.

54. The method of claim 53, wherein the balance angle defines a V-mode, wherein the distal end wheel is lifted and the proximal end wheel is at the contact point.

55. The method of claim 53, wherein the balance angle defines a C-balancing mode, wherein the proximal end wheel is lifted and the distal end wheel is at the contact point.

56. The method of claim 54, wherein activating the first motors rotates a tread mounted on the distal end wheel and the proximal end wheel.

57. A robotic system comprising:

a body comprising a chassis;

two drive wheels rotatably mounted on axles disposed on opposite sides of the body;

a motor for independently driving each drive wheel;

a pair of elongated arms rotatably mounted on opposite sides of and perpendicular to the chassis, each arm having a proximal end disposed on a corresponding axle, and a distal end;

a second wheel disposed on the distal end of each arm in a common plane with the corresponding drive wheel;

a boom arm pivotably mounted on the chassis, the boom arm comprising a weighted portion and connector arms, wherein one connector arm is mounted on each side of the chassis so that the weighted portion is disposed parallel to the chassis;

at least one second motor connected to the connector arms; and

a linkage between the at least one second motor and the connector arms, wherein activation of the at least one second motor rotates one of the chassis and the boom arm relative to the other;

wherein independent activation of the at least one second motor shifts a center of gravity for balancing on one of the distal end or proximal end of the drive arms;

a system controller for generating a signal for actuating each motor;

one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, throwing and catching; and

a power source for providing power to operate the motors, the system controller and the one or more sensors.

58. The robotic system of claim 57, wherein the system controller controls the drive motors and the at least one second motor to reactively shift the center of gravity for stability.

59. The robotic system of claim 57, wherein the linkage between the at least one second motor and the connector arm and a linkage between the drive motor and the drive wheel are incorporated into a two-degree of freedom joint.

60. The robotic system of claim 57, wherein the drive wheels and the second wheels each comprise sprockets and the elongated arms have treads mounted thereon that are driven by the sprockets.

61. The robotic system of claim 57 further comprising a platform connected to the chassis.

62. The robotic system of claim 57, wherein the platform is adapted for mounting a payload or instrument.

63. A robotic system comprising:

a frame;

a plurality of momentum exchange elements mounted on the frame, each element comprising:

a housing;

a wheel disposed within the housing;

a motor for independently driving the wheel, wherein each wheel comprises a reaction wheel;

one or more axes for attaching each element to the frame;

a system controller for generating a signal for actuating each motor;

one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, climbing, hopping, balancing, throwing and catching; and

a power source for providing power to operate the motors, the system controller and the one or more sensors.

64. The robotic system of claim 63, wherein the frame comprises a geometrical structure so that the plurality of momentum exchange elements are distributed about the frame to individually or simultaneously generate angular momentum in a plurality of different directions.

65. The robotic system of claim 63, wherein the one or more axes comprises a single gimbal axis, each having a corresponding gimbal motor.

66. The robotic system of claim 63, wherein the one or more axes comprises a double gimbal axis, each having two corresponding gimbal motors.

67. The robotic system of claim 63, further comprising a shell enclosing the frame and momentum exchange elements.

68. The robotic system of claim 67, wherein the shell is spherical or ellipsoidal.

69. The robotic system of claim 63, further comprising a buoyancy compensating means.

70. The robotic system of claim 63, wherein the frame has a cubic configuration and the plurality of momentum exchange elements comprises four single gimbal control moment gyroscopes.

71. A method for moving a robot in a desired direction within a fluid near a solid surface or a free surface of the fluid, the method comprising:

providing a shell having a seal against the fluid, the shell having a spherical or ellipsoidal shape;

enclosing a frame within the shell, the frame supporting at least one momentum exchange element;

actuating the at least one momentum exchange element to generate an aggregate torque to induce an angular acceleration of the robot, wherein the angular acceleration produces a linear acceleration of the robot in the desired direction.

72. A robotic system comprising:

a body comprising a cylinder having a rotational axis, the cylinder having two ends, each end defining a hub having an axle aligned with the rotational axis, the body having a cavity therein defining a storage volume for retaining an object having an object diameter;

a wheel rotatably disposed on each axle;

a motor for independently driving each wheel;

an elongated arm extending away from the body perpendicular to the rotational axis, the elongated arm having a base portion in communication with the storage volume;

a lower body portion disposed on the body opposite the elongated arm, wherein the lower body portion is symmetrical along a plane bisecting the cylinder; and

a curved channel disposed on each side of the bisecting plane having an exit end in communication with the storage volume and an entrance end defined by the hub, the lower body portion and an inner surface of the wheel and having a dimension for receiving the object to produce a frictional contact between the inner surface of the wheel, the hub and the lower body portion, wherein rotation of the wheel draws the object into the channel and into the storage volume;

a system controller for generating a signal for actuating each motor;

one or more sensors in communication with the system controller for generating feedback signals for providing reactive actuation of the motors for generating one or more functions selected from the group consisting of forward motion, backward motion, balancing, throwing and catching; and

a power source for providing power to operate the motors, the system controller and the one or more sensors.

73. The robotic system of claim 72, wherein at least one motor drives a corresponding wheel in a forward direction to draw the object into the channel.

74. The robotic system of claim 72, wherein the motors are adapted for rotating the body relative to the wheels so that the elongated arm is oriented in a horizontal position.

75. The robotic system of claim 72, further comprising a release gate disposed between the storage volume and the base portion of the elongated arm, wherein activation of the release gate releases an object to pass from one of the storage volume and the base portion to the other.

76 The robotic system of claim 72, wherein when the elongated arm is oriented in a horizontal position, activation of the release gate releases the object to the base portion.

77. The robotic system of claim 72, wherein the elongated arm comprises a curved track upon which the object rolls.

78. The robotic system of claim 72, wherein, when the elongated arm is in a horizontal position, rapid activation of the motors rotates the corresponding wheels in a first direction causing the body to rotate around the rotational axis in an opposite direction to rapidly accelerate the horizontal arm toward a vertical position.

79. The robotic system of claim 78, wherein an object disposed on the base portion of the elongated arm rolls toward a distal end of the arm as the elongated arm accelerates toward the vertical position, wherein the object is thrown when the object reaches the distal end of the arm.

80. The robotic system of claim 72, wherein the one or more sensors comprise at least two accelerometers for measuring rotational and translational acceleration, and wherein the system controller compares measured acceleration to control the motors for self-balancing.

81. The robotic system of claim 72, wherein the system controller is responsive to a wireless remote control signal.

82. The robotic system of claim 72, wherein the one or more sensors comprise sensors for detecting location of an object or another robot.

83. The robotic system of claim 82, wherein the system controller responds autonomously to feedback from the sensors.

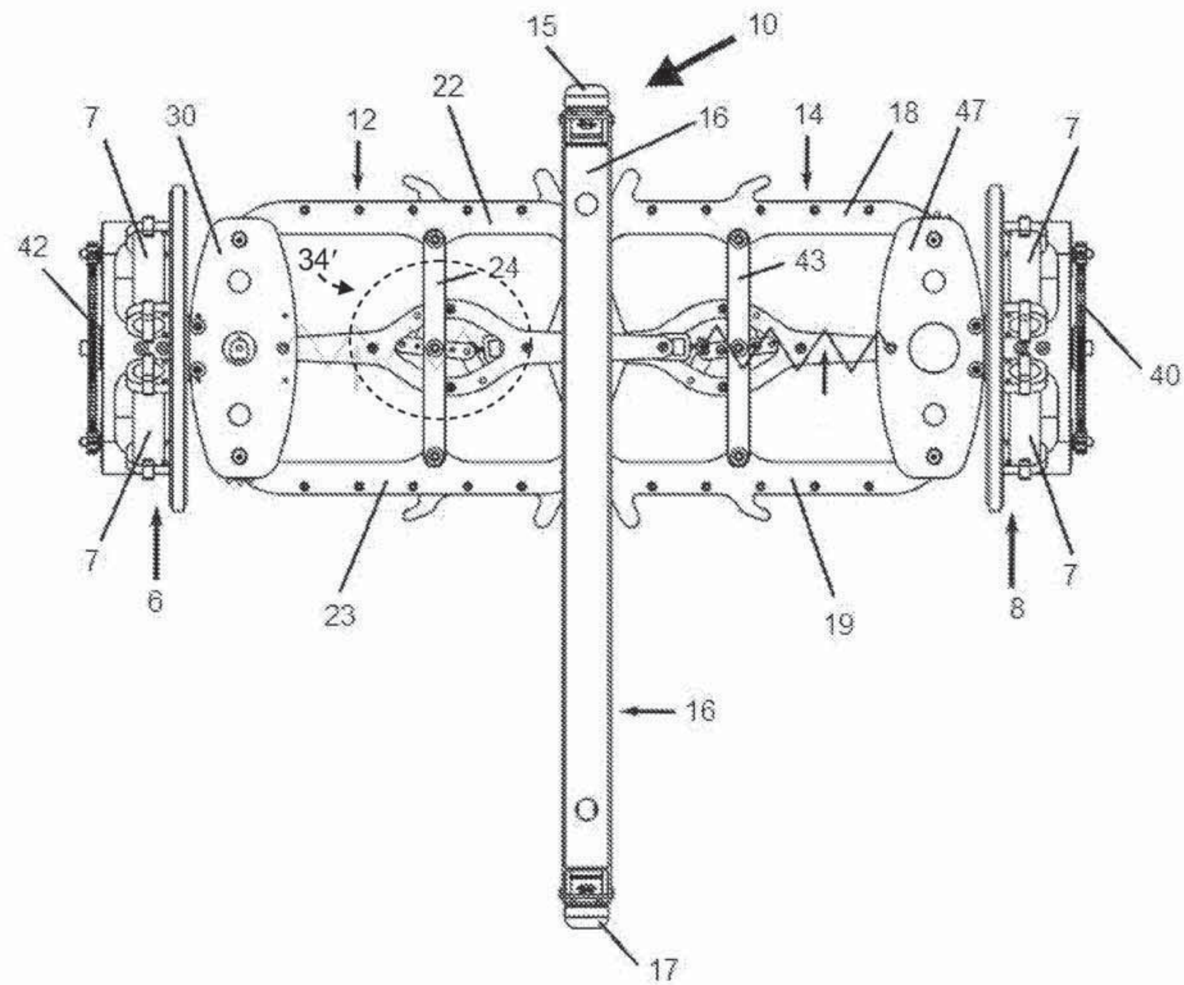


FIG. 1a

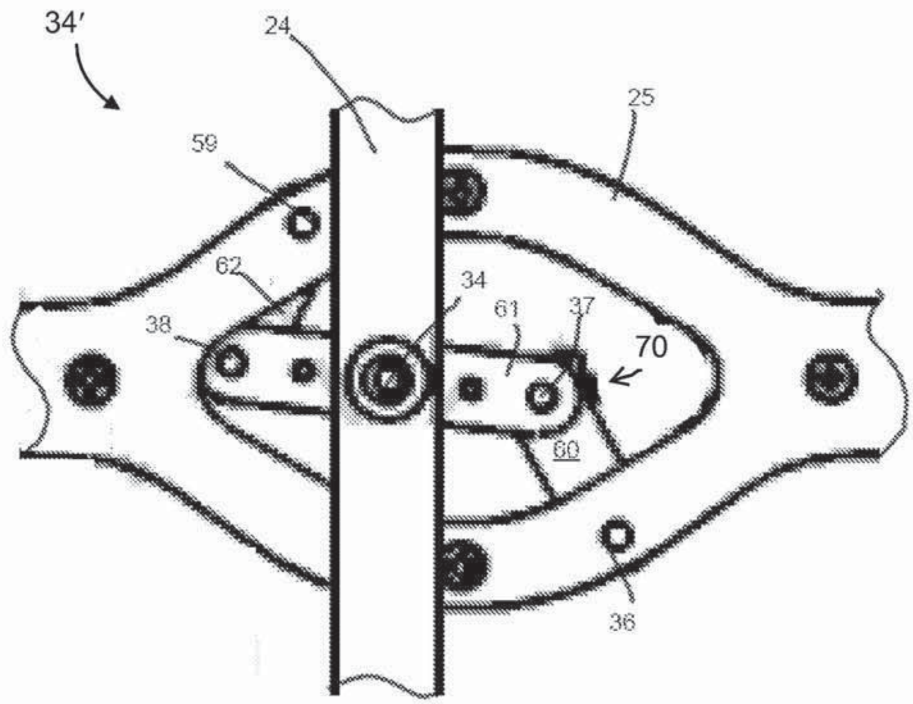
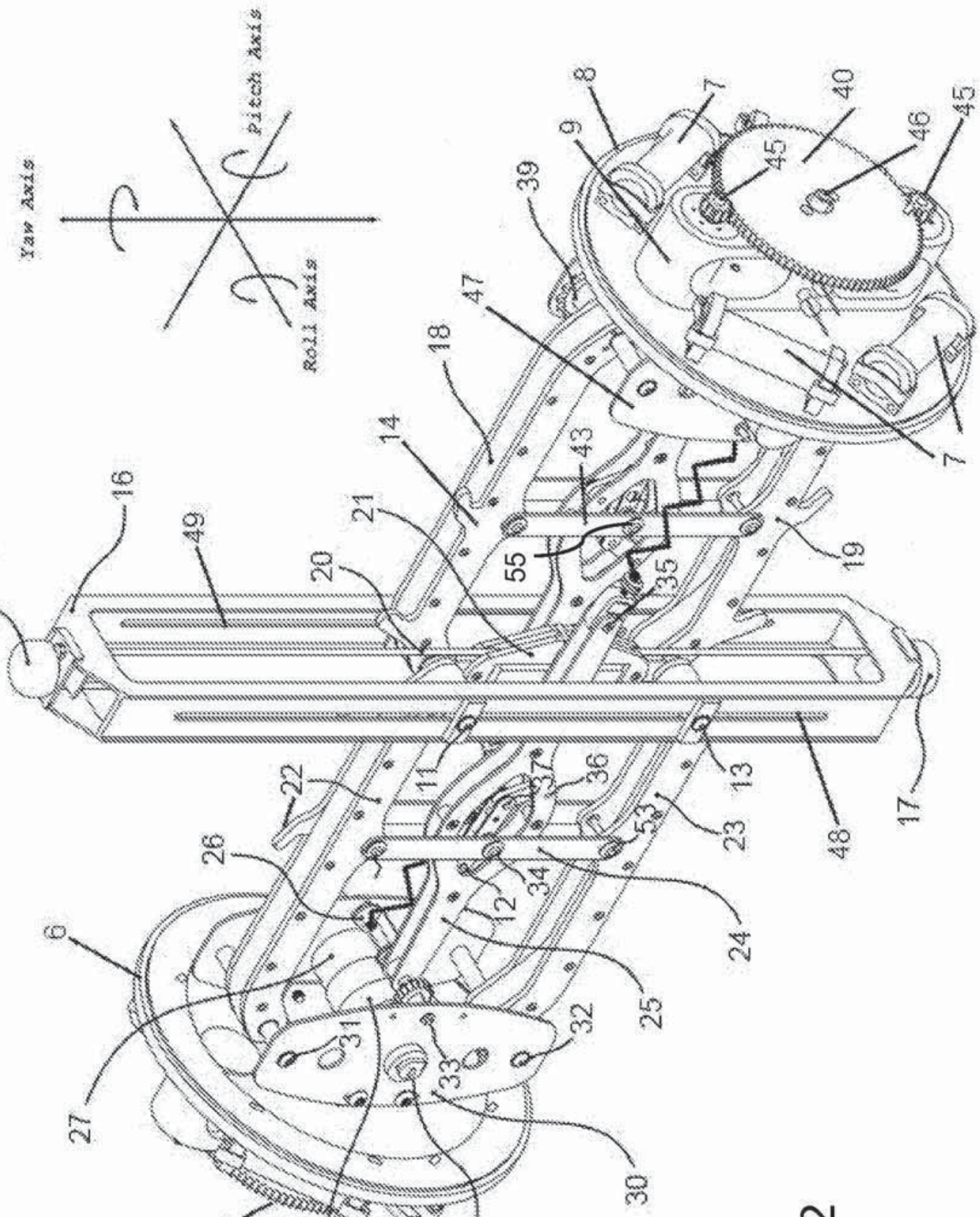


FIG 1b


Yaw Axis
Pitch Axis
Roll Axis
6
7
8
9
11
12
13
14
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16
17
18
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20
21
22
23
24
25
26
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53
55

FIG. 2

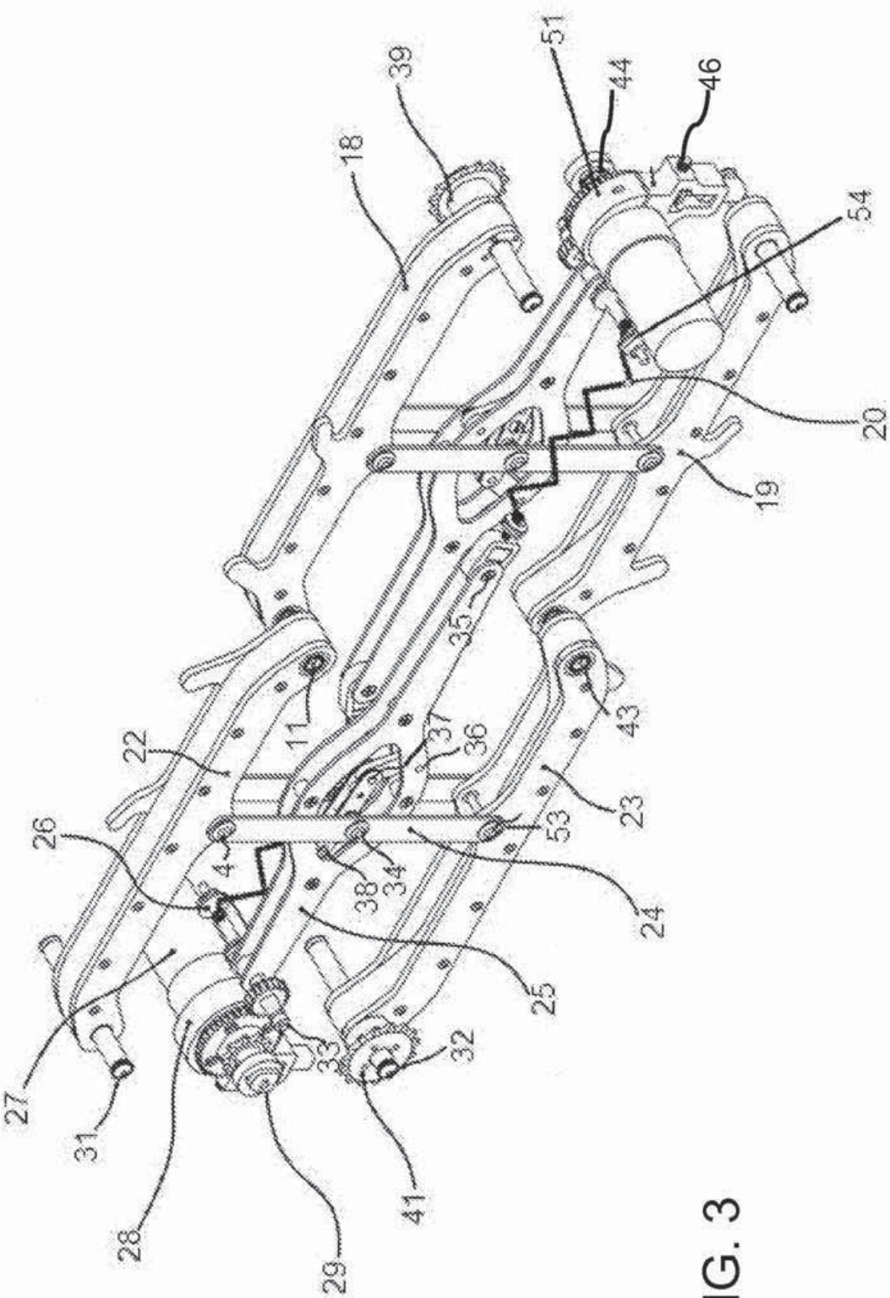

51
44
46
39
18
54
20
19
35
11
43
22
37
36
23
53
26
4
38
34
24
25
27
31
33
32
28
29
41

FIG. 3

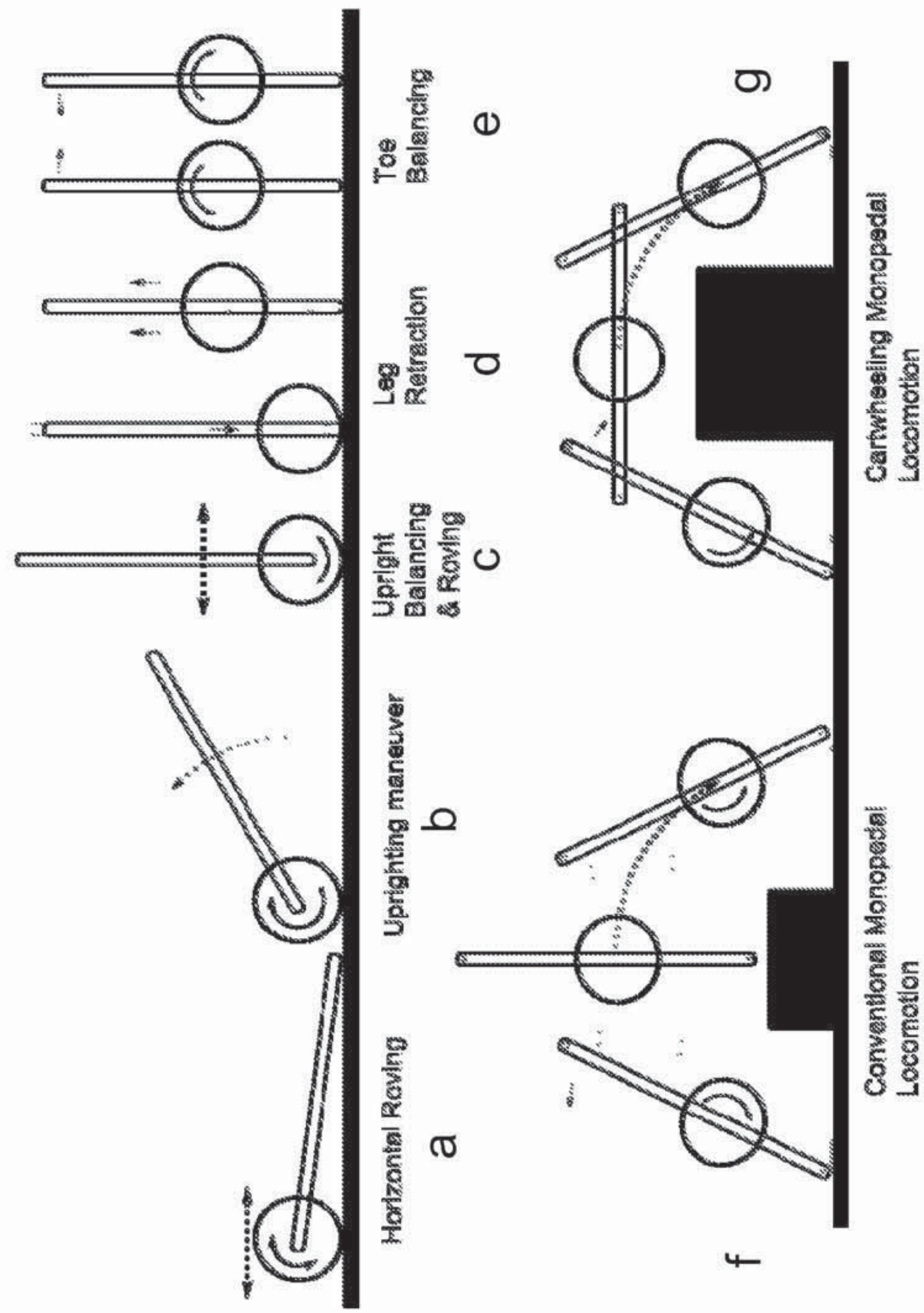

Horizontal Roving
a
Uprighting maneuver
b
Upright Balancing & Roving
c
Leg Retraction
d
Toe Balancing
e
f
Conventional Monopedal Locomotion
Cartwheeling Monopedal Locomotion
g

FIG. 4

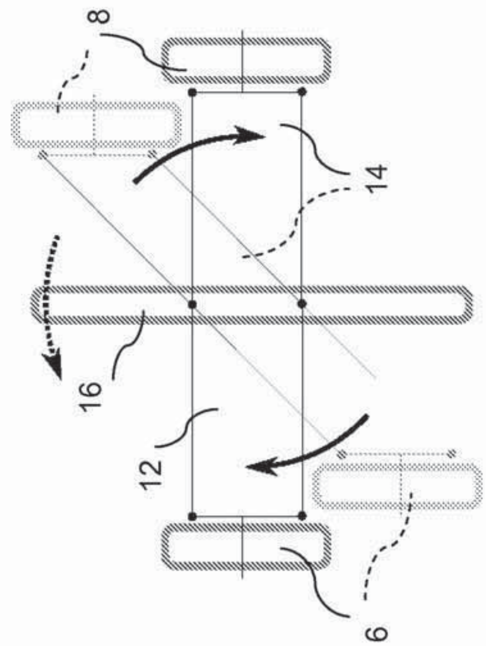


FIG. 5b

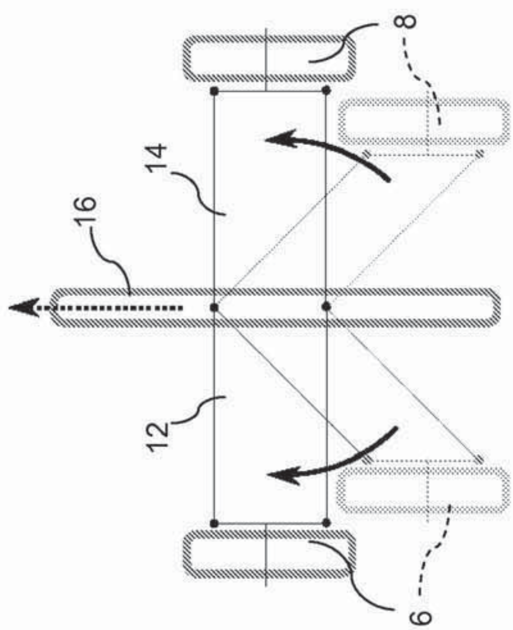


FIG. 5a

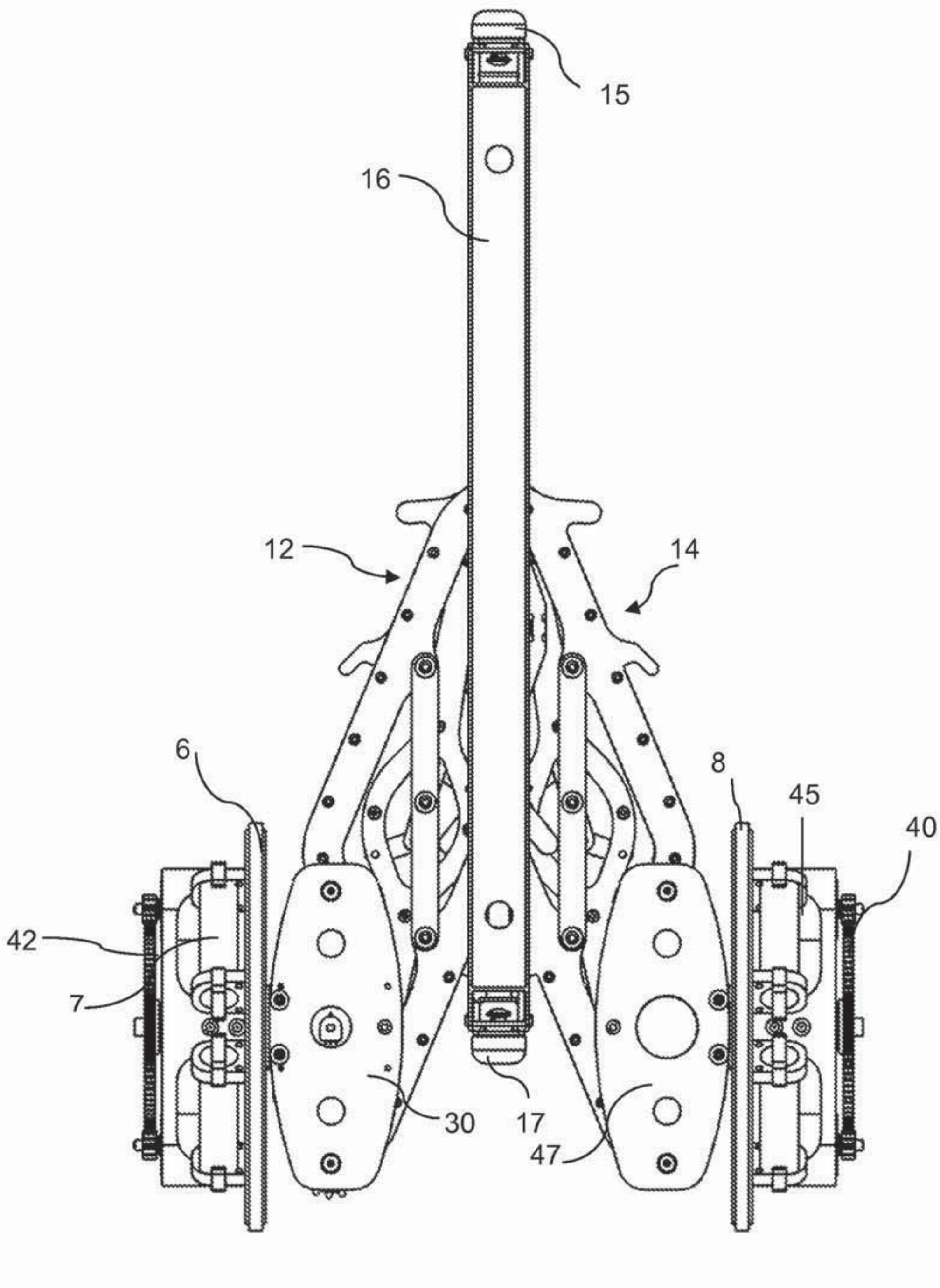


FIG. 6

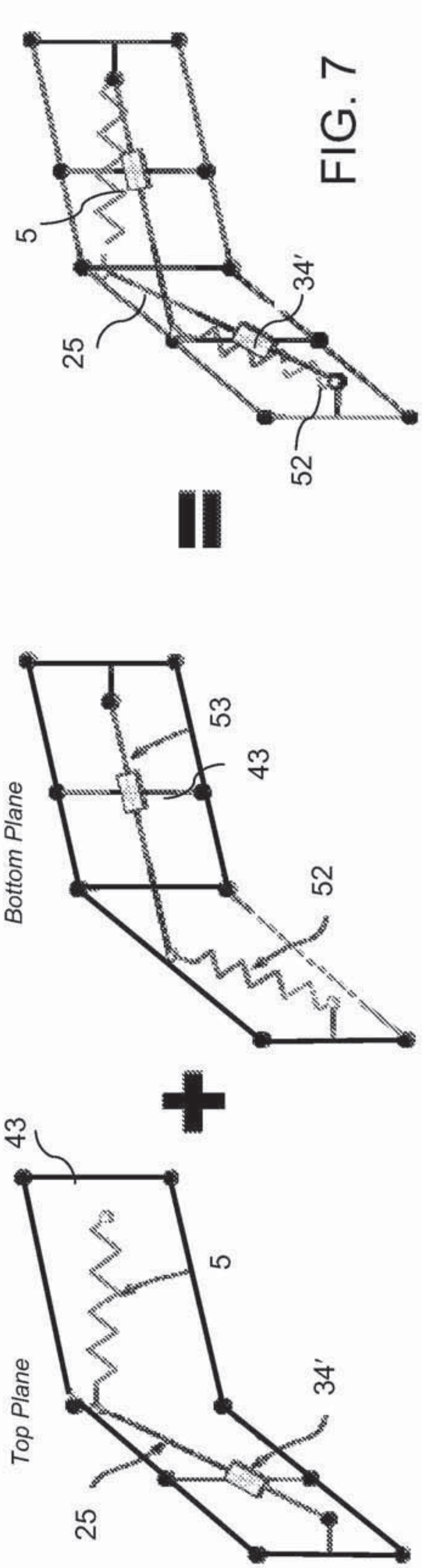

Top Plane
25
34′
5
43
Bottom Plane
52
43
53
25
5
34′
52

FIG. 7

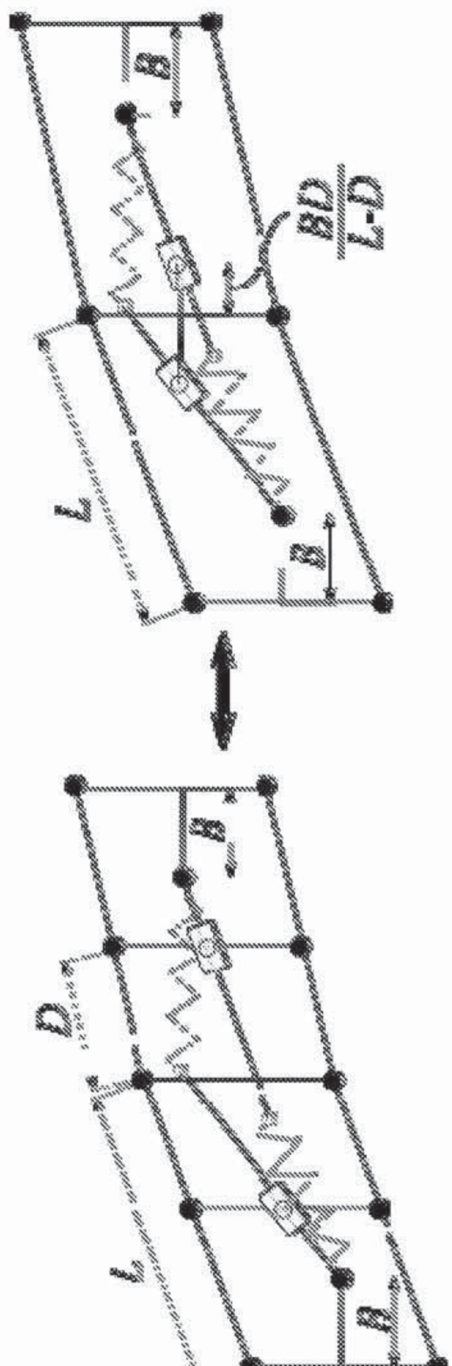
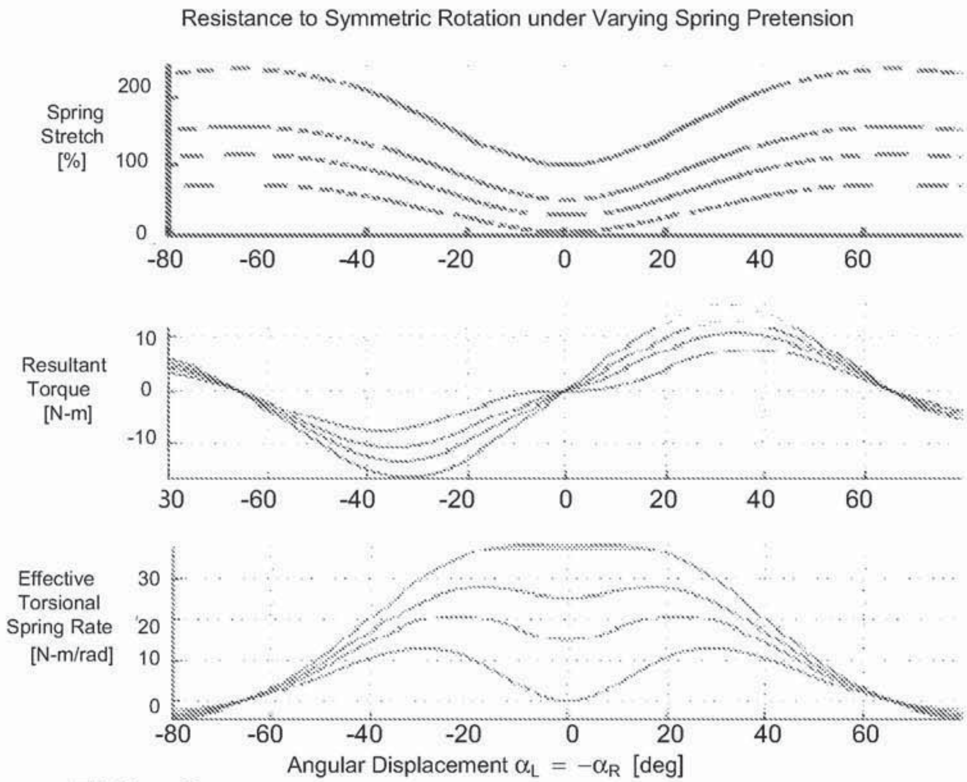
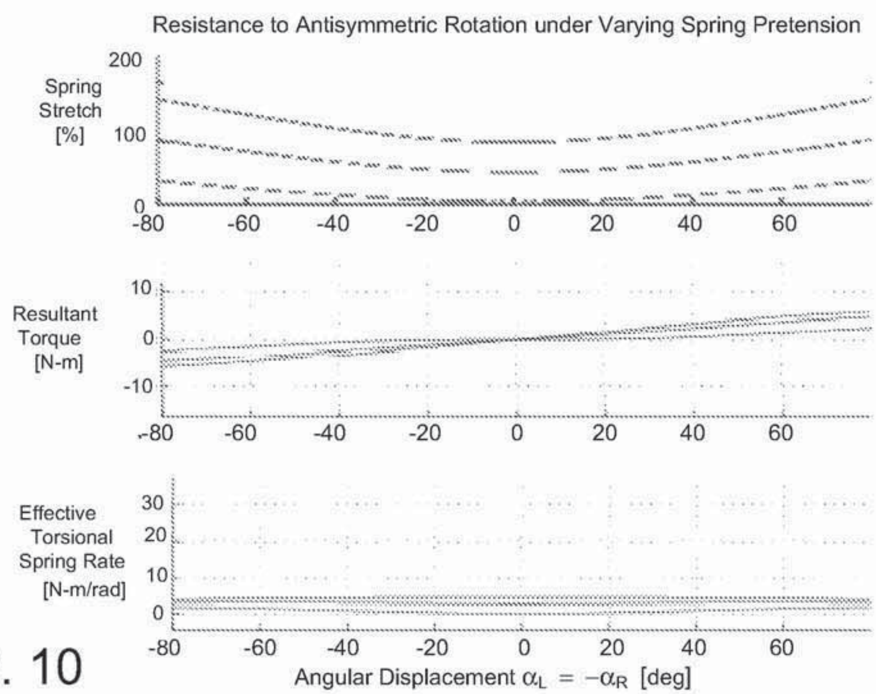

L
D
B
B
L
B
BD
L-D
B

FIG. 8



Resistance to Symmetric Rotation under Varying Spring Pretension
Spring Stretch [%]
200
100
0
-80
-60
-40
-20
0
20
40
60
Resultant Torque [N-m]
10
0
-10
30
-60
-40
-20
0
20
40
60
Effective Torsional Spring Rate [N-m/rad]
30
20
10
0
-80
-60
-40
-20
0
20
40
60
Angular Displacement $\alpha_L = -\alpha_R$ [deg]

FIG. 9



Resistance to Antisymmetric Rotation under Varying Spring Pretension
Spring Stretch [%]
200
100
0
-80
-60
-40
-20
0
20
40
60
Resultant Torque [N-m]
10
0
-10
-80
-60
-40
-20
0
20
40
60
Effective Torsional Spring Rate [N-m/rad]
30
20
10
0
-80
-60
-40
-20
0
20
40
60
Angular Displacement $\alpha_L = -\alpha_R$ [deg]

FIG. 10

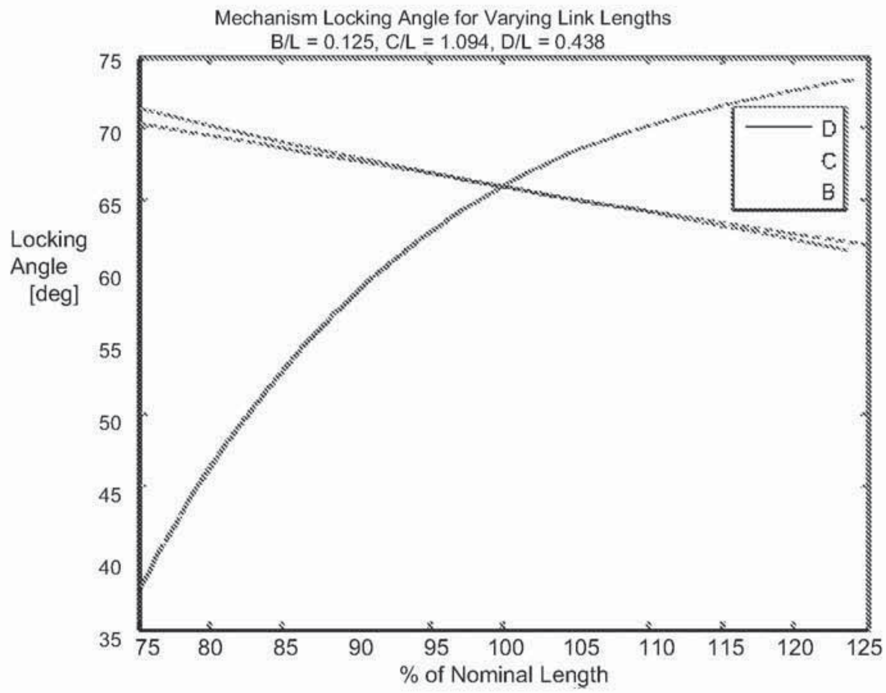

Mechanism Locking Angle for Varying Link Lengths
B/L = 0.125, C/L = 1.094, D/L = 0.438
Locking Angle [deg]
75
70
65
60
55
50
45
40
35
75 80 85 90 95 100 105 110 115 120 125
% of Nominal Length
D
C
B

FIG. 11

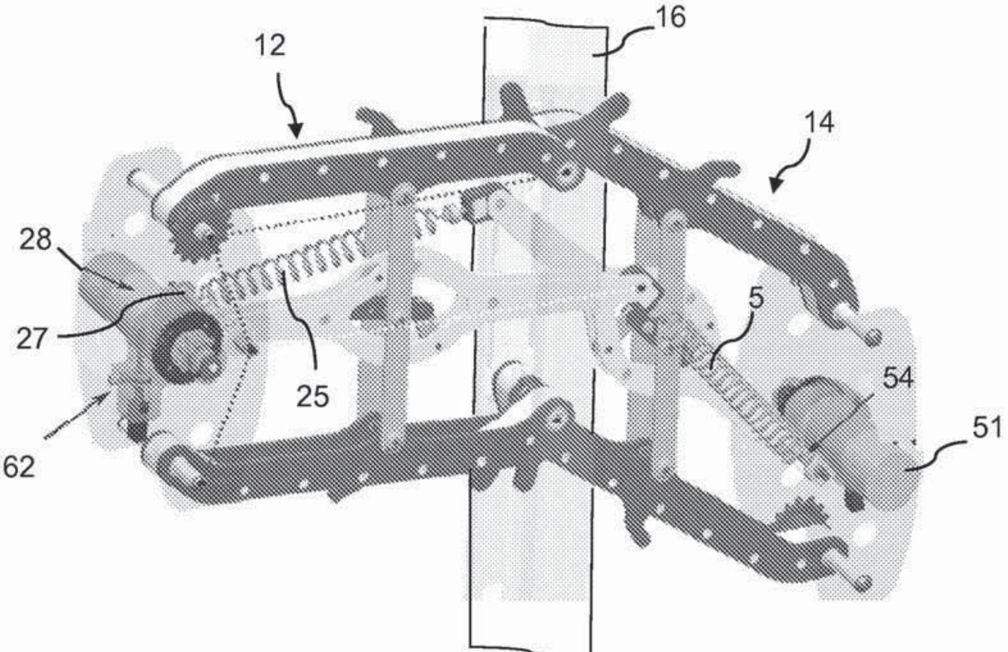


FIG. 12

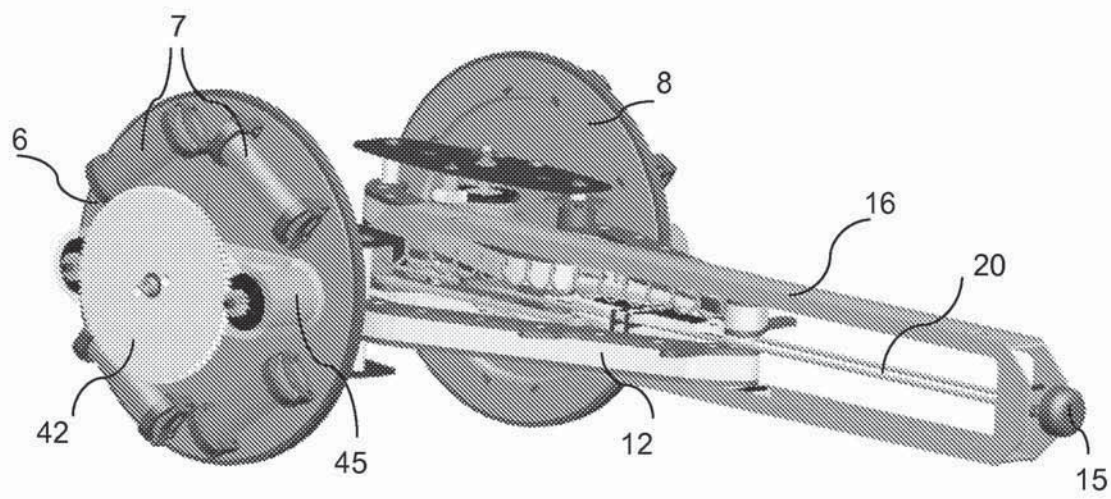


FIG. 13

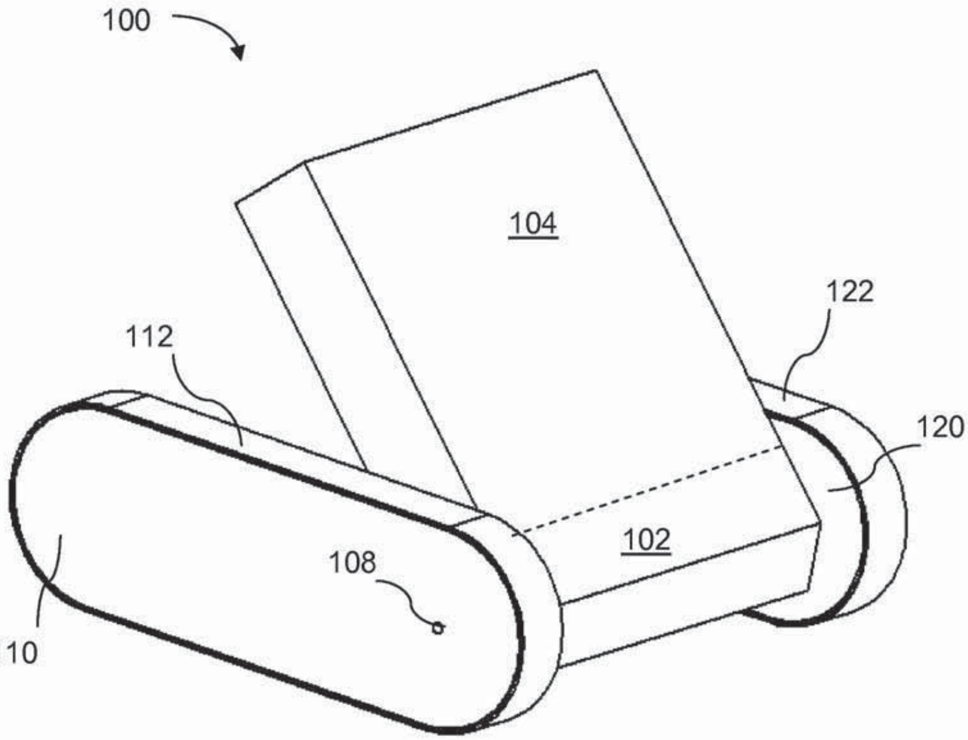


FIG. 14a

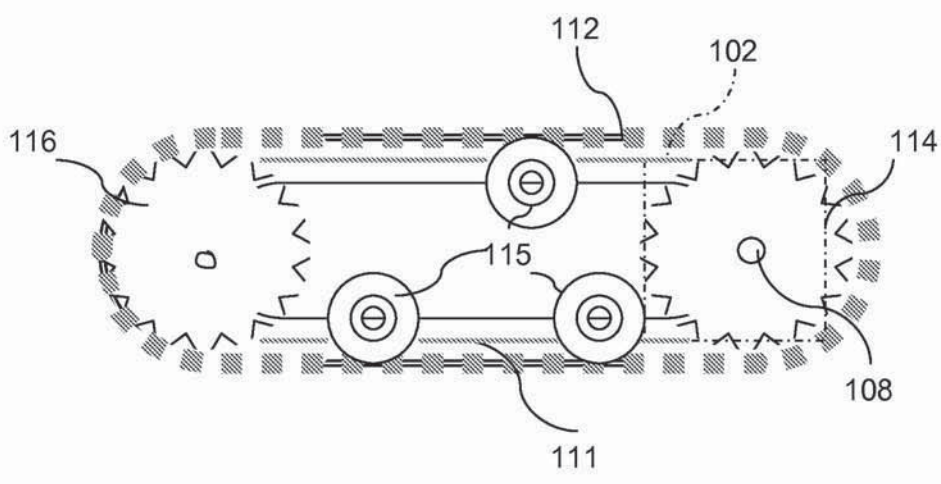


FIG. 14b

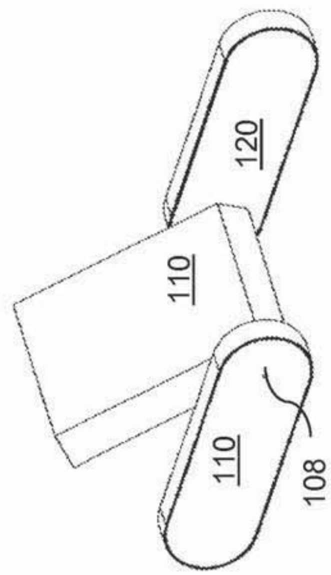


FIG. 15c

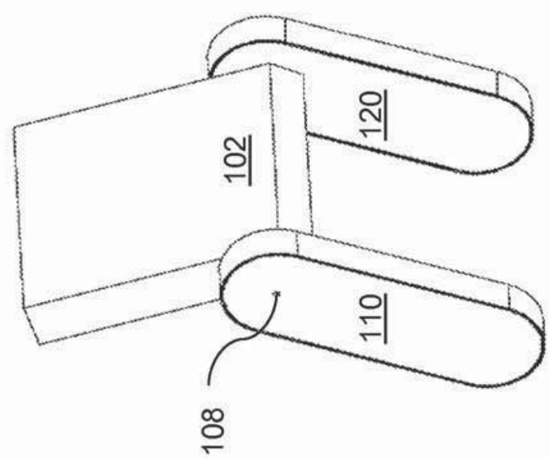


FIG. 15b

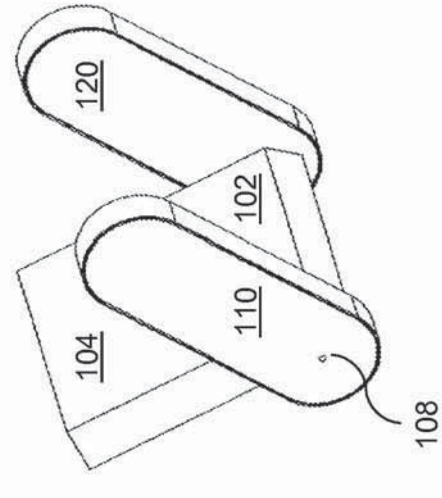


FIG. 15a

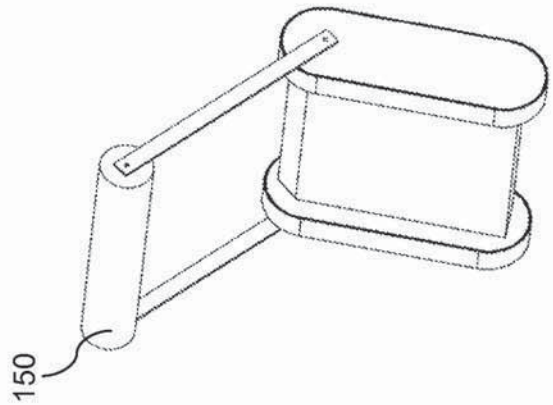


FIG. 16c

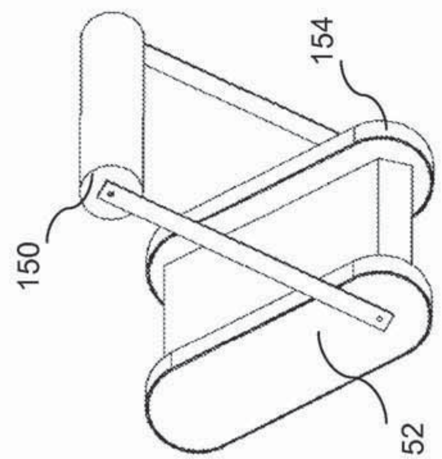


FIG. 16b

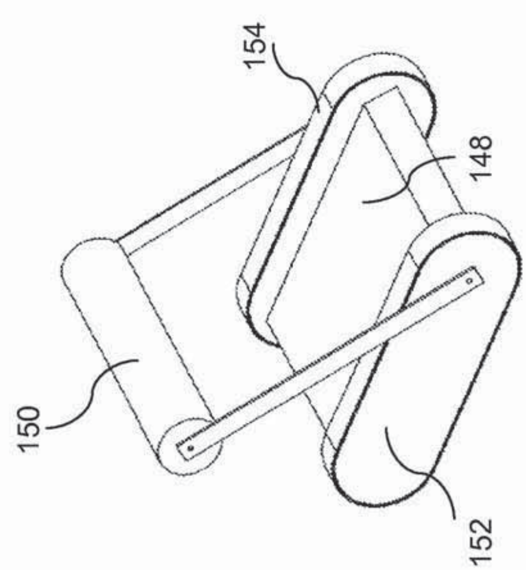


FIG. 16a

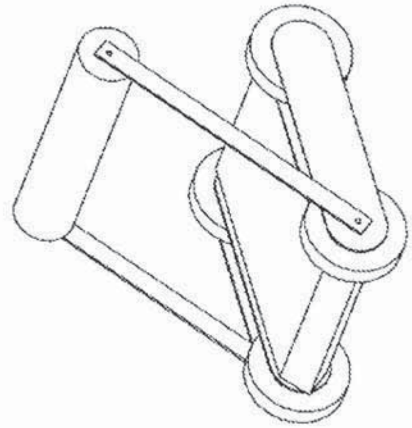


FIG. 18

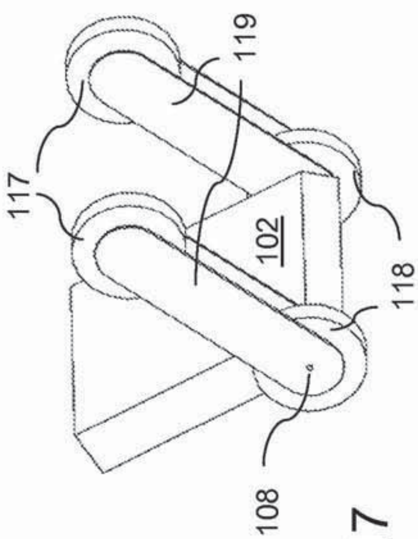


FIG. 17

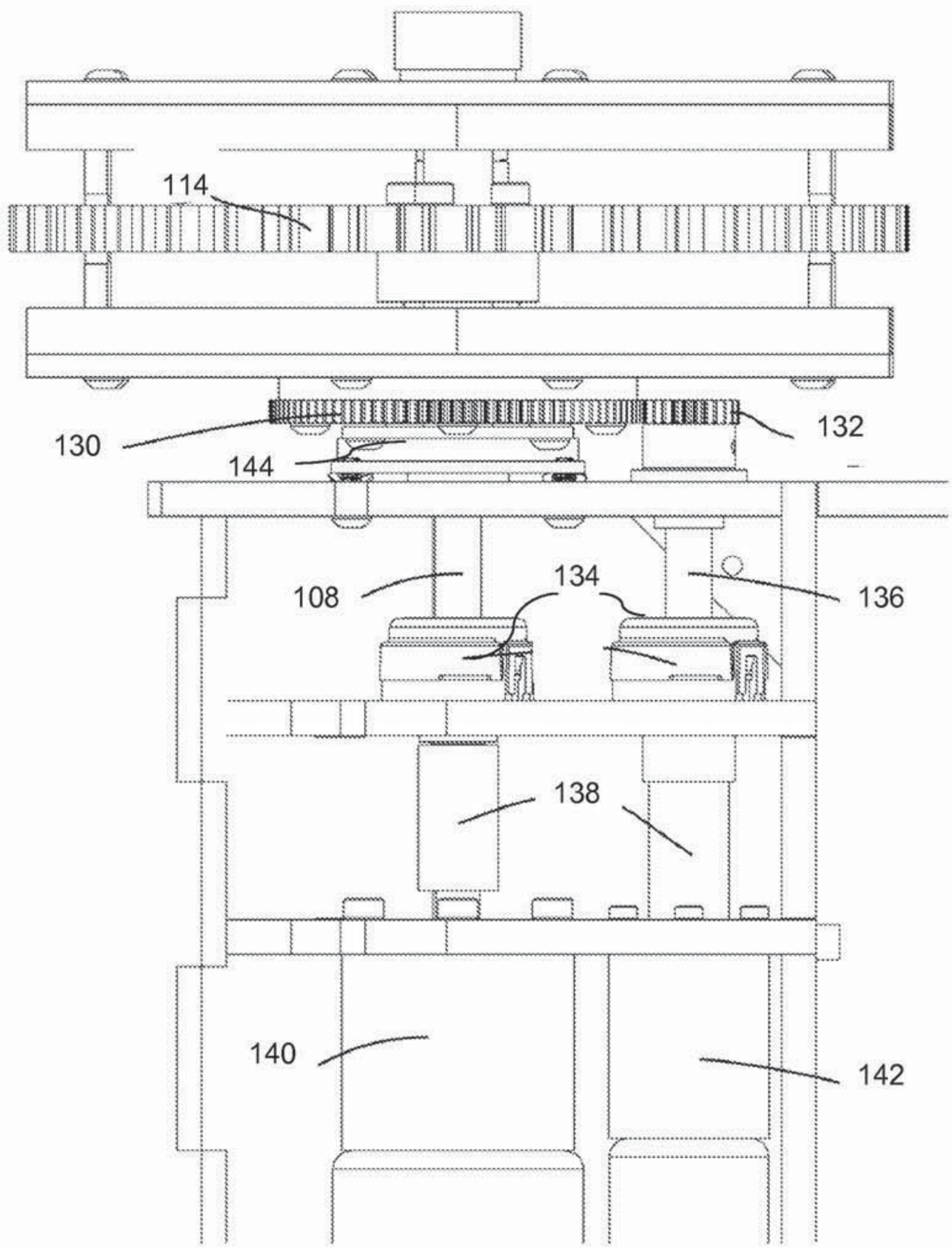


FIG. 19

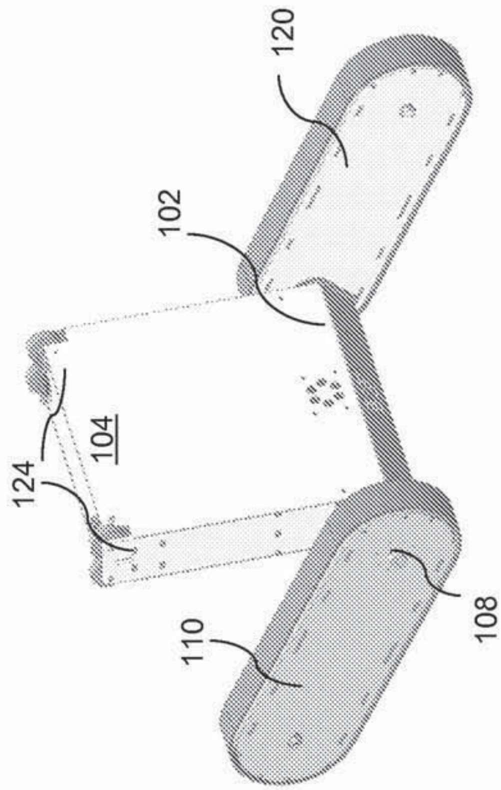


FIG. 20b

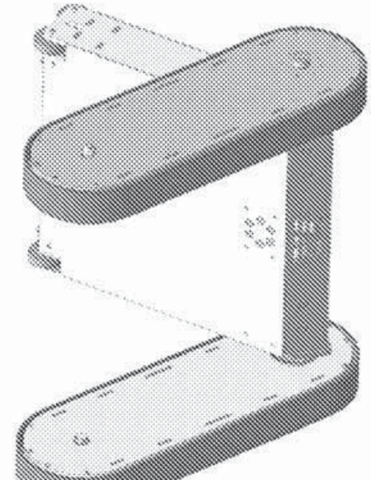


FIG. 20d

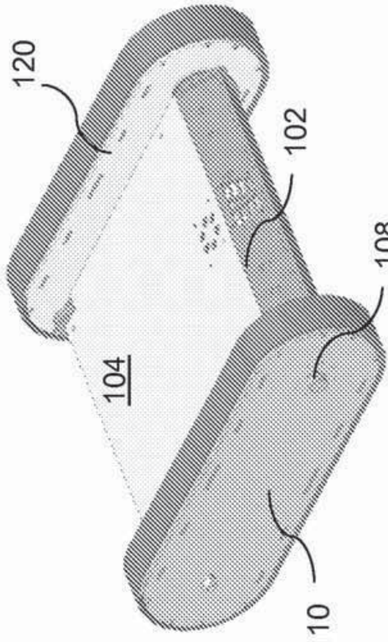


FIG. 20a

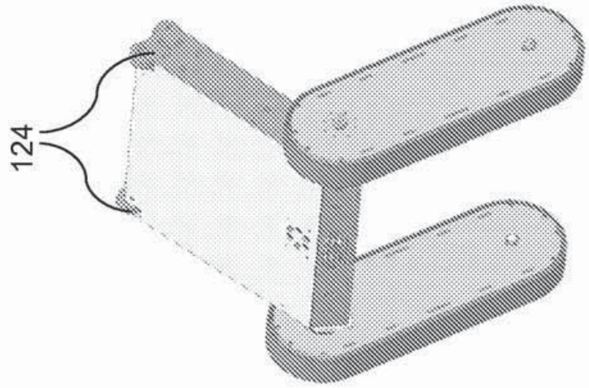


FIG. 20c

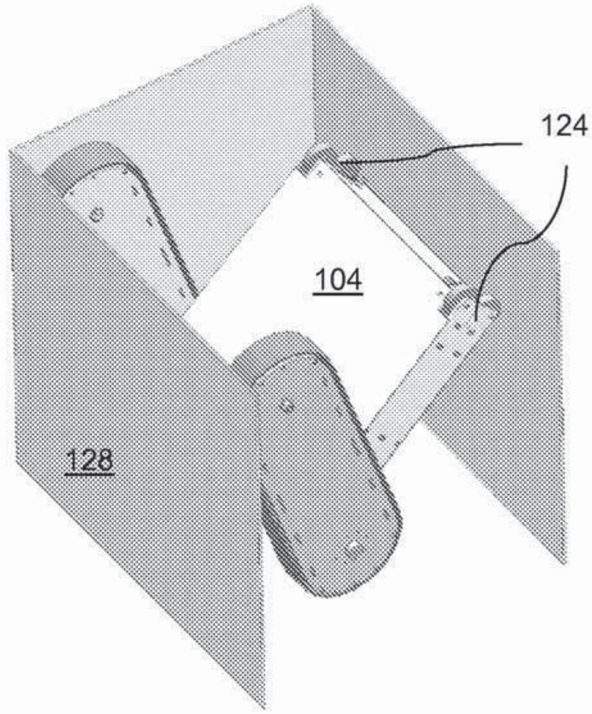


FIG. 21a

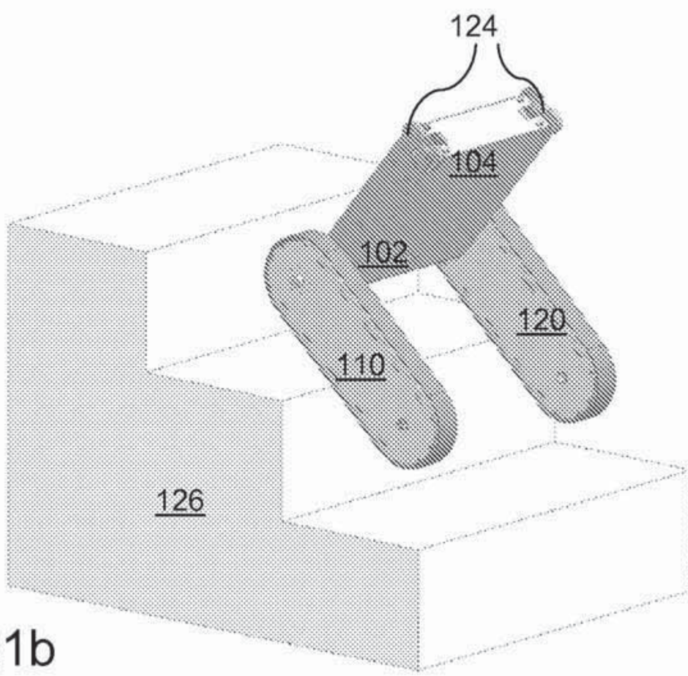


FIG. 21b

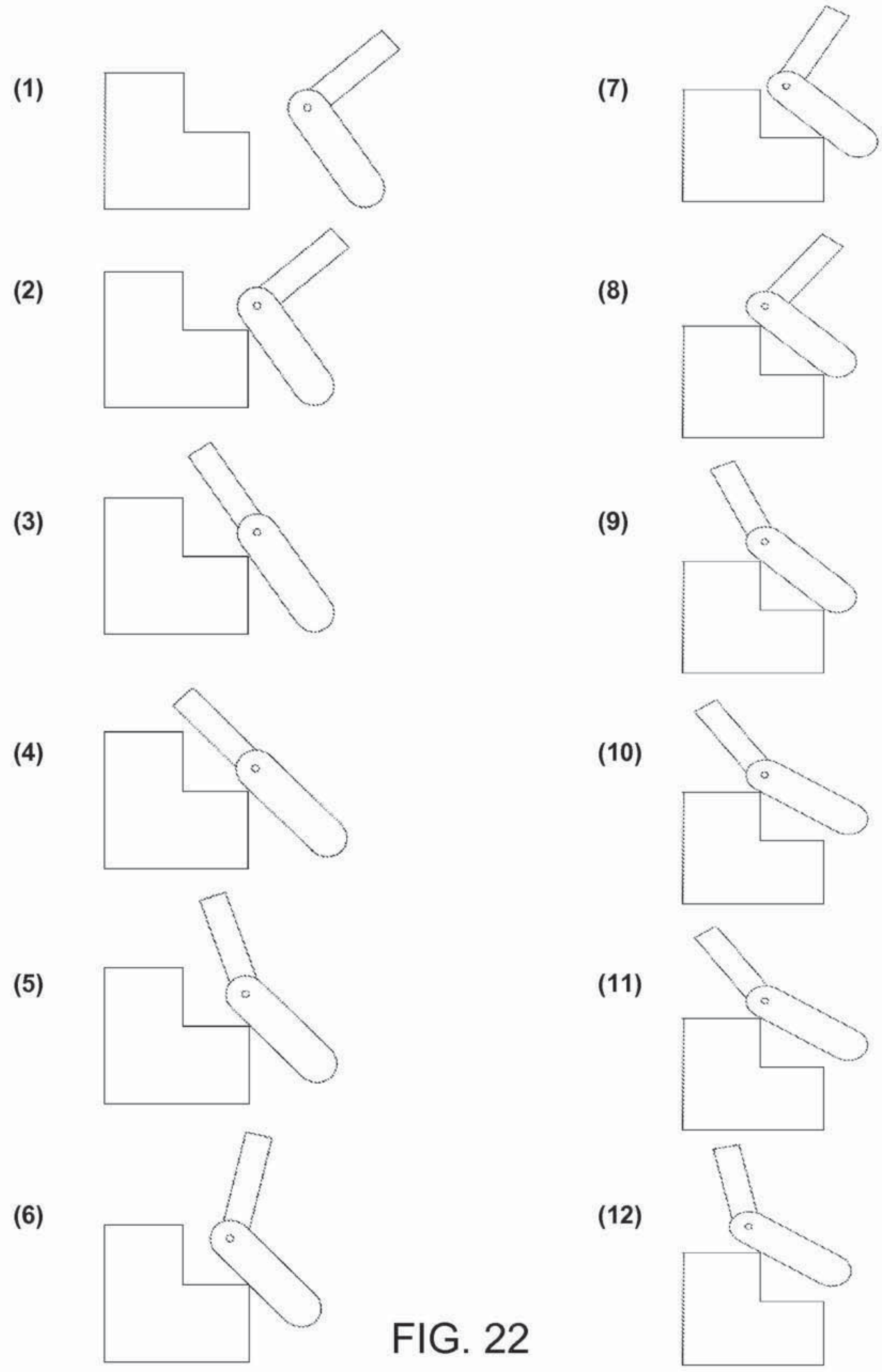
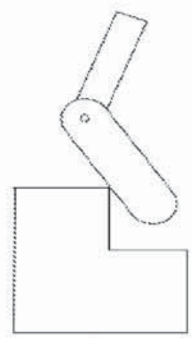
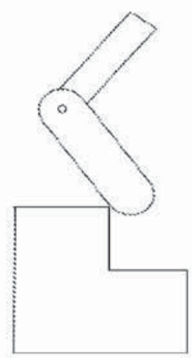


FIG. 22

(13)



(14)



(15)

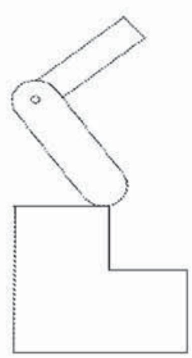


FIG. 22
(continued)

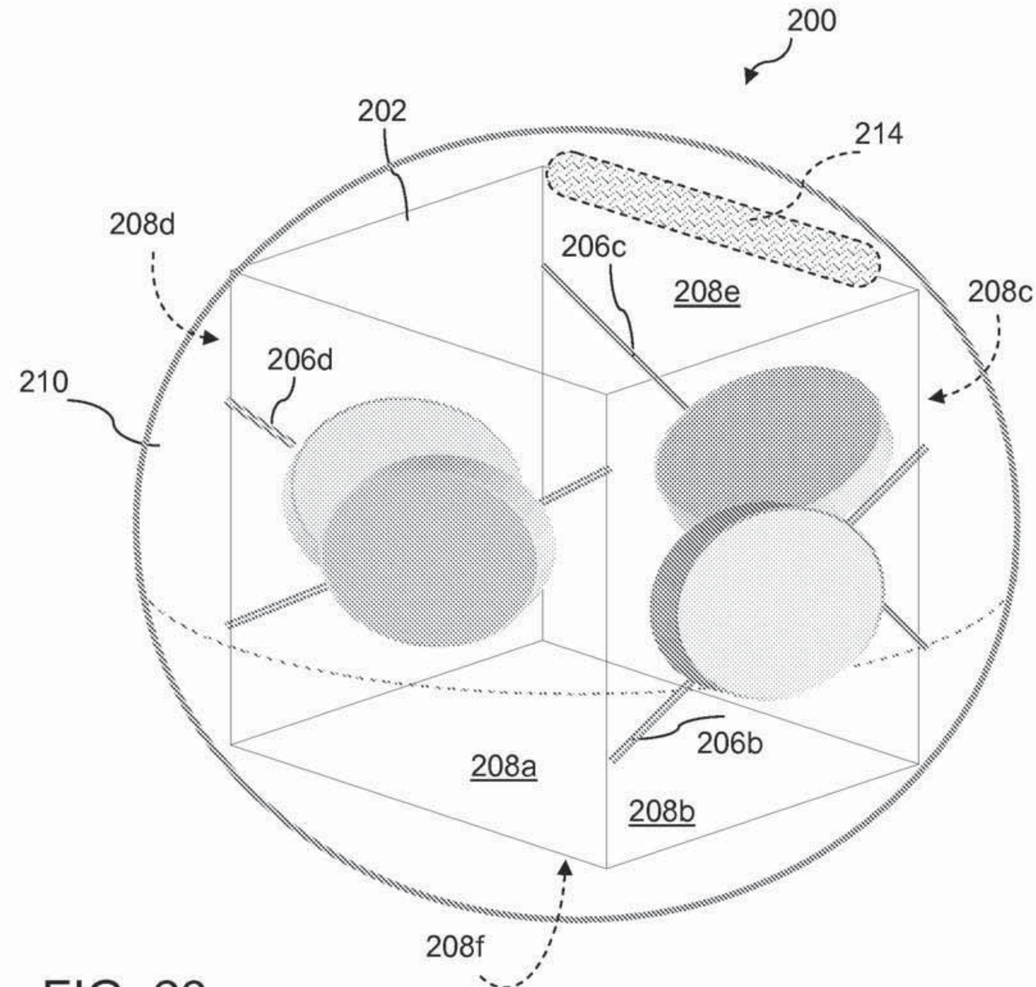


FIG. 23

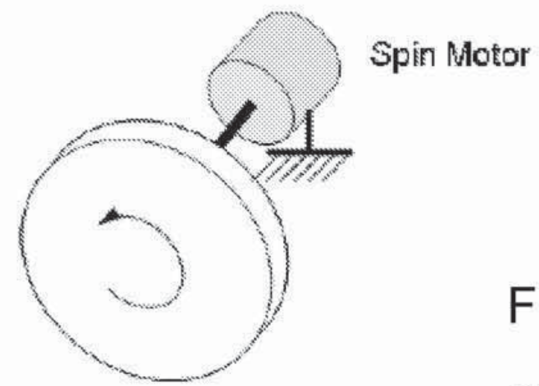


FIG. 24a

PRIOR ART

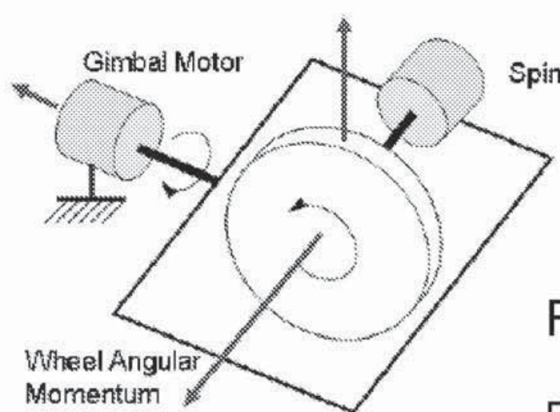


FIG. 24b

PRIOR ART

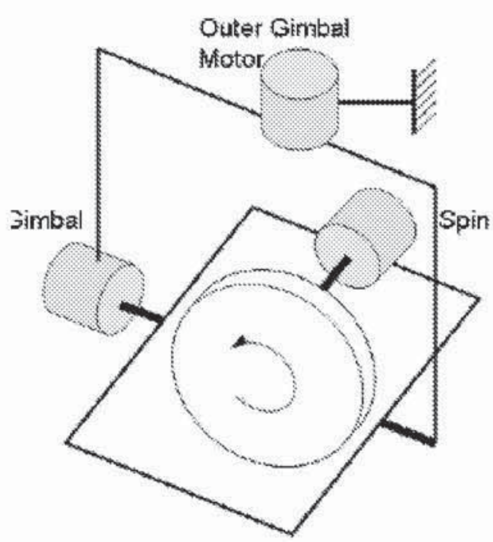


FIG. 24c

PRIOR ART

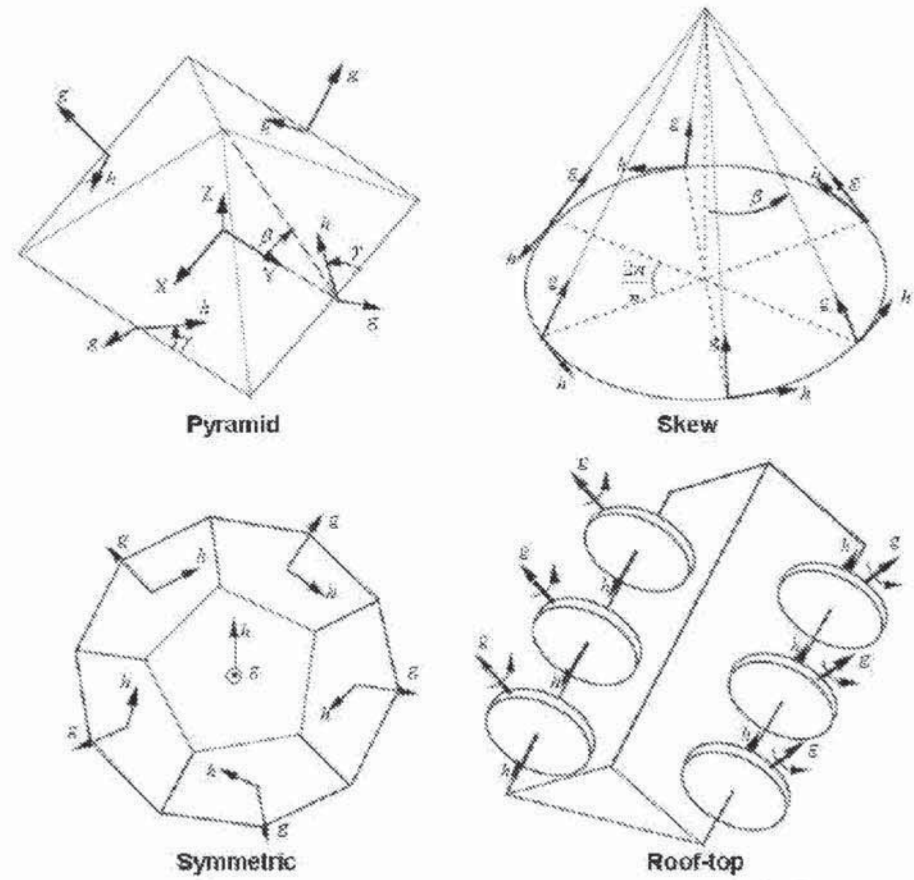


FIG. 25

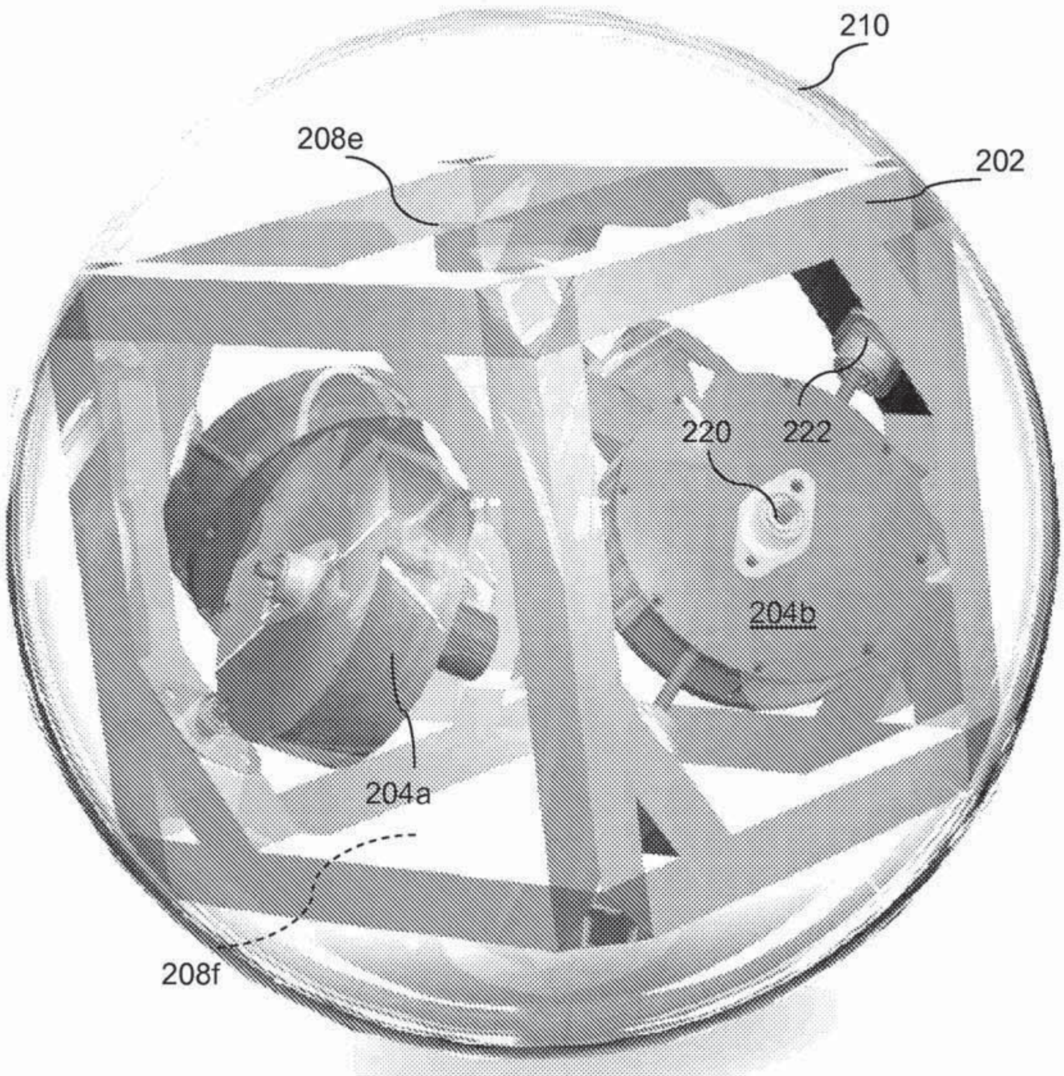


FIG. 26

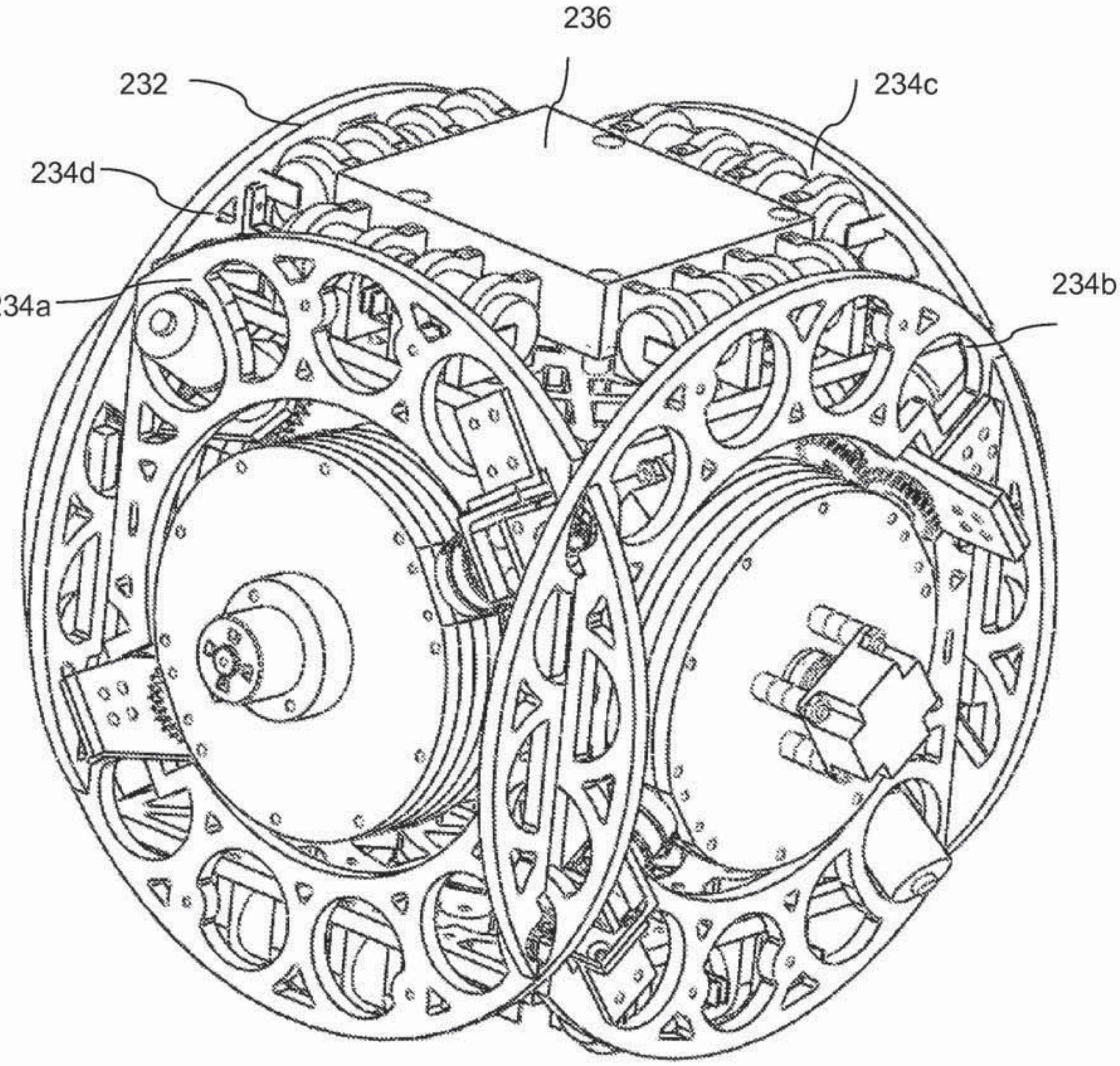


FIG. 27a

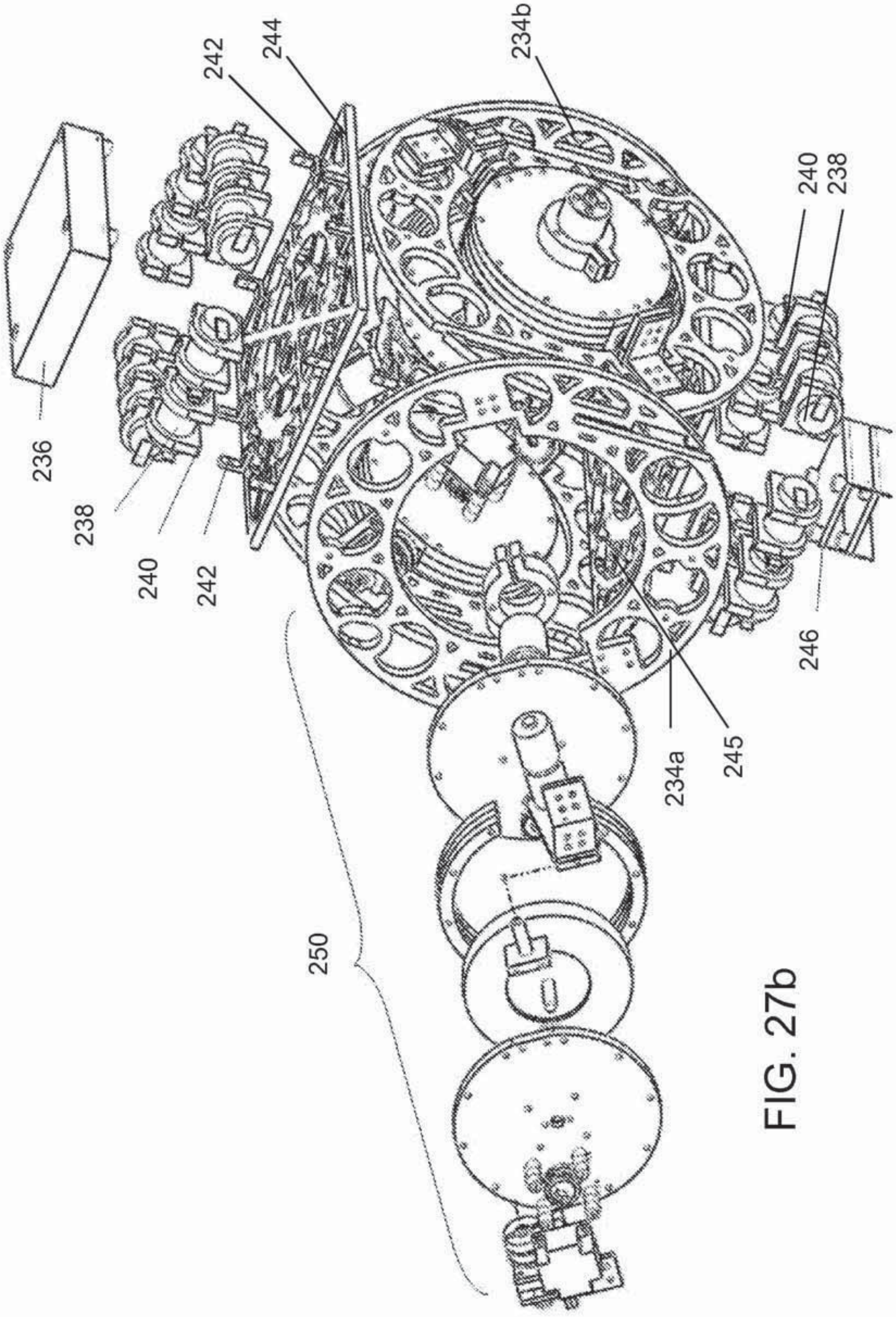
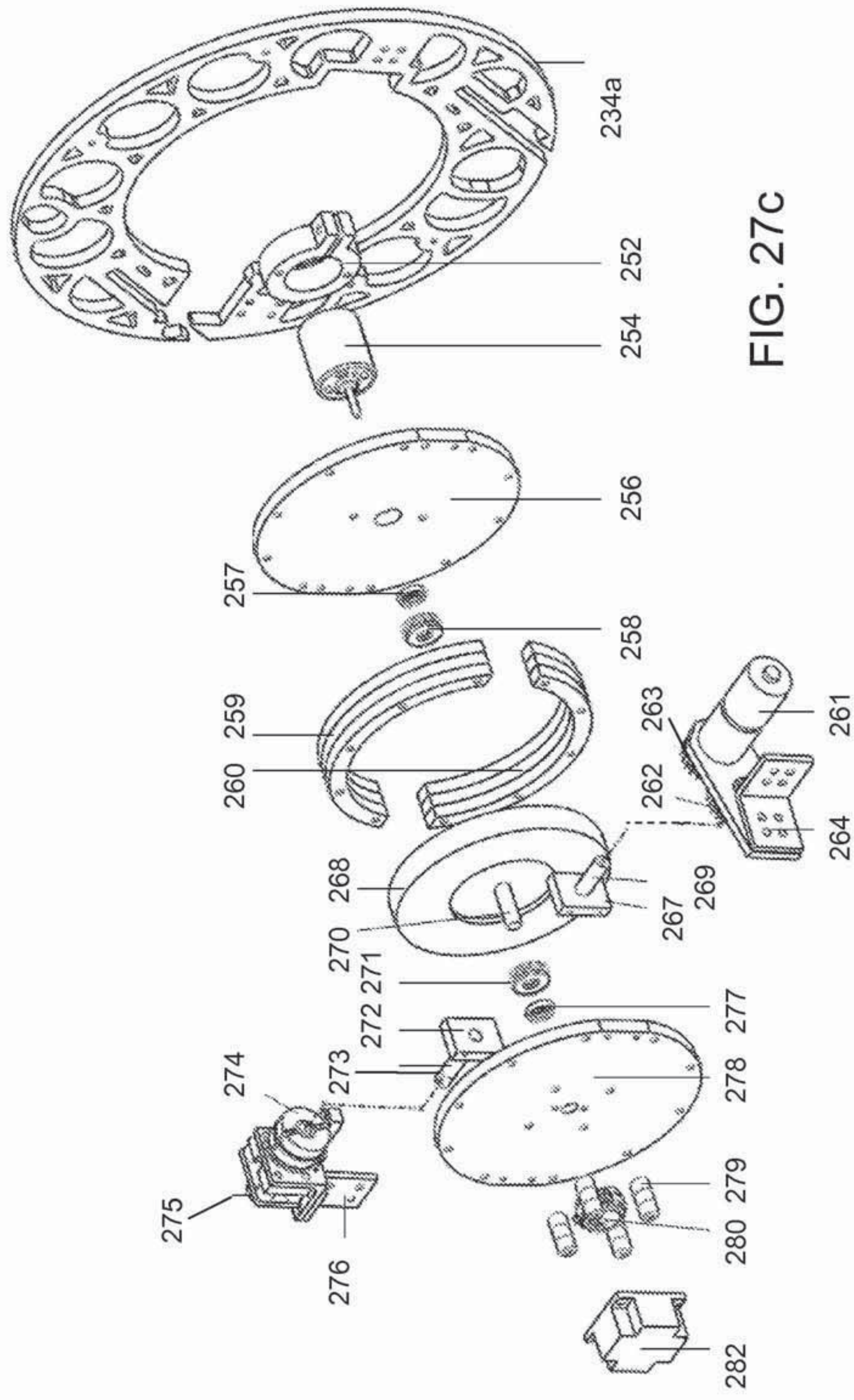


FIG. 27b


234a
252
254
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259
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FIG. 27c

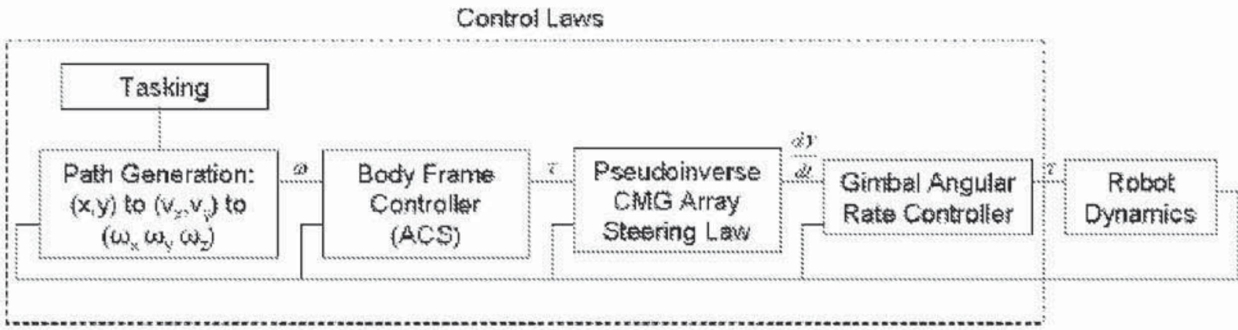


FIG. 28

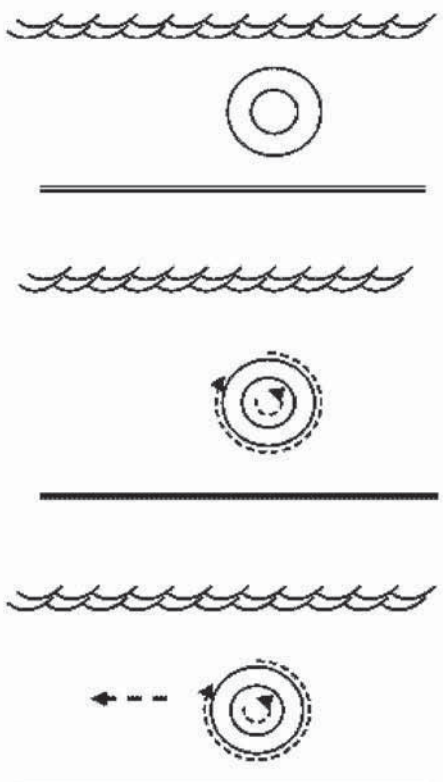


FIG. 29a

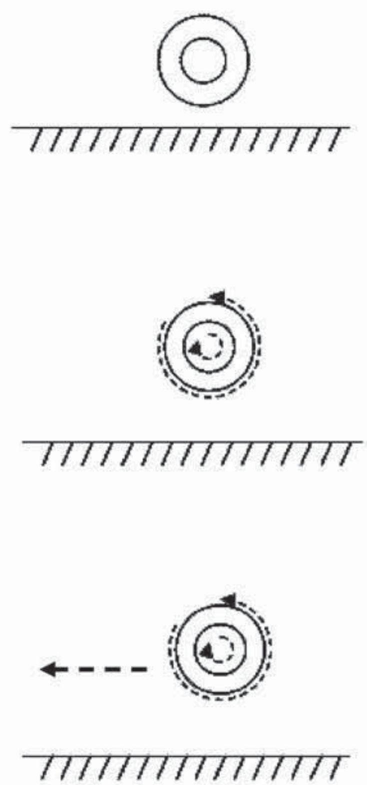


FIG. 29b

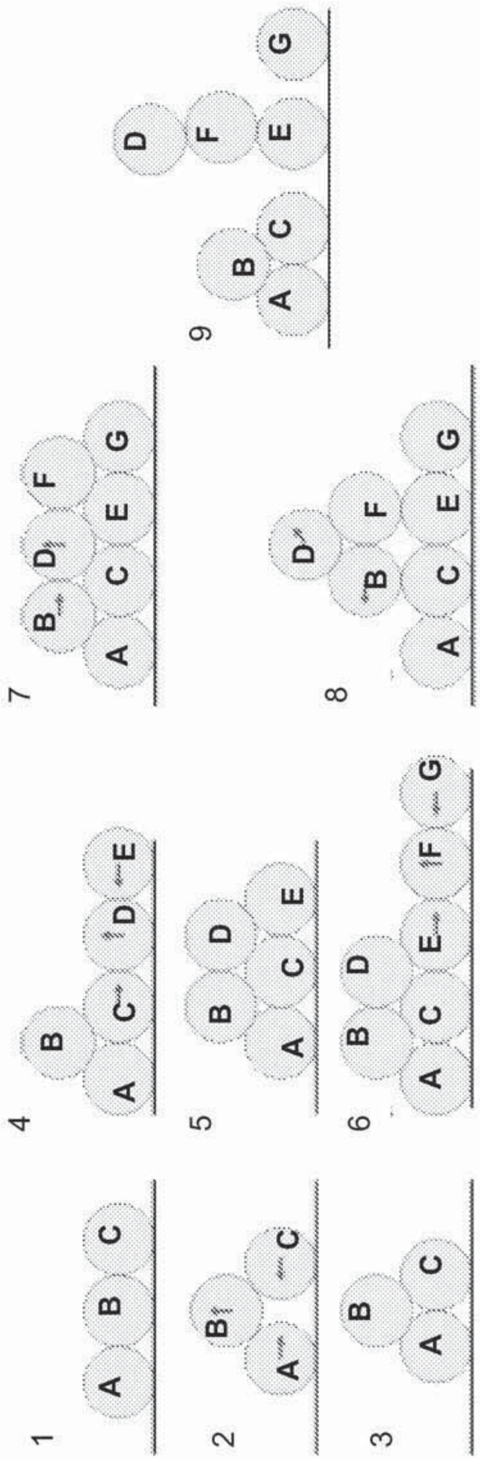
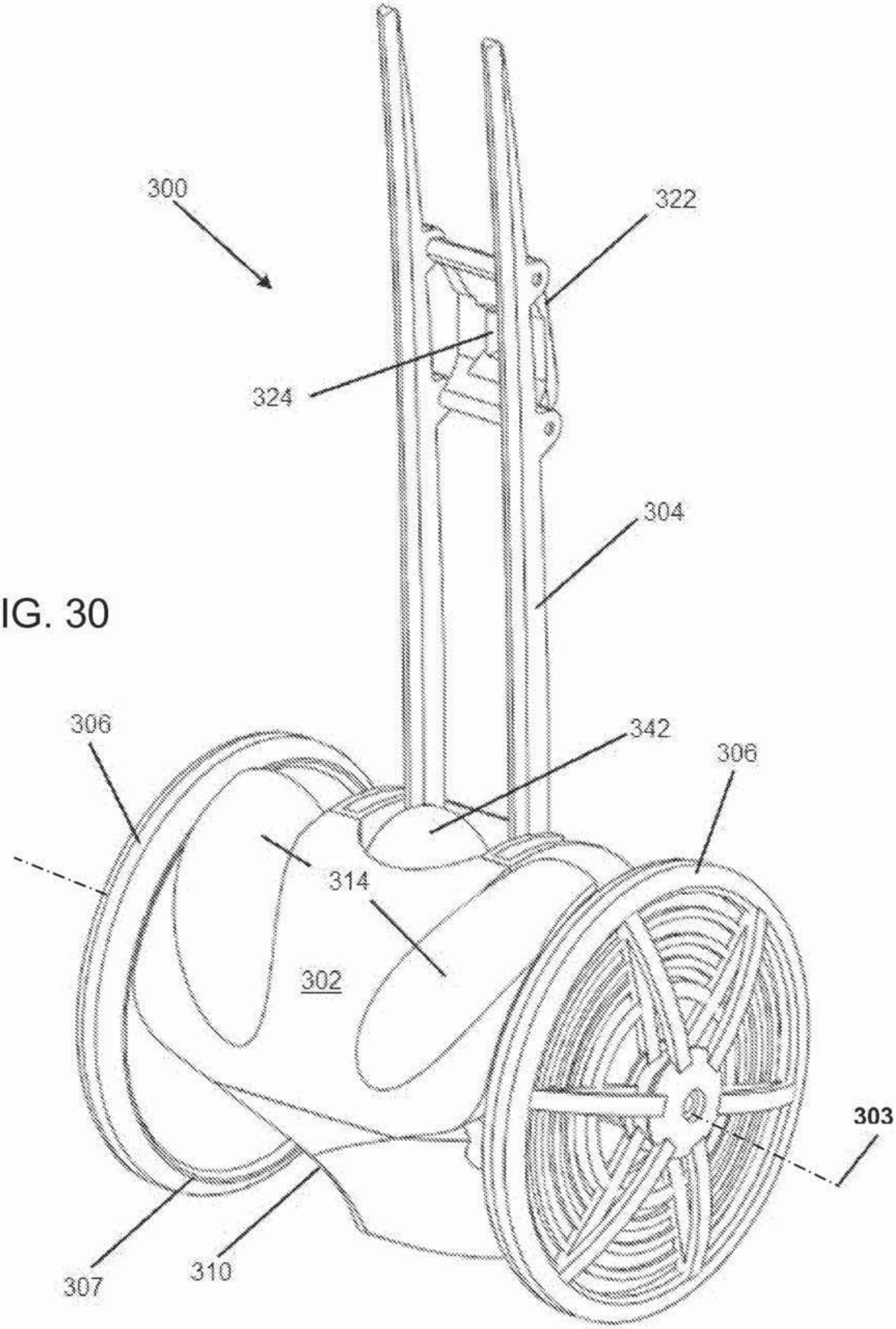

1
A B C
2
A B C
3
A B C
4
A B C D E
5
A B C D E
6
A B C D E F G
7
A B C D E F G
8
A B C D E F G
9
A B C D E F G

FIG. 29c

FIG. 30



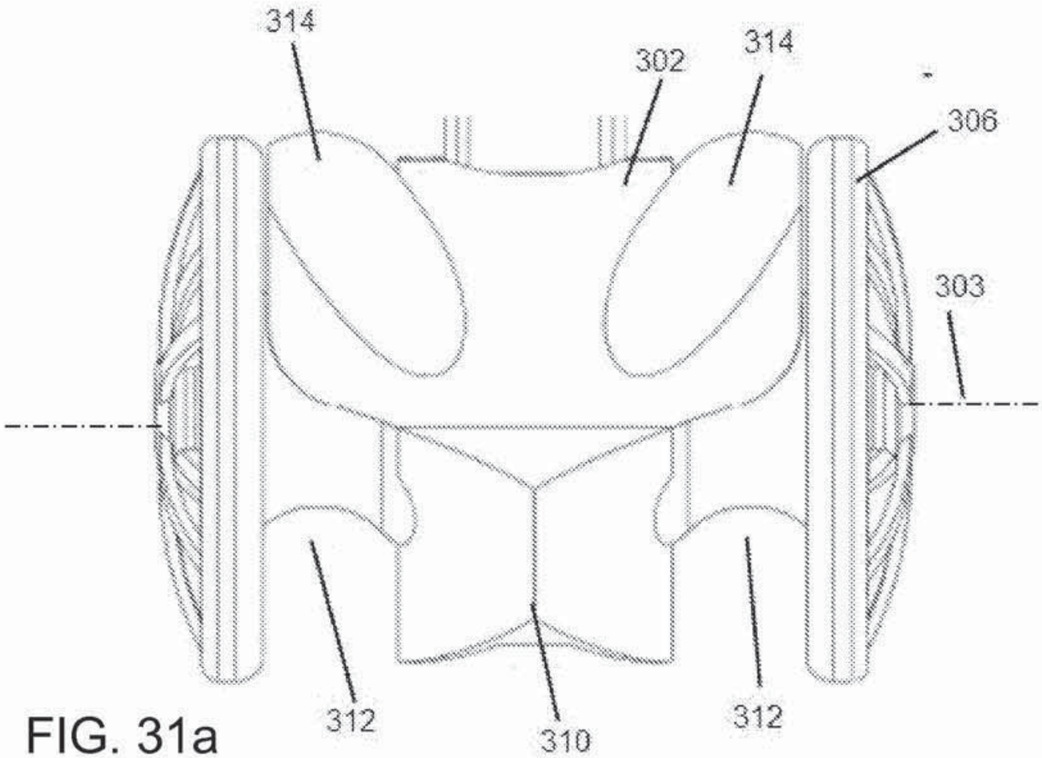


FIG. 31a

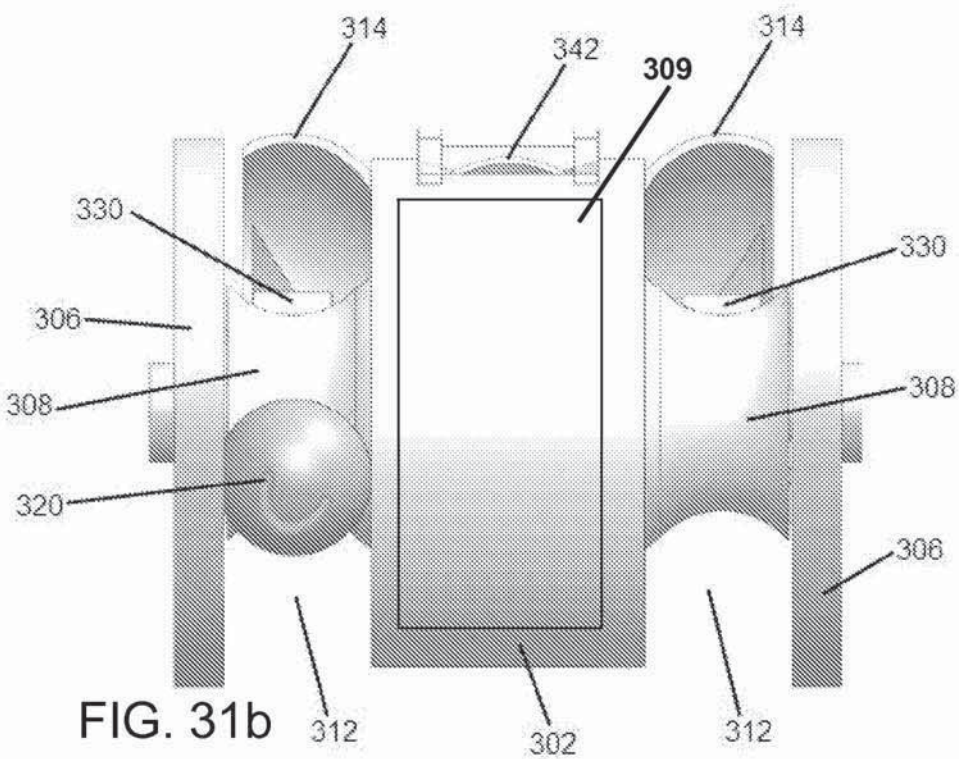


FIG. 31b

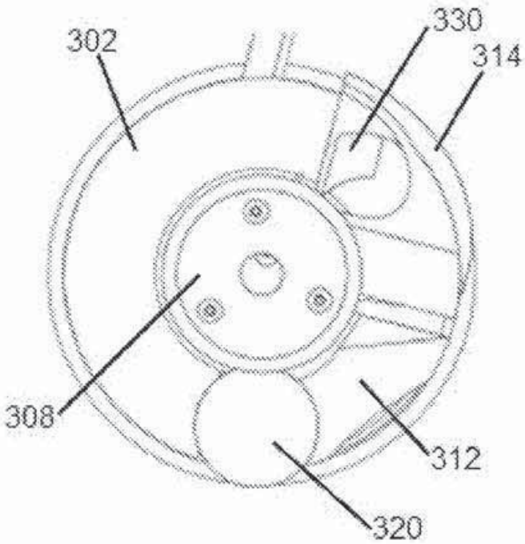


FIG. 32a

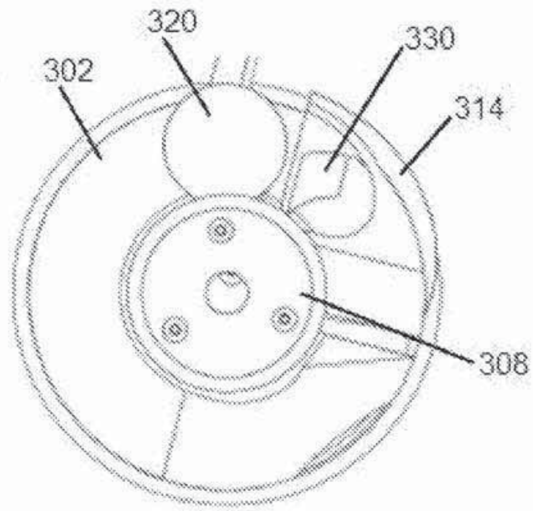


FIG. 32b

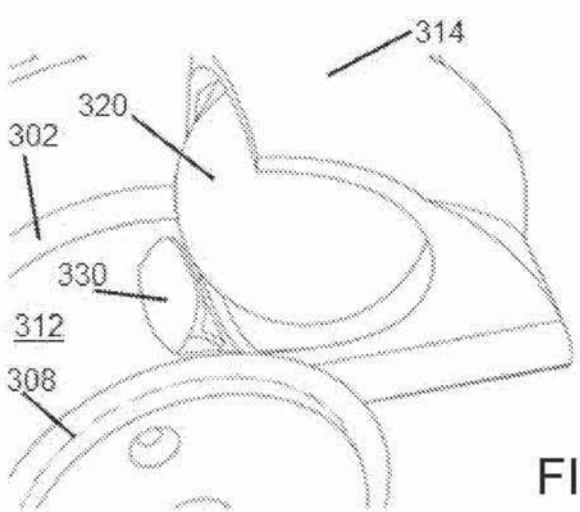


FIG. 33

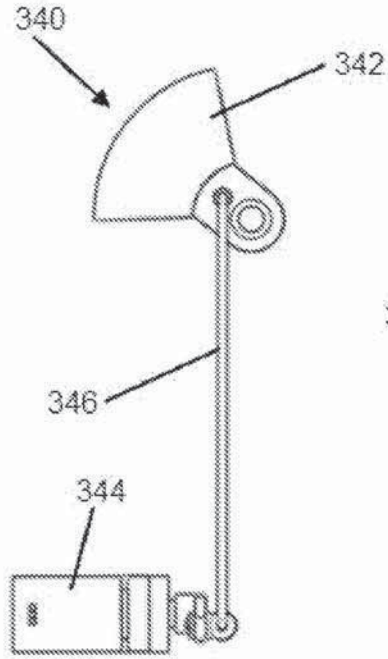


FIG. 34a

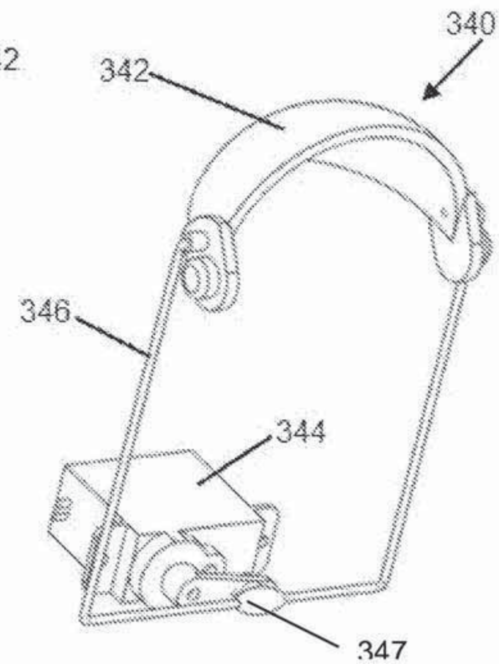


FIG. 34b

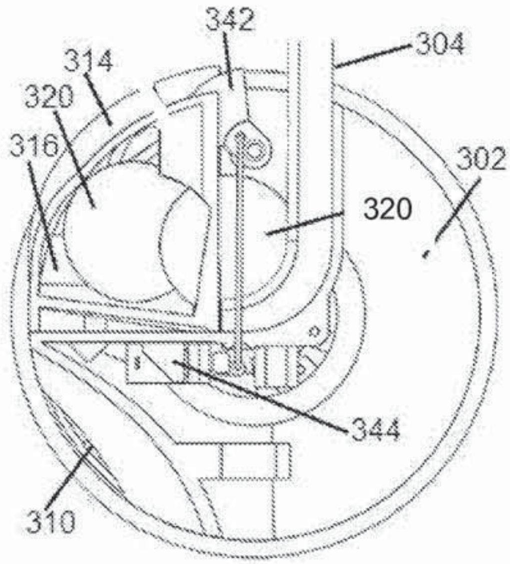


FIG. 35a

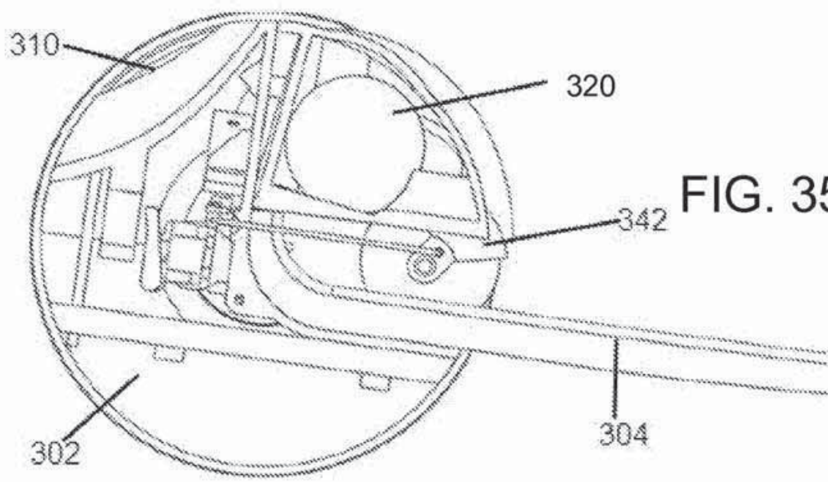


FIG. 35b

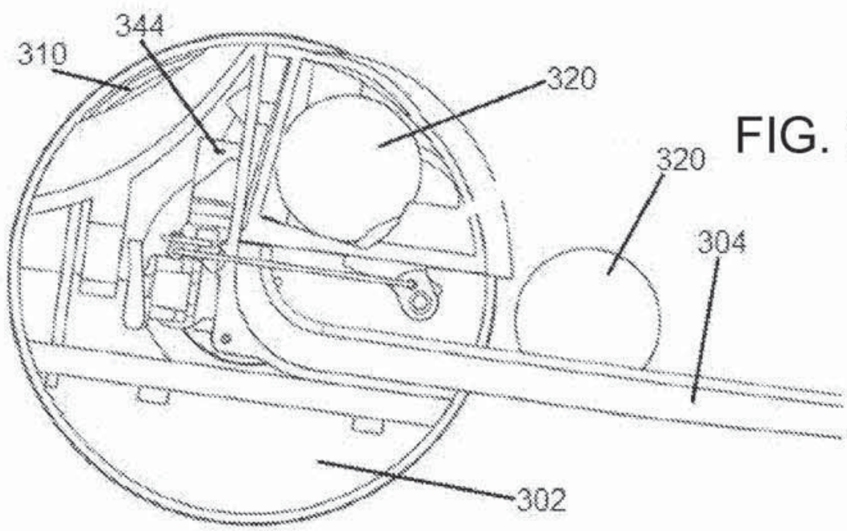


FIG. 35c

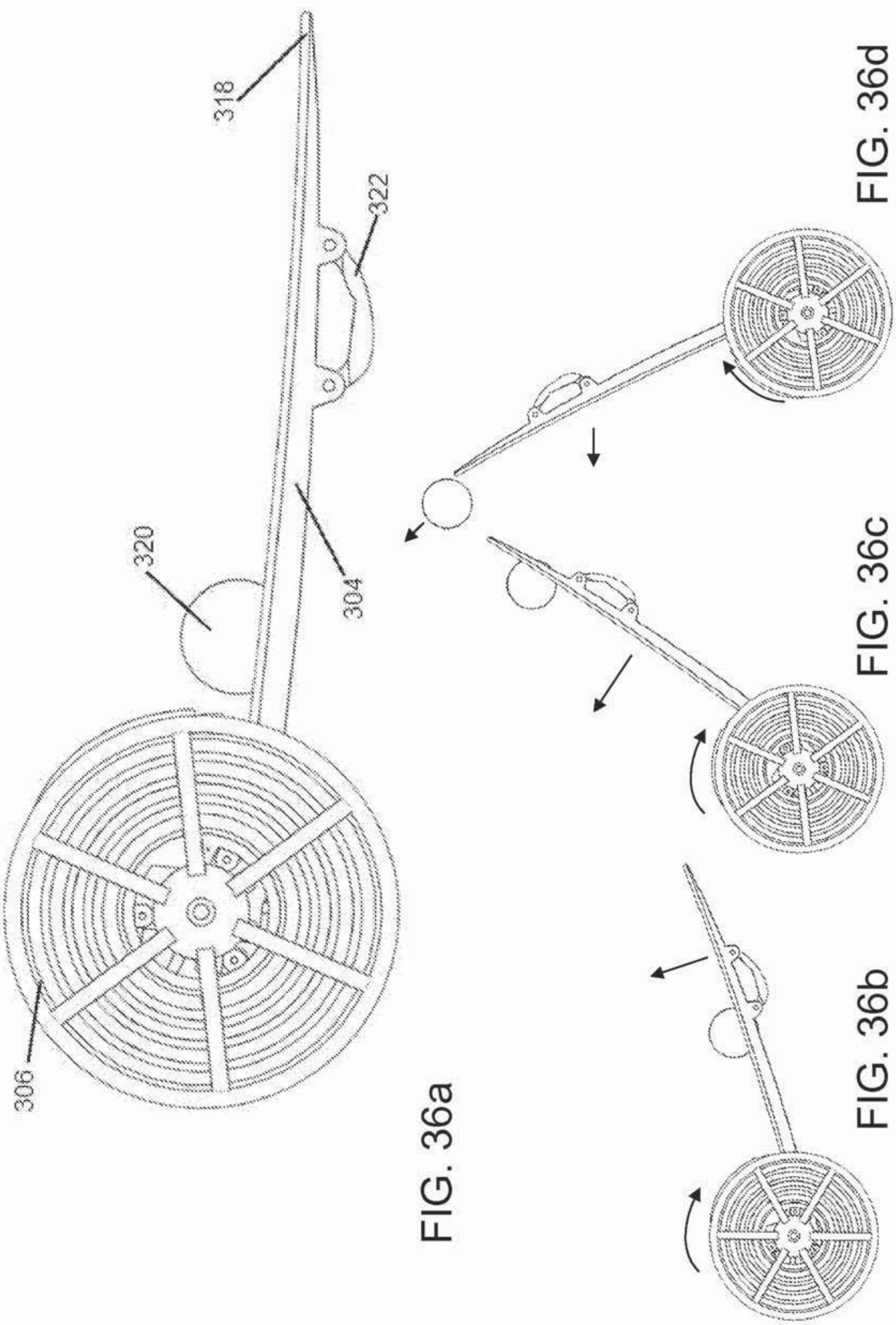


FIG. 36a

FIG. 36b

FIG. 36c

FIG. 36d

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U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	111845-US0032
	Application Number	

Title of Invention	Multimodal Dynamic Robotic Systems

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Applicant Information:

Applicant 1

Applicant Authority ◉ Inventor ◯ Legal Representative under 35 U.S.C. 117 ◯ Party of Interest under 35 U.S.C. 118

Prefix	**Given Name**	**Middle Name**	**Family Name**	**Suffix**
	Thomas	R.	Bewley	

Residence Information (Select One) ◉ US Residency ◯ Non US Residency ◯ Active US Military Service

City	San Diego	**State/Province**	CA	**Country of Residence**	US

Citizenship under 37 CFR 1.41(b)	US

Mailing Address of Applicant:

Address 1	8429 Via Mallorca #112
Address 2	

City	San Diego	**State/Province**	CA
Postal Code	92037	**Country**	US

Applicant 2

Applicant Authority ◉ Inventor ◯ Legal Representative under 35 U.S.C. 117 ◯ Party of Interest under 35 U.S.C. 118

Prefix	**Given Name**	**Middle Name**	**Family Name**	**Suffix**
	Christopher		Schmidt-Wetekam	

Residence Information (Select One) ◉ US Residency ◯ Non US Residency ◯ Active US Military Service

City	Solana Beach	**State/Province**	CA	**Country of Residence**	US

Citizenship under 37 CFR 1.41(b)	US

Mailing Address of Applicant:

Address 1	1015 Via Mil Cumbres
Address 2	

City	Solana Beach	**State/Province**	CA
Postal Code	92075	**Country**	US

Applicant 3

Applicant Authority ◉ Inventor ◯ Legal Representative under 35 U.S.C. 117 ◯ Party of Interest under 35 U.S.C. 118

Prefix	**Given Name**	**Middle Name**	**Family Name**	**Suffix**
	Andrew		Cavender	

Residence Information (Select One) ◉ US Residency ◯ Non US Residency ◯ Active US Military Service

City	San Diego	**State/Province**	CA	**Country of Residence**	US

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	111845-US0032
	Application Number	

Title of Invention	Multimodal Dynamic Robotic Systems

Citizenship under 37 CFR 1.41(b)	US			
Mailing Address of Applicant:				
Address 1	8730 Costa Verde Blvd. Apt. #2517			
Address 2				
City	San Diego	**State/Province**	CA	
Postal Code	92122	**Country**	US	

Applicant 4

Applicant Authority (●) Inventor ( ) Legal Representative under 35 U.S.C. 117 ( ) Party of Interest under 35 U.S.C. 118

Prefix	**Given Name**	**Middle Name**	**Family Name**	**Suffix**
	Nicholas		Morozovsky	

Residence Information (Select One) (●) US Residency ( ) Non US Residency ( ) Active US Military Service

City	La Jolla	**State/Province**	CA	**Country of Residence**	US
Citizenship under 37 CFR 1.41(b)	US				
Mailing Address of Applicant:					
Address 1	1 Miramar Street., # 929440				
Address 2					
City	La Jolla	**State/Province**	CA		
Postal Code	92092	**Country**	US		

Applicant 5

Applicant Authority (●) Inventor ( ) Legal Representative under 35 U.S.C. 117 ( ) Party of Interest under 35 U.S.C. 118

Prefix	**Given Name**	**Middle Name**	**Family Name**	**Suffix**
	Benjamin	A.	Sams	

Residence Information (Select One) (●) US Residency ( ) Non US Residency ( ) Active US Military Service

City	La Jolla	**State/Province**	CA	**Country of Residence**	US
Citizenship under 37 CFR 1.41(b)	US				
Mailing Address of Applicant:					
Address 1	1 Miramar Street Box # 929279				
Address 2					
City	La Jolla	**State/Province**	CA		
Postal Code	92092	**Country**	US		

Applicant 6

Applicant Authority (●) Inventor ( ) Legal Representative under 35 U.S.C. 117 ( ) Party of Interest under 35 U.S.C. 118

Prefix	**Given Name**	**Middle Name**	**Family Name**	**Suffix**
	Po-Ting		Chen	

Residence Information (Select One) (●) US Residency ( ) Non US Residency ( ) Active US Military Service

City	Irvine	**State/Province**	CA	**Country of Residence**	US
Citizenship under 37 CFR 1.41(b)	US				

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	111845-US0032
	Application Number	
Title of Invention	Multimodal Dynamic Robotic Systems	

Mailing Address of Applicant:

Address 1	56 Water Lily		
Address 2			
City	Irvine	**State/Province**	CA
Postal Code	92606	**Country**	US

Applicant 7

Applicant Authority ◉ Inventor ○ Legal Representative under 35 U.S.C. 117 ○ Party of Interest under 35 U.S.C. 118

Prefix	Given Name	Middle Name	Family Name	Suffix
	Matt		Grinberg	

Residence Information (Select One) ◉ US Residency ○ Non US Residency ○ Active US Military Service

City	San Francisco	**State/Province**	CA	**Country of Residence**	US
Citizenship under 37 CFR 1.41(b)	US				

Mailing Address of Applicant:

Address 1	1787 Haight Street		
Address 2			
City	San Francisco	**State/Province**	CA
Postal Code	94117	**Country**	US

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below. For further information see 37 CFR 1.33(a).

☐ **An Address is being provided for the correspondence Information of this application.**

Customer Number	27189	
Email Address	docketing@procopio.com	Add Email Remove Email

Application Information:

Title of the Invention	Multimodal Dynamic Robotic Systems		
Attorney Docket Number	111845-US0032	**Small Entity Status Claimed**	☒
Application Type	Nonprovisional		
Subject Matter	Utility		
Suggested Class (if any)		**Sub Class (if any)**	
Suggested Technology Center (if any)			
Total Number of Drawing Sheets (if any)	34	**Suggested Figure for Publication (if any)**	2

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	111845-US0032
	Application Number	
Title of Invention	Multimodal Dynamic Robotic Systems	

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Enter either Customer Number or complete the Representative Name section below. If both sections are completed the Customer Number will be used for the Representative Information during processing.

Please Select One:	◉ Customer Number	○ US Patent Practitioner	○ Limited Recognition (37 CFR 11.9)
Customer Number	27189		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78(a)(2) or CFR 1.78(a)(4), and need not otherwise be made part of the specification.

Prior Application Status	Pending		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	a 371 of international	PCT/US2010/044790	2010-08-06
Prior Application Status	Expired		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
PCT/US2010/044790	non provisional of	61231672	2009-08-04
Prior Application Status			Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
PCT/US2010/044790	non provisional of	61324258	2010-04-14

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button.

Foreign Priority Information:

This section allows for the applicant to claim benefit of foreign priority and to identify any prior foreign application for which priority is not claimed. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(a).

			Remove
Application Number	Country	Parent Filing Date (YYYY-MM-DD)	Priority Claimed
			◉ Yes ○ No

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U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	111845-US0032
	Application Number	

Title of Invention	Multimodal Dynamic Robotic Systems

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button.

Assignee Information:

Providing this information in the application data sheet does not substitute for compliance with any requirement of part 3 of Title 37 of the CFR to have an assignment recorded in the Office.

Assignee 1

If the Assignee is an Organization check here. ☒

Organization Name	The Regents of the University of California		
Mailing Address Information:			
Address 1	1111 Franklin Street, 5th Floor		
Address 2			
City	Oakland	**State/Province**	CA
Country	US	Postal Code	94607
Phone Number		Fax Number	
Email Address			

Additional Assignee Data may be generated within this form by selecting the **Add** button.

Signature:

A signature of the applicant or representative is required in accordance with 37 CFR 1.33 and 10.18. Please see 37 CFR 1.4(d) for the form of the signature.

Signature	/eleanor musick/			Date (YYYY-MM-DD)	2012-02-06
First Name	Eleanor M.	Last Name	Musick	Registration Number	35623

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these records.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Doc code: IDS
Doc description: Information Disclosure Statement (IDS) Filed

INFORMATION DISCLOSURE STATEMENT BY APPLICANT (**Not for submission under 37 CFR 1.99)**		
	Application Number	
	Filing Date	
	First Named Inventor	Thomas R. Bewley
	Art Unit	
	Examiner Name	
	Attorney Docket Number	111845-US0032

U.S.PATENTS

Examiner Initial*	Cite No	Patent Number	Kind Code[1]	Issue Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	8083013		2011-12-27	Bewley et al.	
	2	5281079		1994-01-25	Lemelson	
	3	2247354		1941-07-01	Berger	
	4	3648408		1972-03-14	Terzian et al.	
	5	4736826		1988-04-12	White et al.	
	6	5279170		1994-01-18	Chen	
	7	5618219		1997-04-08	Simone et al.	
	8	5741169		1998-04-21	Chen	

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	9	6066026		2000-05-23	Bart et al.	
	10	6068073		2000-05-30	Roston et al.	
	11	6227934		2001-05-08	Isaksson et al.	
	12	6247546		2001-06-19	Spletzer et al.	
	13	6308791		2001-10-30	Spletzer et al.	
	14	6502657		2003-01-07	Kerrebrock et al.	
	15	6793026		2004-09-21	De Fazio	
	16	6939197		2005-09-06	Hoeting	
	17	7172488		2007-02-06	Moll et al.	
	18	7249640		2007-07-31	Horchler et al.	
	19	7263955		2007-09-04	Fischer	

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	20	7494398		2009-02-24	Laurienzo	
	21	7882915		2011-02-08	Wishart	
	22	5297981		1994-03-29	Maxim et al.	
	23	6289263		2001-09-11	Mukerjee	
	24	6668951		2003-12-30	Won	

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U.S.PATENT APPLICATION PUBLICATIONS

Examiner Initial*	Cite No	Publication Number	Kind Code1	Publication Date	Name of Patentee or Applicant of cited Document	Pages,Columns,Lines where Relevant Passages or Relevant Figures Appear
	1	20010031604		2001-10-18	Hornsby et al.	
	2	20070199108		2007-08-23	Angle et al.	
	3	20080231221		2008-09-25	Hideki	
	4	20040000439		2004-01-01	Burt et al.	

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	5	20070150110		2007-06-28	Delson	
	6	20070259602		2007-11-08	Dunham	
	7	20080231222		2008-09-25	Hashimoto et al.	
	8	20100122859		2010-05-30	Schroll	

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FOREIGN PATENT DOCUMENTS

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	1							☐

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NON-PATENT LITERATURE DOCUMENTS

Examiner Initials*	Cite No	Include name of the author (in CAPITAL LETTERS), title of the article (when appropriate), title of the item (book, magazine, journal, serial, symposium, catalog, etc), date, pages(s), volume-issue number(s), publisher, city and/or country where published.	T5
	1	ARMOUR, Rhodri H. et al. Rolling in Nature and Robotics: A Review, Journal of Bionic Engineering, 2006, Vol. 3 No. 4, 14 pages	☐
	2	WAI AU, Kwok et al. Decoupled Dynamics and Stabilization of Single Wheel Robot, Proceedings of the 1999 IEEE/ RSJ International Conference on Intelligent Robots and Systems, 7 pages (197-203).	☐

INFORMATION DISCLOSURE STATEMENT BY APPLICANT (**Not for submission under 37 CFR 1.99)**	Application Number	
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	Examiner Name	
	Attorney Docket Number	111845-US0032

	3	BROWN, JR. H. Benjamin et al. A Single-Wheel, Gyroscopically Stabilized Robot, IEEE Robotics & Automation Magazine, September 1997, pp. 39-44.	☐
	4	BROWN, JR. H. Benjamin et al. A Single-Wheel, Gyroscopically Stabilized Robot, IEEE Robotics & Automation Magazine, Proceedings of the 1996 IEEE International Conference on Robotics and Automation, Minneapolis, Minnesota, April 1996, pp. 3658-3663.	☐
	5	CROSSLEY, Vincent A. A Literature Review on the Design of Spherical Rolling Robots, citeseerx.ist.psu.edu, 2006, pp. 1-6.	☐
	6	NANDY, Gora C. et al. Dynamic Model of a Gyroscopic Wheel, Proceedings of the 1998 IEEE International Conference on Robotics & Automation, Leuven, Belgium, May 1998, p;p. 2683-2688.	☐
	7	OU, Yongsheng et al. Gyroscopically Stabilized Robot: Balance and Tracking, International Journal of Advanced Robotic Systems, Volume 1 Number 1 (2004), ISSN 1729-8806, pp. 23-32.	☐
	8	SCHMIDT-WETEKAM, Christopher et al. An Arm Suspension Mechanism for an Underactuated Single Legged Hopping Robot, 2011 IEEE International Conference on Robotics and Automation, Shanghai International Conference Center, May 9-13, 2011 Shanghai China, pp. 5529-5534	☐
	9	SCHMIDT-WETEKAM, Christopher et al. Design, Optimization, and Control of a New Class of Reconfigurable Hopping Rovers, Proceedings of the 46th IEEE Conference on Decision and Control, New Orleans, LA USA, December 12-14, 2007, pp. 5150-5155.	☐
	10	SCHMIDT-WETEKAM, Christopher et al. Inertial Rotation Center Position Estimation for a Perching Treaded Vehicle, 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, September 25-30, 2011, San Francisco, CA US, pp. 4097-4102.	☐
	11	SRIVASTAVA, Deepak Kumar. Slow Rotation of Concentric Spheres with Source at Their Centre in a Viscous Fluid, Hindawi Publishing Corporation, Journal of Applied Mathematics, Volume 2009, Article ID 740172, 13 pages.	☐
	12	TSAI, Shu-Jen et al. Control of the Gyrover, A Single-Wheel Gyroscopically Stabilized Robot, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'99), October 1999, pp. 179-184.	☐
	13	XU, Yangsheng et al. Dynamic Mobility with Single-Wheel Configuration, The International Journal of Robotics Research, Vol. 18, No. 7, July 1999, pp. 728-738.	☐

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	14	YLIKORPI, Tomi et al. Ball-shaped Robots, Climbing & Walking Robots, Towards New Applications, Book ediated by Houxiang Zhang, ISBN 978-3-902613-16-5, Itech Education and Publishing, Vienna, Austria, October 2007, pp. 235-256.	☐
	15	International Search Report and Written Opinion issued April 26, 2011 in PCT/US2010/044790, 10 pages.	☐

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EXAMINER SIGNATURE

Examiner Signature		Date Considered	

*EXAMINER: Initial if reference considered, whether or not citation is in conformance with MPEP 609. Draw line through a citation if not in conformance and not considered. Include copy of this form with next communication to applicant.

[1] See Kind Codes of USPTO Patent Documents at www.USPTO.GOV or MPEP 901.04. [2] Enter office that issued the document, by the two-letter code (WIPO Standard ST.3). [3] For Japanese patent documents, the indication of the year of the reign of the Emperor must precede the serial number of the patent document. [4] Kind of document by the appropriate symbols as indicated on the document under WIPO Standard ST.16 if possible. [5] Applicant is to place a check mark here if English language translation is attached.

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CERTIFICATION STATEMENT

Please see 37 CFR 1.97 and 1.98 to make the appropriate selection(s):

☐ That each item of information contained in the information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(1).

OR

☐ That no item of information contained in the information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the person signing the certification after making reasonable inquiry, no item of information contained in the information disclosure statement was known to any individual designated in 37 CFR 1.56(c) more than three months prior to the filing of the information disclosure statement. See 37 CFR 1.97(e)(2).

☐ See attached certification statement.

☐ The fee set forth in 37 CFR 1.17 (p) has been submitted herewith.

☒ A certification statement is not submitted herewith.

SIGNATURE

A signature of the applicant or representative is required in accordance with CFR 1.33, 10.18. Please see CFR 1.4(d) for the form of the signature.

Signature	/eleanor musick/	Date (YYYY-MM-DD)	2012-02-06
Name/Print	Eleanor M. Musick	Registration Number	65623

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C. 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether the Freedom of Information Act requires disclosure of these record s.

2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.

3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

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