(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
26 May 2017 (26.05.2017)

(10) International Publication Number
WO 2017/087986 A1

(51) International Patent Classification:
B25J 5/00 (2006.01) *B25J 9/00* (2006.01)
B25J 11/00 (2006.01) *B25J 9/10* (2006.01)

(21) International Application Number:
PCT/US2016/063205

(22) International Filing Date:
21 November 2016 (21.11.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/258,327 20 November 2015 (20.11.2015) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*

(54) Title: NON-ANTHROPOMORPHIC BIPEDAL ROBOTIC SYSTEM

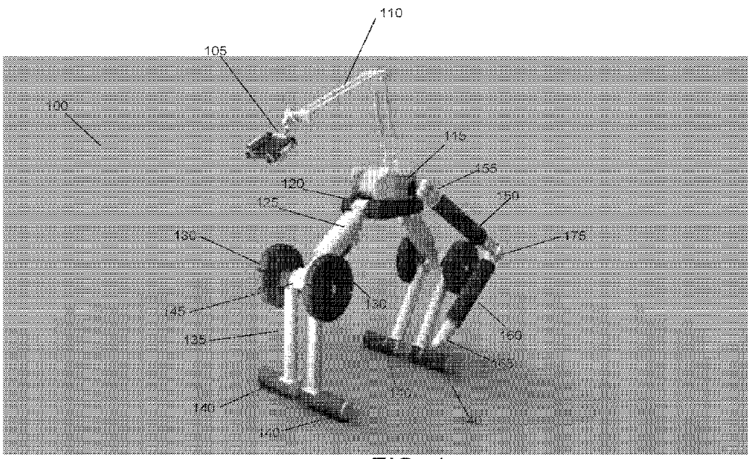

FIG. 1

(57) Abstract: A bipedal robot where the legs are configured such that extraneous movement during bipedal motion is constrained to one plane. In particular, the extraneous movement is constrained to the sagittal plane of the robot. The robot has an upper body and a pair of legs. The upper body has a sagittal plane and a coronal plane where the sagittal plane and the coronal plane are substantially perpendicular. Each of the pair of legs includes an upper portion and a lower portion. Hip joints and connected at opposing ends of the upper body along the sagittal plane and have one degree of freedom around an axis parallel to the coronal plane. One end of the upper portion of each leg connects to a hip joint. A knee joint in each leg has one degree of freedom around an axis parallel to the coronal plane connects to the second end of the upper portion of the leg and to one end of each of the at least one lower portions. A foot then connects to the second end of the at least one lower portions of each leg.

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Non-Anthropomorphic Bipedal Robotic System

CROSS REFERENCED APPLICATIONS

[0001] This Application claims priority to U.S. Provisional Patent Application 62/258,327 entitled "Non-Anthropomorphic Bipedal Robotic System" filed November 20, 2015 that is hereby incorporated by reference as if set forth herewith.

FIELD OF THE INVENTION

[0002] This invention relates to robotics. More particularly, this invention relates to bipedal robots. Still more particularly, this invention relates to providing a bipedal robot that is stable and agile enough to operate in uneven terrain using bipedal locomotion.

BACKGROUND

[0003] Recent advancements in the field of robots have provided unique and elegant solutions to some of the world's most difficult problems. One issue that offers a large scale application for robotic systems is the task of navigating and analyzing inhospitable and/or unstructured environments. Robots can be designed to withstand harsh conditions, including acute temperatures, dangerous chemicals, and nuclear radiation. This makes robots ideal for use in hostile operating environments and/or a variety of disaster relief situations including (but not limited to) operating within nuclear power plants and nuclear waste disposal facilities. Using robots in these sorts of conditions offers a practical and safe way to handle nuclear materials and traverse irradiated areas. The challenges associated with hardening robots to make them robust enough to withstand the harsh conditions of disaster relief situations can be incredibly nuanced. For instance, to be able to conduct any sort of mapping or data collection, a robot must first have the mobility necessary to travel through the facilities. The locomotion problem is one that has been around as long as robots have existed.

[0004] One solution to the locomotion problem is to mimic one of the most successful and mobile natural locomotion and manipulation platforms: the human being using bipedal motion. It is generally agreed that a humanoid form with two legs for walking would be most effective at performing human-like tasks in an environment designed for humans.

[0005] Humanoid robots that use bipedal motion have existed for many years. One example of a humanoid robot using bipedal motion is CHARLI (Cognitive Humanoid Autonomous Robot with Learning Intelligence) and described in Lahr, D.F., Hong, D.W., "The Development of CHARLI: A Linear Actuated Powered Full Size Humanoid Robot", Proceedings URAI 2008, Seoul, Korea, November 2008. Unfortunately, modern robots using the traditional humanoid form can be incredibly complex, expensive, and prone to problems, making them unsuitable for most industrial applications. For example, traditional bipedal robots are a three dimensional control and stability problem. The conventional walking performed by bipedal robots causes displacement of the Center of Mass (CoM) in both the directions parallel and perpendicular to the desired motion of travel. The displacement perpendicular to the direction of travel can be viewed as the CoM leaving a sagittal plane of the robot. This displacement results in many robots incorporating an assortment of expensive sensors with a sophisticated closed loop control algorithm in order to perform simple walking tasks or balancing. Otherwise, the robot is prone to tipping and/or falling over. At the present time, the computing power that is typically present on a robotics platform can struggle to perform the controlled loop algorithm in a manner that allows a robot to perform tasks such as walking in real time.

SUMMARY OF THE INVENTION

[0006] The above and other problems are solved and an advance in the art is made by a non-anthropomorphic bipedal robotic system in accordance with some embodiments of the invention. In accordance with some of the embodiments of the invention, a robot is configured in the following manner.

[0007] An upper body of the robot has a sagittal plane and a coronal plane. The sagittal plane is substantially along a longitudinal axis of the upper body. Furthermore, the sagittal plane and the coronal plane are substantially perpendicular. A first leg and a second leg of the robot include an upper portion and at least one lower portion. A first hip joint connects to a first end of the upper body substantially along the sagittal plane and has one degree of freedom around an axis substantially parallel to the coronal plane and to one end of the upper portion of the first leg. A second hip joint connects to a second end of the upper body distal from the first end substantially along the sagittal plane and having one degree of freedom around an axis substantially parallel to the coronal plane and to one end of the upper portion of the second leg.

[0008] A first knee joint has one degree of freedom around an axis substantially parallel to the coronal plane and is connected to a second end of the upper portion of the first leg and a first end of each of the at least one lower portions of the first leg. A second knee joint having one degree of freedom around an axis substantially parallel to the coronal plane and is connected to a second end of the upper portion of the second leg and a first end of each of the at least one lower portions of the second leg. A set of feet are connected to the lower portions of the legs in that each foot is connected to at least one lower portion of one of the first and second legs. Control circuitry housed in the upper body provides bipedal movement using the first and second legs by activating actuators in the first and second hip joints and first and second knee joints.

[0009] In accordance with some embodiments, a first pair of wheels are affixed to the robot at first end with a first wheel on one side of the sagittal plane and the second wheel on a second side of the sagittal plane. A second pair of wheels is also affixed to the robot at a second end with a first wheel on one side of the sagittal plane and the second wheel on a second side of the sagittal plane. In accordance with some of these embodiments, the control circuitry is configured to move the first and second legs from a first position where the plurality of feet contact the ground for bipedal pedal motion and a second position where the wheels are in contact with the ground and the first and second legs are positions to not impede wheeled movement and to drive the wheels using a motor to cause wheeled locomotion when the first and second legs are in the second position. In accordance with a number of these embodiments the first pair of wheels are connected to the knee joint in the first leg and the second pair of wheels are connected to the knee joint in the second set of legs.

[0010] In accordance with some embodiments, the robot includes at least one arm connected to the upper body. In accordance with some of these embodiments, the at least one arm includes a first arm on one side of sagittal plane substantially along the coronal plane, and a second arm on a second side of the sagittal plane substantially along the coronal plane. In many of these embodiments, the at least one arm is controlled by the control circuitry to assist in bipedal motion. In accordance with a number of embodiments, each at least one arm has four degrees of motion. More particularly, each at least one arm has two degrees of freedom in a should joint, one degree of freedom in an elbow joint, and one degree of freedom in a wrist joint in accordance with some embodiments. Furthermore, each at least one arm includes a gripper at an end of the arm distal the upper body in accordance with many of these embodiments. In accordance with several embodiments, the gripper includes a lockable elastic element. In accordance with some further embodiments, the gripper at the end of each at least one arm is retractable into the arm.

[0011] In accordance with some embodiments, the robot also includes a neck that extends out of a top side of the upper body substantially along the sagittal plane. In many embodiments a sensor array affixed to the neck. In a number of embodiments the sensor array includes at least one sensor selected from the group consisting of a high definition camera and a Lidar. In accordance with some other embodiments the neck is articulated.

[0012] In accordance with some embodiments, the control circuitry controls bipedal movement using an open loop walking algorithm. In accordance with many of these embodiments, the open loop walking algorithm is based upon 3D-LIPM.

[0013] Furthermore, in accordance with a number of embodiments, each foot includes an elastic actuator.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Figure 1 illustrates a bipedal robot in a bipedal locomotion configuration accordance with an embodiment of the invention.

[0015] Figure 2 illustrates a sagittal plane and coronal plane of the bipedal robot shown in Figure 1.

[0016] Figure 3 illustrates a resilient and compliant foot of a bipedal pedal robot in a relaxed and coiled mode in accordance with an embodiment of the invention.

[0017] Figure 4 illustrates the bipedal robot of Figure 1 in a wheeled locomotion configuration in accordance with an embodiment of the invention.

[0018] Figure 5 illustrates a bipedal robot in accordance with an embodiment of the invention travelling across an even terrain.

[0019] Figure 6 illustrates a bipedal robot in accordance with an embodiment of this invention performing a hopping motion.

[0020] Figure 7 illustrates the height (clearance) that a bipedal robot in accordance with an embodiment of this invention can achieve during a hopping motion.

[0021] Figure 8 illustrates a bipedal robot in accordance with an embodiment of the invention travelling across uneven terrain.

[0022] Figure 9 illustrates a bipedal robot in accordance with an embodiment of the invention travelling across uneven terrain.

[0023] Figure 10 illustrates a bipedal robot in accordance with an embodiment of this invention using rotation of a main body to change direction in accordance with an embodiment of this invention.

[0024] Figures 11A and 11B are mechanical drawings illustrating the legs of the bipedal robot shown in FIGS. 5 – 10.

[0025] Figure 12 is a schematic diagram of the electrical system and motors of the bipedal robot shown in FIGS. 5 – 11B.

DETAILED DISCLOSURE OF THE INVENTION

[0026] Turning now to the drawings, a robot that uses bipedal locomotion in accordance with some embodiments of this invention is described. For purposes of this discussion, a robot that uses bipedal locomotion at least some of the time is referred to as a bipedal robot. In accordance with many embodiments of this invention, a highly stable yet mobile bipedal robot that can be used in a variety of environments including (but not limited to) extreme and unstructured environments is provided. In accordance with some embodiments of this invention, the mobility problem of the bipedal robot is solved by creating a platform that can walk on two feet like a human (bipedal locomotion). In accordance with some embodiments of this invention, the bipedal robot performs bipedal locomotion using legs that are rotated ninety degrees from a traditional bipedal robot and/or human. In such a configuration, a first leg or manipulator is pivotally connected to a body of the robot in a first location and a second leg or manipulator is pivotally connected to a body of the robot in a second location aligned along an axis in the direction of forward motion of the robot. Walking in this configuration is comparable to movement of a human or bipedal robot “shuffling” sideways and has greater inherent stability while walking compared to traditional bipedal robots. As is discussed further below, the joints utilized in the legs or manipulators of the robot can be specifically configured for greater range of motion along the axis aligning the legs. In many embodiments, the knee joints pivot around an axis that is perpendicular to the axis of the legs (in contrast to a human shuffling sideways). In several embodiments, the legs do not include ankle joints or include ankle joints that pivot around a single axis (i.e. joints with fewer degrees of freedom than a human ankle). In addition, a bipedal robot in accordance with many embodiments may also have compliant feet.

[0027] In several embodiments, bipedal locomotion of the robot can be augmented by providing wheels so that robot can adopt a pose in which the robot can drive on the wheels like a rover (wheeled locomotion). The wheeled locomotion allows the robot to be stable, fast, and efficient in known, structured environments, while the bipedal locomotion allows the robot to overcome obstacles created from unknown unstructured environments. In accordance with some embodiments, the wheels are situated proximate the knees of the robot. Due to the specialized nature of the legs of the robot, locating wheels at the knees of the robot enables the robot to adopt a pose in which a first set of one or more wheels attached at the knee (or in another location) of a first leg contact the ground in front of the robot and a second set of one or more wheels attached at the knee (or in another location) of a second leg contact the ground behind the robot. In this way, the robot has the ability to switch from a walking mode to a stable driving mode easily.

[0028] In accordance with many embodiments of this invention, the bipedal robot also includes one or more articulated arms (manipulators) and/or an articulated neck. In accordance with some embodiments, the one or more arms of the bipedal robot used for balance and fall prevention by pushing off the ground when the robot detects that it is falling during travel over uneven terrain in accordance with some embodiments. The one or more articulated arms also give the robot a large range of motion to perform non-destructive testing and sample collection in accordance with many embodiments. In accordance with a number of embodiments, sensors used to locomotion in bipedal and/or wheeled locomotion are mounted on and/or to the articulated neck. In accordance with some particular embodiments, the articulated neck has one or more high resolution cameras and/or sensor array mounted atop the neck to allow the robot to use the neck to move the camera(s) and/or sensor array to inspect hard to reach areas of interest.

[0029] In accordance with some embodiments, the bipedal robot is built out of carbon fiber tubes and aluminum brackets, creating a lightweight modular frame. The slender profile of the carbon fiber tubes gives each limb a large range of motion allowing the robot to be foldable and collapsible for storage and deployment purposes in accordance with many embodiments. The same foldable attributes give the bipedal robot the ability to stand up after the robot has fallen down in accordance with many of these embodiments. As can readily be appreciated, any of a variety of materials can be used in the construction of a bipedal robot in accordance with various embodiments of the invention. Bipedal robots of methods of walking using bipedal robotics platforms in accordance with a number of embodiments of the invention are discussed further below.

Bipedal Robot Configuration

[0030] The body of a bipedal robot in accordance with an embodiment of this invention is shown in FIG. 1. A sagittal plane and a coronal plane of the bipedal robot 100 shown in Figure 1 are shown in Figure 2.

Upper Body

[0031] The upper body 115 of bipedal robot 100 houses the majority of the sensing and manipulation equipment for the robot. Upper body 115 includes electronic components, a sensor array, two arms, and a neck. In accordance with some embodiments of the invention, the electronic components include, but are not limited to, a control computer and batteries. In many embodiments, the sensor array includes, but is not limited to, a Lidar sensor, an inertial measurement unit (IMU), a high definition camera, and a radiation sensor. As can readily be appreciated, the specific sensors incorporated within a bipedal robotics platform implemented in accordance with an embodiment of the invention are largely dependent upon the requirements of specific applications.

[0032] The two arm manipulators are mounted on upper body 115 on opposite sides of the sagittal plane 205 along the coronal plane 210 of the bipedal robot 100. Each arm includes an upper arm 155 and a lower arm 160. Each arm has four degrees of freedom in accordance with some embodiments. In accordance with a number of embodiments, the degrees of freedom of the arm include two degrees of freedom at the shoulder 155, one degree of freedom at the elbow 175, and one degree of freedom at the wrist 165. The arms are used for grasping and manipulating objects and tools in accordance with some embodiments. In accordance with a number of embodiments, the arms also assist in the stabilization of the robot while traversing uneven terrain. Furthermore, the ends 165 of each of the arms may have a lockable elastic element built in to allow the gripper to conform to uneven surfaces during manipulation of nondestructive testing equipment in accordance with many embodiments. The gripper at the ends 165 of the arms may be retractable in order to prevent damage while they are being used to assist in bipedal locomotion in accordance with a number of embodiments. As can readily be appreciated, the specific characteristics of manipulators utilized on bipedal robotics platforms in accordance with various embodiments of the invention are largely dependent upon the requirements of a given operating environment.

[0033] The neck 110 is mounted to the upper body 115 on the sagittal plane. The neck 110 has a high definition camera and a Lidar mounted at the end of the neck 110 to allow inspection above obstacles and in tight spaces in accordance with many embodiments.

Legs

[0034] In accordance with some embodiments of the invention, the mechanical design of bipedal robot 100 simplifies the control and stability problem during walking motions to a two dimensional planar problem. The simplification constrains the robot to the sagittal plane thus minimizing any displacement perpendicular to the desired direction of travel. Limiting displacement to the plane of travel can make simple walking and balancing tasks feasible using open loop control.

[0035] In order to achieve the desired simplification in accordance with some embodiments of this invention, the legs of the bipedal robot 110 are rotated ninety degrees about the axis parallel to gravity so that the knees and feet of the robot point outwards. The motion profile of the walking in accordance with these embodiments now more closely resembles that of a crab walking. This eliminates the need to swing one leg in front of the other. The bipedal robot 100 walks by swinging the leading leg to the side and then pulling the trail leg back to the original configuration in accordance with some of these embodiments. This "sidewalking" motion achieves the desired two dimensional constraints with only two degrees of freedom on each leg.

[0036] In the illustrated embodiment, the legs are mounted to upper body 115 on opposing ends of upper body 115 substantially along the sagittal plane 205. Each leg includes an upper portion 125 and two lower portions 135. The upper and lower portions 125 and 135 of the legs are fabricated using carbon fiber tubes and aluminum brackets in accordance with some embodiments of the invention. These materials are chosen to create a simple, lightweight frame. The upper portion 125 of each leg is connected to upper body 115 by hip joint 120 and to the two lower portions 135 by knee joint 145. A pair of Wheels 130 is affixed to each leg at knee joint 125 for use in wheeled locomotion as described in more detail below with respect to FIG. 4. One skilled in the art can appreciate that the wheels 130 may be affixed to other portions of bipedal robot 100 in accordance with some various other embodiments of the invention. In addition, the specific materials utilized in the construction of a bipedal robotics platform in accordance with various embodiments of the invention is typically dependent upon the specific applications for which a given robot is designed.

[0037] The hip joint 120 has one degree of freedom around an axis substantially parallel to the coronal plane. The knee joint 145 has one degree of around a second axis that is substantially parallel to the coronal axis. In order to be able to turn, an additional degree of freedom around an axis substantially perpendicular to the first axis of the hip joint 120 is added to the hip joint 120 in accordance with some embodiments.

[0038] In the shown embodiment, there are no degrees of freedom at the ankles of robot 100. The lack of ankles significantly reduces the weight and moment of inertia of each leg. Without ankles, compliant feet 140 are used to account for uneven terrain. The combination of lightweight materials, low actuator count, and unique leg orientation allows us to create an efficient, agile, and stable system with low complexity. As can readily be appreciated, additional joints and/or joints having additional degrees of freedom can be incorporated into the legs of a bipedal robotics platform implemented in accordance with various embodiments of the invention as appropriate to the requirements of a specific application.

[0039] A bipedal robot that provides bipedal and wheeled locomotion in accordance with an embodiment of this invention is described with reference to FIGS. 1 and 2. However, other configurations of a robot that provides bipedal and/or wheeled locomotion in accordance with some other embodiments of this invention are possible.

Compliant Feet

[0040] Legged robots are traditionally designed to be mechanically rigid with high gain position controlled joints. This means that it is imperative for the planned trajectories of the feet to match the terrain contours with a high degree of precision. Thus, the traditional design of the legs works well in a laboratory setting where the environment is known. However, the traditional design often fails once introduced to real world conditions. A past solution to this problem is a Series of Elastic Actuators (SEA) on the feet that add a compliant element to a traditional position controlled actuator. Adding these elastic actuators to the feet yields better shock resistance and control. However, the elastic actuators also reduce the power of the other actuators and greatly increase the complexity of the leg.

[0041] As such, the bipedal robot 100 in accordance with some embodiments has feet having compliant end effectors rather than compliant actuators at each link for the feet. Adding compliance in using compliant end effectors is far simpler mechanically than using SEAs but still has most if not all of the added benefits. Complaint feet can also conform to various ground geometries, alleviating some of the problems of uneven terrain.

[0042] A compliant foot in accordance with an embodiment of the invention is shown in FIG. 3. The compliant feet shown in FIG. 3 combine two types of elastic elements. The toes 305 of the foot are made out of thin plates. In accordance with some embodiments, the plate of toe 305 is 1074 spring steel that extends out away from the body in a unique orientation. With this structure, the toe 305 bends and provides a restorative force anytime the robot deviates from a desired equilibrium position. The bending also creates potential energy in the toes that can be utilized to generate more efficient walking algorithms. A second elastic component is a foam heel 310.

[0043] The elastic elements in the foot can be implemented using any of a variety of techniques. For example, the second elastic element of the feet can be implemented using a pneumatic heel. In accordance with some embodiments, the pneumatic heel includes an array of inflatable compartments. Each compartment may have an inlet valve, release valve, and pressure sensor in accordance with many embodiments. The unique design of these compartments let the pneumatic heel act like a spring or a damper depending on the states of the valves. When the foot is striking the ground, the release valve is opened to creating a damping effect, absorbing the shock caused by the impulse of the heel strike in accordance with many embodiments. The diameter of the release valve can be controlled in order to change the damping coefficient in accordance with a number of embodiments. Once the foot is in contact with the ground, the release valve can be closed and the inlet valve used to control the pressure in each compartment in some of these embodiments. Changing the pressure in the compartments gives the heel the ability to adapt to uneven or sloped terrain by adjusting the compliance and/or changing the surface area in contact of the foot with the ground.

[0044] Although, a compliant foot for a bipedal robot in accordance with an embodiment of the invention is described above, other embodiments of a compliant foot in accordance with various other embodiments of this invention are possible. Furthermore, bipedal robots in accordance with embodiments of the invention can utilize conventional feet employed in traditional bipedal robotics platforms. The specific choice of foot employed in a given bipedal robotics platform implemented in accordance with an embodiment of the invention is typically dependent upon the requirements of the specific applications for which a given robot is intended.

Wheel Configuration

[0045] Bipedal locomotion is an effective way to cross rough terrain and manmade environments. However, bipedal locomotion can be somewhat less efficient when traversing relatively flat, smooth ground. This suggests an effective mode of travel for a robot, which combines the speed and simplicity of wheeled driving with the utility of bipedal walking. Accordingly, bipedal robots in accordance with several embodiments of the invention incorporate sets of wheels that can be positioned in front and behind the body of the robot during wheeled locomotion.

[0046] Incorporating continuously driven wheels on the bipedal robot in accordance with some embodiments of this invention is a nontrivial task with particular nuances. By placing the wheels 130 at the knee joints 145 in accordance with the shown embodiment of the invention and connecting the wheel by belt or chain to motors proximate the hip joint 120, the inertial impact of the additional mass to the system can be reduced relative to locating the motors in the legs themselves. Having wheels at the knees is feasible for a legged platform such as biped robot 100 because biped robot 100 can invert the lower portions 135 of the legs at the knee joints 145 and slowly lower wheels 130 to the ground until the wheels make contact with the ground to configure robot 100 in a wheeled locomotion configuration. Bipedal robot 100 in a wheel locomotion configuration in accordance with an embodiment of this invention is shown in FIG. 4. The wheels 130 being connected at the knee joint 145 in the shown embodiment is also efficient from a power standpoint because the knee joint actuators no longer need to support the weight of the entire robot during wheeled travel. In accordance with some other embodiments, the wheels may be connected to bipedal robot 100 at the level of hip joints 125. However, this configuration relinquishes the additional degrees of freedom from the hip joints that are available for adjusting to various gradations in the wheels 135 at the knee arrangement.

[0047] Although a wheel configuration for a bipedal robot in accordance with an embodiment of the invention is described above with reference to FIG. 4, other wheel configurations in accordance with some other embodiments of the invention are possible.

Locomotion

[0048] Bipedal locomotion is an interesting problem that is constantly evolving. In more recent times, many algorithms for bipedal walking make use of simple dynamic models such as the 3D-Linear Inverted Pendulum Model (3D-LIPM) to generate stable gaits. This model describes a biped as an inverted pendulum with the center of mass moving above its pivot point at the ankle joint. In accordance with some embodiments, the 3D-LIPM has been implemented to control the bipedal locomotion of biped robot 100 and is effective at creating a stable gait. In several embodiments, the mobile robot uses various gaits including a quasi-static gait and a dynamic gait.

[0049] The quasi-static gait starts with the center of mass of the robot between both of the feet. The robot then shifts the center of mass over top of one of the legs. This shift allows the other leg to have time to lift up and take a step. Now the center of mass can be shifted to the lead leg and the trail leg can now lift up and pull itself back. This process is repeated continuously to take multiple steps.

[0050] The dynamic gait uses algorithms developed by Shuuji Kajita and described in S. Kajita, H. Hirukawa, K. Harada, and K. Yokoi, *Introduction to Humanoid Robotics* (2014). This gait is much more analogous to how humans walk. The initial step is similar to the quasi-static where the center of mass is shifted over top of the trail leg. This once again allows the lead leg to step out. After this the Center of Mass keeps going rather than coming to a stop. The legs keep moving in order to catch the Center of Mass allowing for a more dynamic type of walking.

[0051] Currently, generating bipedal gaits for walking across smooth, flat ground is difficult but manageable thanks to use of the 3D-LIPM in the accordance with the shown embodiment. It is much more challenging to create gaits that can handle rough and unstructured terrain. Many researchers utilize high fidelity feedback control to manage difficult terrain, but this control often sacrifices speed for precision. In contrast to these systems, bipedal robot 100 uses open loop control in accordance with some embodiments to traverse uneven terrain simply due to the “mechanical intelligence” provided by compliance in the feet of bipedal robot 100. The compliance of the also allows for some unique motions to be generated such as jumping up and down or even running in accordance with various embodiments. These sorts of movements can be utilized to bypass areas with large obstructions or loose rubble and debris. To this effect, open loop, vertical jumping has been implemented in a bipedal robot prototype in accordance with an embodiment of the invention. More advanced forms of jumping such as prancing and galloping may be used in some various other embodiments.

[0052] In order to be able to change the heading of the bipedal robot 100, a third degree of freedom can be added to each leg at the hip joint 120 in accordance with some embodiments. The third degree of freedom of hip joint 120 allows the foot to reach any point in 3D space. During walking (bipedal locomotion), a foot can be placed outside the sagittal plane, reorienting the robot in accordance with many of these embodiments. In accordance with a number of embodiments, a single degree of freedom can be incorporated into the waist of the robot. The bipedal robot may then be turned by using the waist and incorporating the arms. In accordance with some of these embodiments, the robot uses the compliant feet to propel the robot into the air. As the bipedal robot is in the air, a motor quickly rotates the waist. The torque generated by the rotating waist creates an impulse on the robot arms and legs, turning them in opposite directions. Once the robot has landed back on the ground, the hip returns to an original position as the friction between the feet and ground dissipates any remaining momentum. Various other methods of turning can be achieved by placing additional degrees of freedom along the robot in accordance with various other embodiments of the invention. In addition, robotics platforms in accordance with many embodiments of the invention can incorporate multiple pairs of legs to enable the robotics platform to select a direction of motion from a static position employing multiple pairs of legs by retracting one or more unused pairs of legs leaving a selected pair of legs aligned along a direction of intended forward motion for walking.

[0053] Although various modes of locomotion are described above with reference to some embodiments of the invention, other modes of locomotion may be achieved in accordance with other various embodiments of the invention.

Preliminary Results of A Prototype Robot in Accordance with an Embodiment of the Invention

[0054] A bipedal robot prototype in accordance with an embodiment of the invention described above with respect to FIGS. 1-4 comprises of a pair of two degree of freedom legs with compliant feet and one waist motor with arms for turning in the method described above. The bipedal robot prototype uses open loop control with zero feedback during locomotion and is still able to execute different types of locomotion. Preliminary test results show that that a bipedal robot in accordance with some embodiments of this invention is capable of conducting stable walking, dynamic walking, turning, and jumping.

[0055] The bipedal robot prototype uses an open loop walking algorithm that is based on 3D-LIPM. Variations of different parameters in the algorithm give different results. A few of the varied parameters includes, but are not limited to, the link lengths, the material feet, and the bipedal robot body design.

[0056] In an embodiment in which the bipedal robot prototype has 16-inch links between each joint, the bipedal robot prototype is able to stably walk at speeds of 0.6 km/h. The movement of the bipedal robot prototype in accordance with an embodiment of the invention having 16-inch links between the joints is shown in FIG. 5. Each captured motion 505-512 shows the bipedal robot prototype moving at the speed of 0.6 km/h that is approximately ⅙ of an average human's walking speed and is a figure well-above most other bipedal robots. With different link lengths, feet design, and feedback, the walking algorithm can be optimized to achieve faster walking with greater stability. Embodiments of the bipedal robot with each of 12-inch and 16-inch link lengths have been tested, and minimal modifications in controls were required to get the different robots to walk. The versatility of the different embodiments of the bipedal robot prototype also shows the robustness of the robot's core design concept of simplifying walking onto a plane to solve instability arising from a three dimensional space.

[0057] In accordance with some embodiments, the compliant feet allow a bipedal robot in accordance with an embodiment of the invention to conduct a series of standing jumps without feedback. The series of standing jumps is unprecedented in bipedal robots, as most jumping algorithms require intense sensor feedback and operator intervention. In the preliminary tests with the bipedal robot prototype in accordance with an embodiment of the invention, the robot's heels reached a maximum height of 6-inches as shown in FIGS 6 and 7. Different link lengths and material in accordance with various other embodiments can increase the jumping height beyond the demonstrated figures. Not only does the series of jumping motions demonstrate the inherent stability of the design behind a bipedal robot in accordance with some embodiments of the invention, but it also shows the potential versatility of such a bipedal robot.

[0058] The bipedal robot prototype has also demonstrated traversal of uneven terrains. Without feedback, the bipedal robot prototype in accordance with an embodiment of this invention could step over a surface that was 2.25-inches above the ground (shown in image 804) and still maintain a stable posture in captured motions 801-803 shown in FIG. 8. An enlarged view of the bipedal robot prototype 100 in accordance with an embodiment of the invention stepping over an obstacle 905 is shown in FIG. 9.

[0059] As the key concept behind a bipedal robot in accordance with some embodiments of this invention is constraining the motion onto a single plane during forward (or backward) motion, the bipedal locomotion may initially seem ineffective in reality. However, the modularity of the prototype's hardware allows simple modifications to turn the robot. In accordance with a number of embodiments, the bipedal robot may be configured such that a rotating arm at the current "upper body" of the bipedal robot, which turns during a jump, creates a moment of inertia that turns the entire robot. Without feedback, a bipedal robot prototype operated in accordance with some of these embodiments is able to rotate about the center of the upper body as shown in images 1001-1010 of FIG. 10.

[0060] Mechanical drawings of the legs of the bipedal robot photographed in FIGS. 5 – 10 are shown in FIGS. 11A and 11B. A schematic diagram of the electrical system and motors of the robotics platform photograph in FIGS. 5 – 10 is shown in FIG. 12. As can readily be appreciated, the motors of the bipedal robot shown in FIGS. 5 – 12 are controlled by signals provided by a computer system 1200 that includes a processor executing robot control software. In the illustrated embodiment, the robot control software implements open source algorithms. As can readily be appreciated, the robot control software can configure the robot to implement any of a variety of algorithms for controlling the joints of the robot including (but not limited to) closed source algorithms.

[0061] These preliminary results from the bipedal robot prototype in accordance with an embodiment of this invention show that robots designed in accordance with some of the various embodiments of the invention as a solution to rough and uneven terrains that only bipedal robots can access. Depending on the environment, there may be some hardware constraints on bipedal robots designed in accordance to some of the embodiments of the invention. Nonetheless, further gait optimization and feedback integration will increase the performance of the robot in accordance with the embodiments. Consequently, the versatility and stability of the design concept is proven through these results, and additional hardware refinements on a case-by-case situation depending on the different environments will mold the robot to perform better in the given setting.

[0062] Although the present invention has been described in certain specific aspects, many additional modifications and variations would be apparent to those skilled in the art. It is therefore to be understood that the present invention can be practiced otherwise than specifically described without departing from the scope and spirit of the present invention. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive. Accordingly, the scope of the invention should be determined not by the embodiments illustrated, but by the appended claims and their equivalents.

WHAT IS CLAIMED IS:

1. A robot comprising:

an upper body having a sagittal plane and a coronal plane where the sagittal plane is substantially along a longitudinal axis of the upper body and the sagittal plane and the coronal plane are substantially perpendicular;

a first leg and a second leg where each of the first and second legs includes an upper portion and at least one lower portion;

a first hip joint connected to a first end of the upper body substantially along the sagittal plane and having one degree of freedom around an axis substantially parallel to the coronal plane and one end of the upper portion of the first leg is connected to the first hip joint;

a second hip joint connected to a second end of the upper body distal from the first end substantially along the sagittal plane and having one degree of freedom around an axis substantially parallel to the coronal plane and one end of the upper portion of the second leg is connected to the second hip joint;

a first knee joint having one degree of freedom around an axis substantially parallel to the coronal plane and is connected to a second end of the upper portion of the first leg and a first end of each of the at least one lower portions of the first leg;

a second knee joint having one degree of freedom around an axis substantially parallel to the coronal plane and is connected to a second end of the upper portion of the second leg and a first end of each of the at least one lower portions of the second leg;

a plurality of feet wherein each foot is connected to at least one lower portion of one of the first and second legs; and

control circuitry housed in the upper body for providing bipedal movement using the first and second legs by activating actuators in the first and second hip joints and first and second knee joints.

2. The robot of claim 1 comprising:

a first pair of wheels affixed to the robot at first end where a first wheel of the pair of wheels is on one side of the sagittal plane and the second wheel of the pair is on a second side of the sagittal plane;

a second pair of wheels affixed to the robot at a second end where a first wheel of the second pair of wheels is on one side of the sagittal plane and the second wheel of the second pair is on a second side of the sagittal plane; and

where the control circuitry is configured to move the first and second legs from a first position where the plurality of feet contact the ground for bipedal pedal motion and a second position where the wheels are in contact with the ground and the first and second legs are positions to not impede wheeled movement and to drive the wheels using a motor to cause wheeled locomotion when the first and second legs are in the second position.

3. The robot of claim 2 wherein the first pair of wheels are connected to the knee joint in the first leg and the second pair of wheels are connected to the knee joint in the second set of legs.

4. The robot of claim 1 further comprising:

at least one arm connected to the upper body.

5. The robot of claim 4 wherein the at least one arm comprises:

a first arm on one side of sagittal plane substantially along the coronal plane; and

a second arm on a second side of the sagittal plane substantially along the coronal plane.

6. The robot of claim 6 wherein the arm are controlled by the control circuitry to assist in bipedal motion.

7. The robot of claim 4 wherein each at least one arm has four degrees of motion.

8. The robot of claim 7 wherein each at least one arm has two degrees of freedom in a should joint, one degree of freedom in an elbow joint, and one degree of freedom in a wrist joint.

9. The robot of claim 4 wherein each at least one arm include a gripper at an end of the arm distal the upper body.

10. The robot of claim 9 wherein the gripper includes a lockable elastic element.

11. The robot of claim 9 wherein the gripper at the end of each at least one arm is retractable into the arm.

12. The robot of claim 1 further comprising a neck that extends out of a top side of the upper body substantially along the sagittal plane.

13. The robot of claim 12 further comprising a sensor array affixed to the neck.

14. The robot of claim 13 wherein the sensor array includes at least one sensor selected from the group consisting of a high definition camera and a Lidar.

15. The robot of claim 12 wherein the neck is articulated.

16. The robot of claim 1 wherein the control circuitry controls bipedal movement using an open loop walking algorithm.

17. The robot of claim 15 wherein the open loop walking algorithm is based upon 3D-LIPM.

18. The robot of claim 1 wherein each foot in the plurality of feet comprises an elastic actuator.

19. A method for providing locomotion in a robot comprising:

configuring the robot in a bipedal mode for bipedal motion when surrounding terrain is uneven wherein the bipedal configuration positions a lead leg and a trailing leg of a robot in a position that rotated substantially 90 degrees from a traditional robot;

shifting the center of gravity of the robot over the trailing leg;

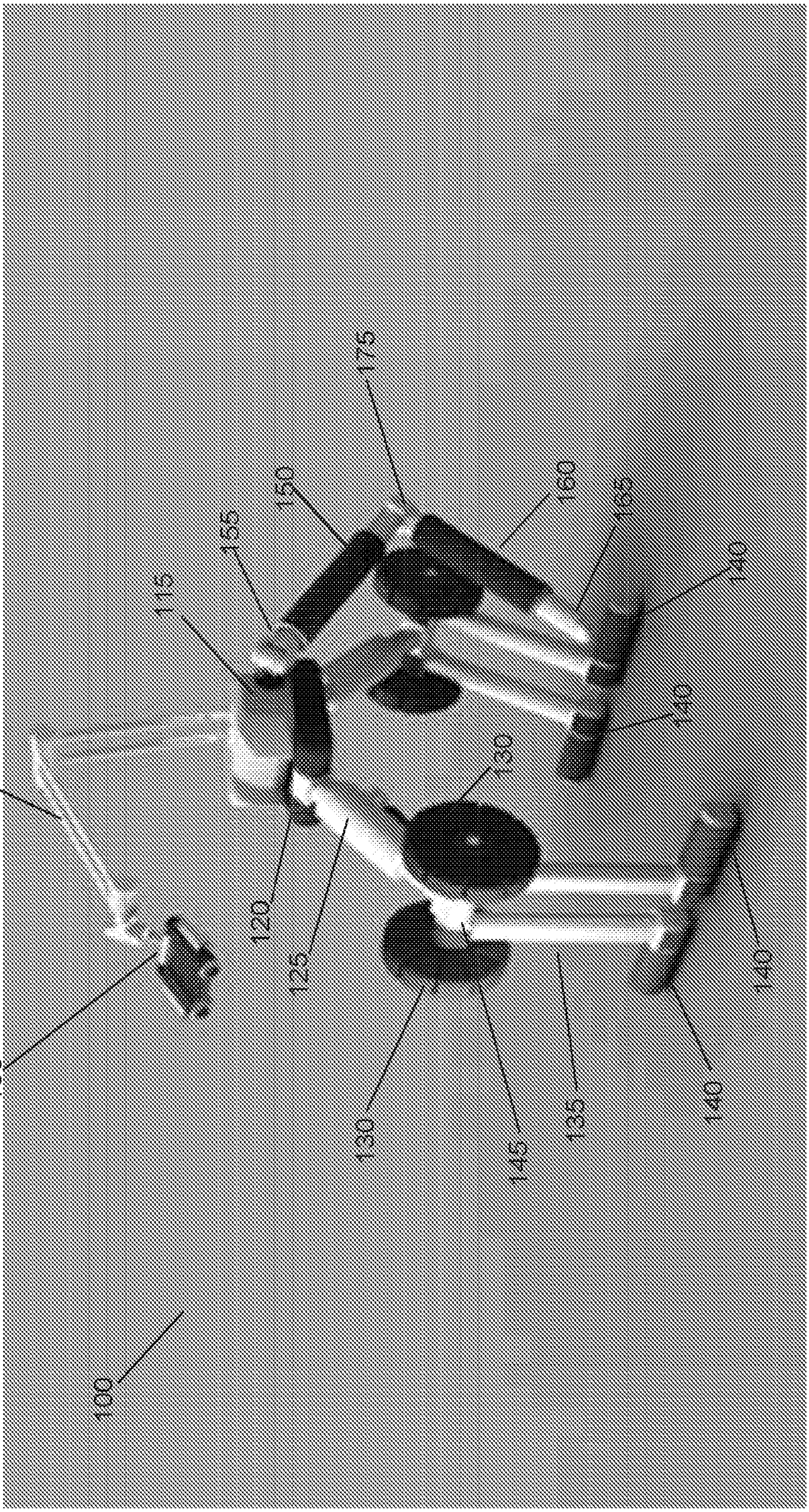
taking a step forward with the lead leg;

shifting the center of gravity of the robot over the lead leg;

moving the trailing leg in the direction of the lead leg;

configuring the robot in a wheeled mode for rolling motion when the terrain is even wherein the wheeled mode places one or more wheels in contact with the ground free from any impediments; and

turning the wheels to cause the robot to travel in a desired direction.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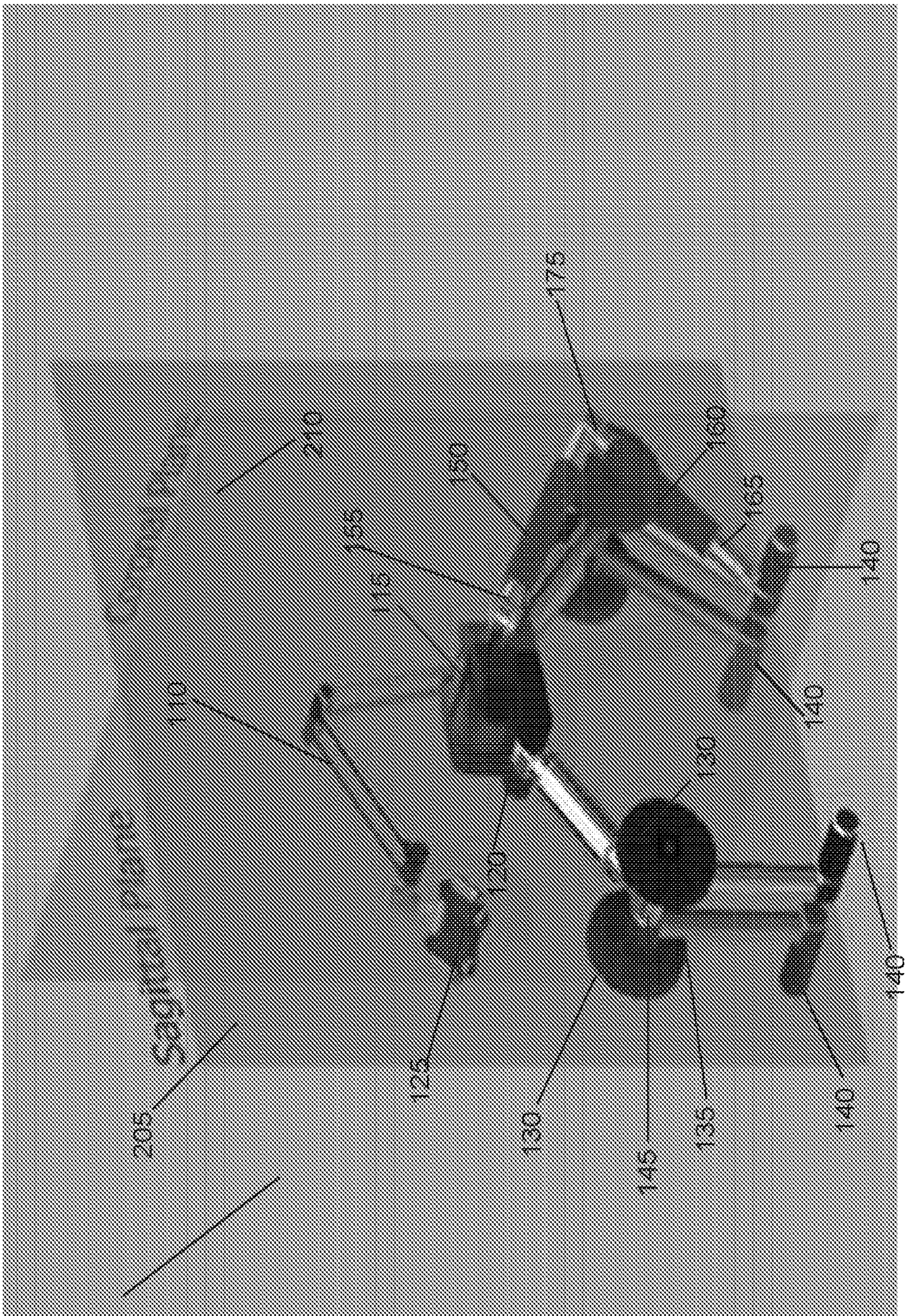
175

FIG. 1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140

FIG. 2

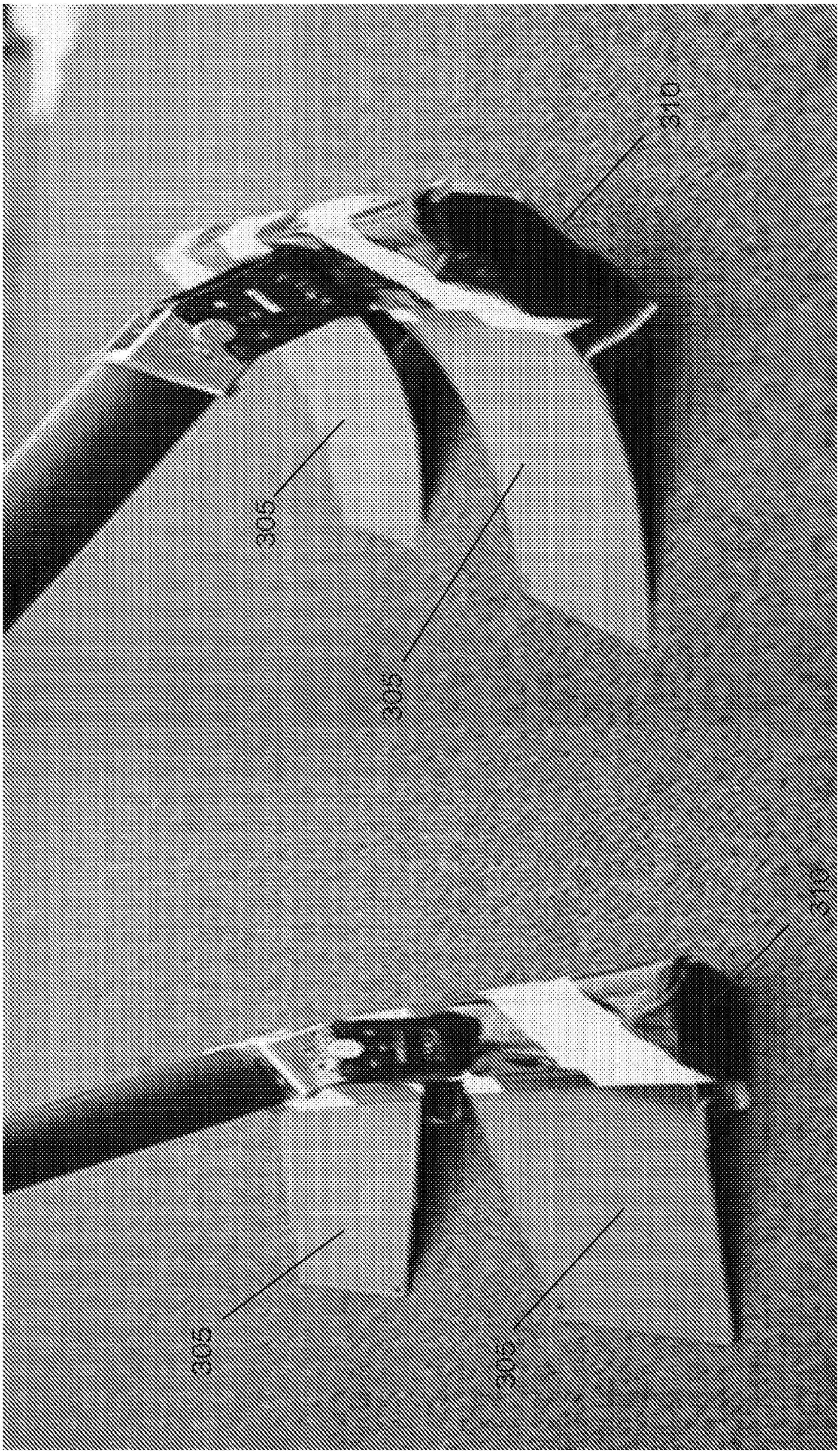


FIG. 3

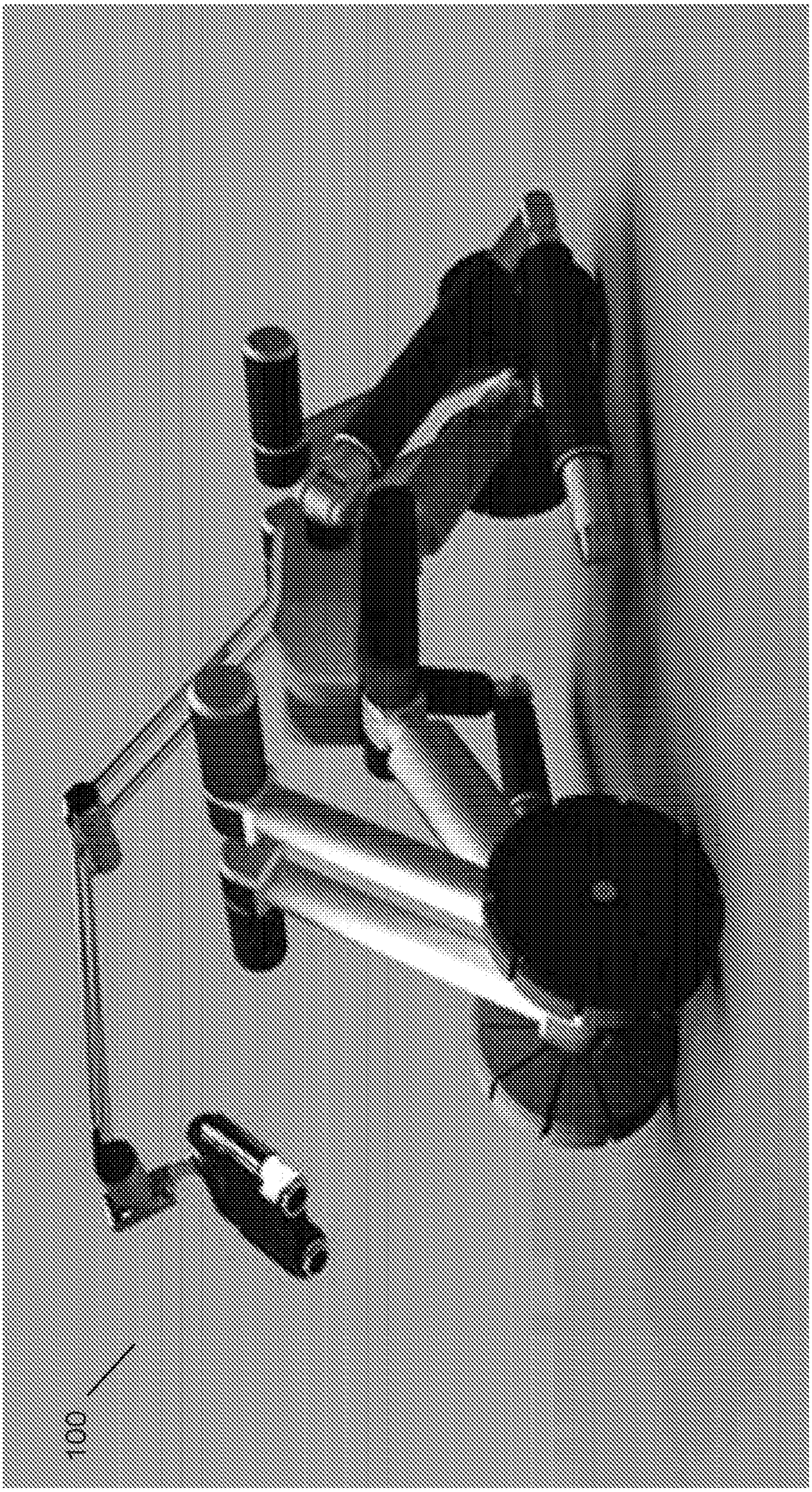
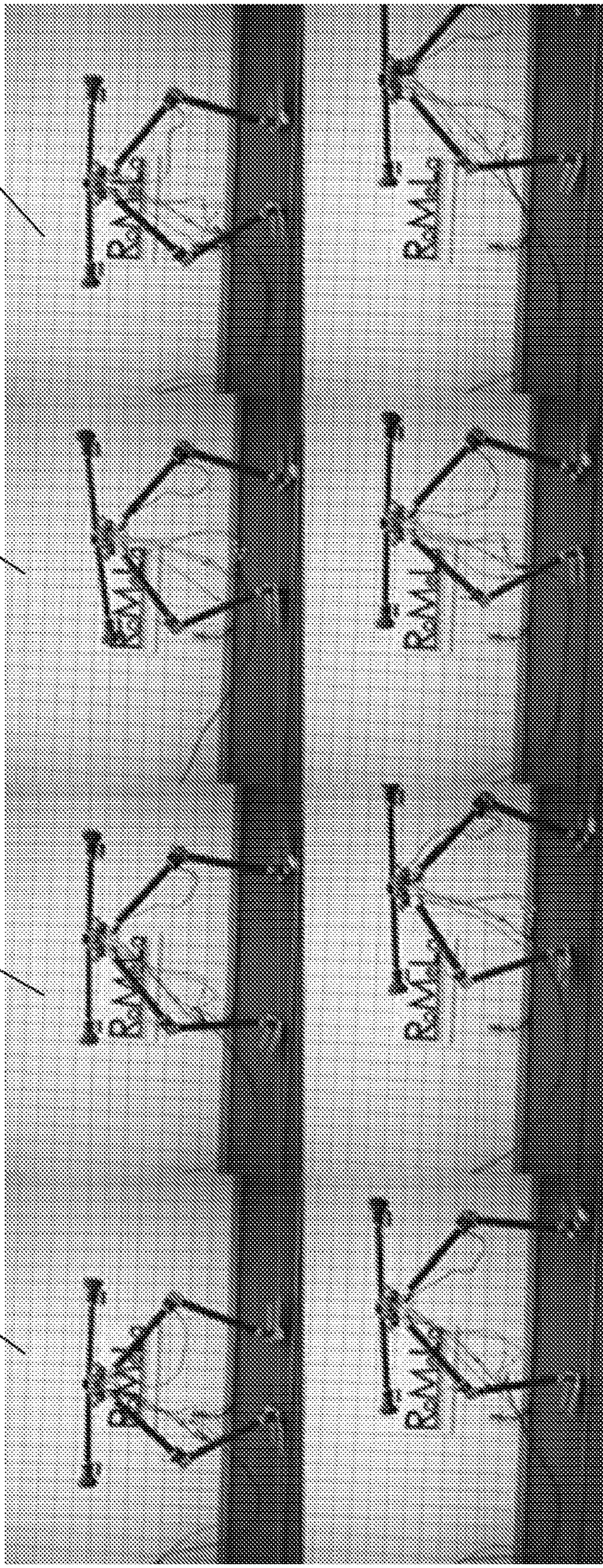


FIG. 4



505 506 507 508 509 510 511 512

FIG. 5

100

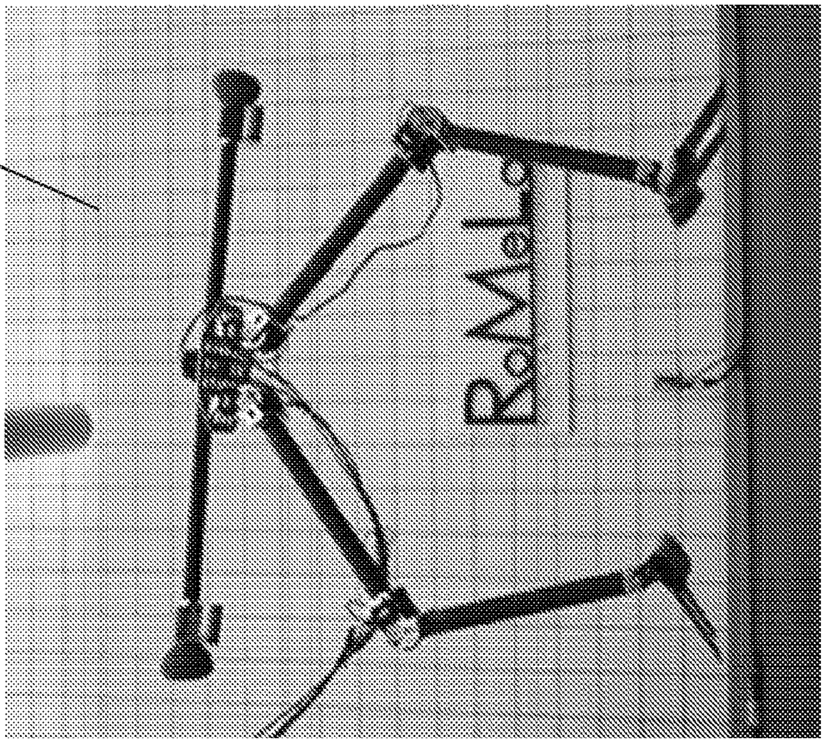


FIG. 6

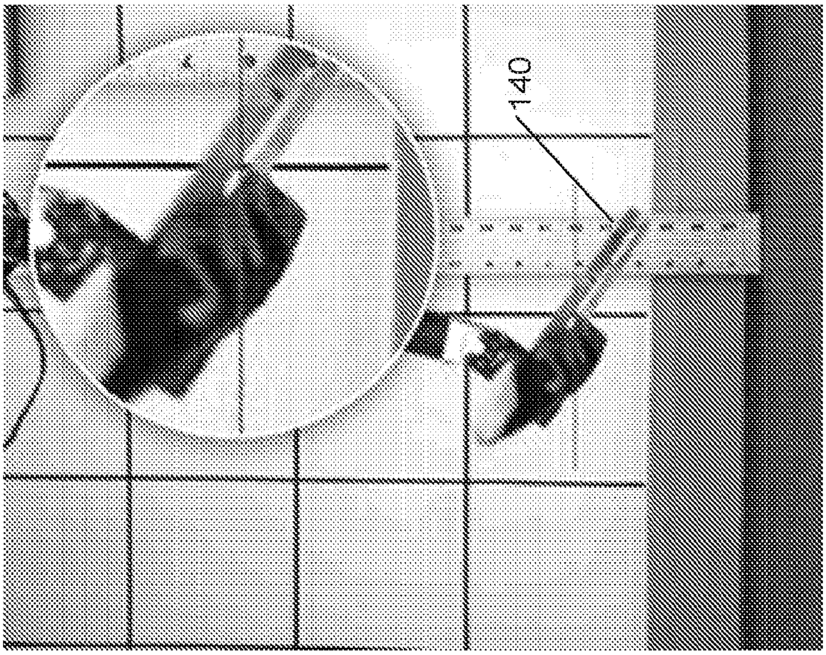


FIG. 7

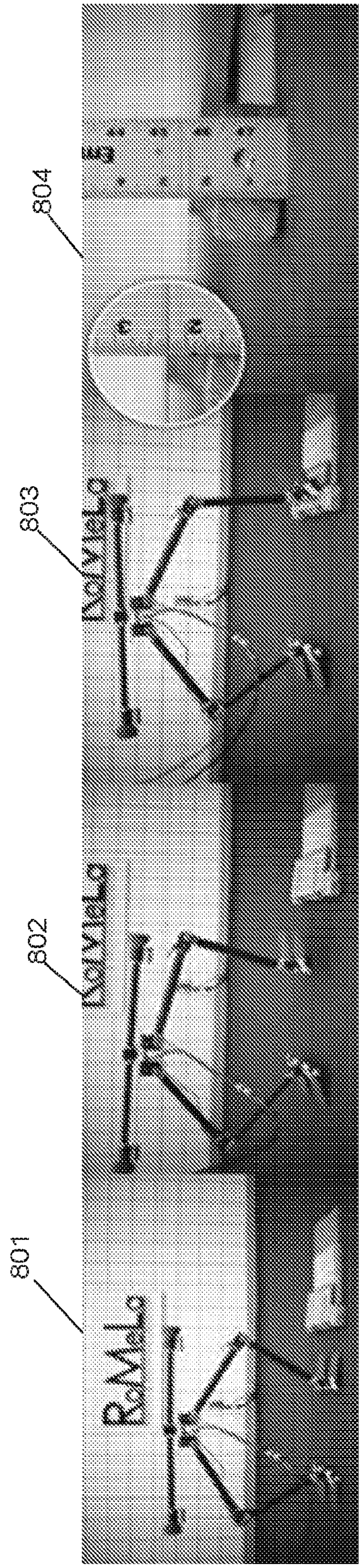


FIG. 8

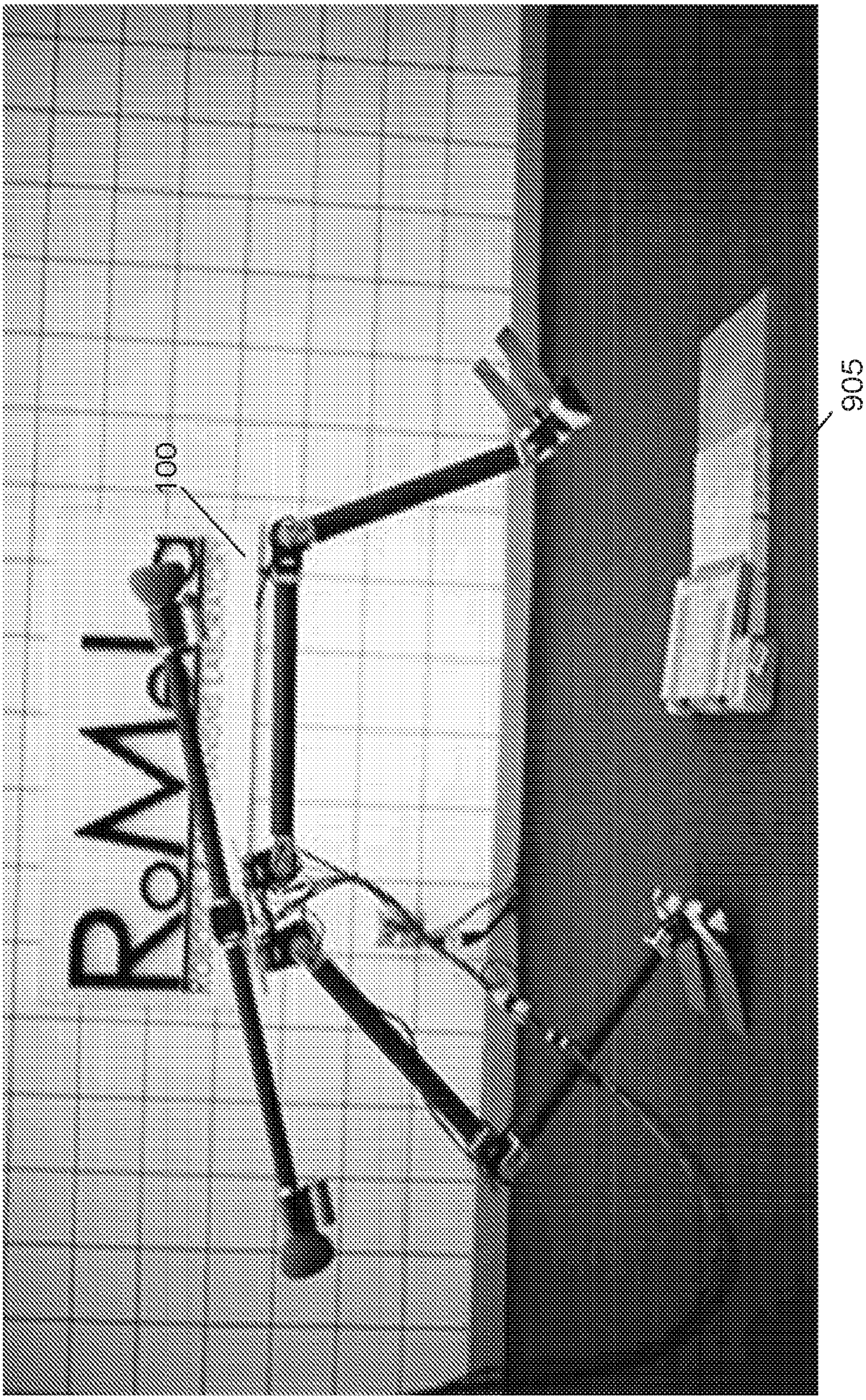


FIG. 9

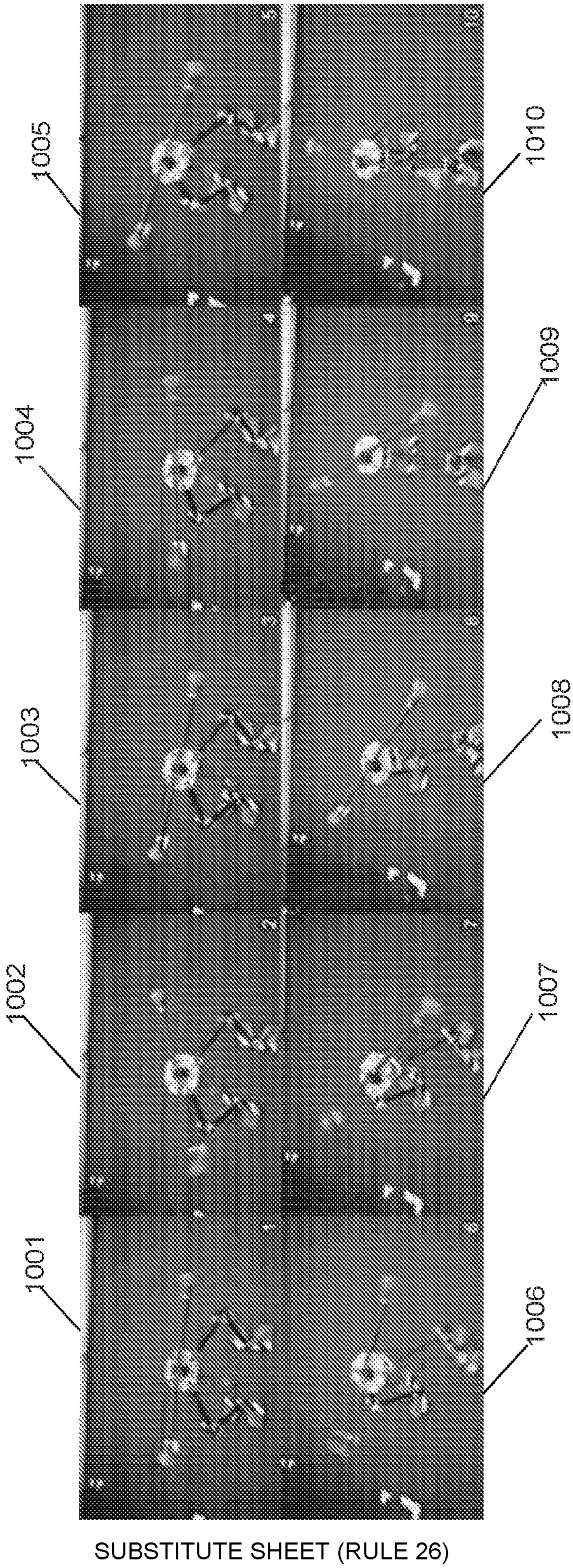


FIG. 10

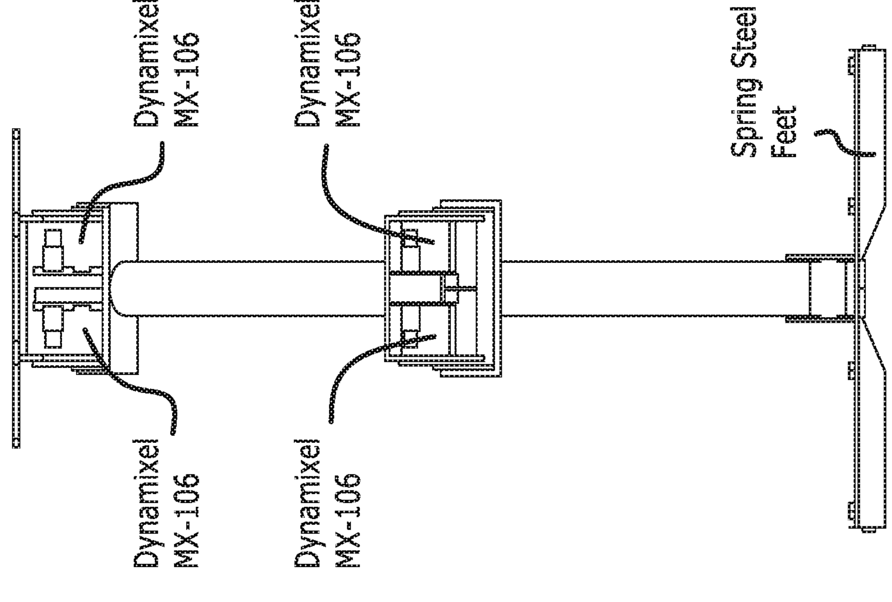


FIG. 11A

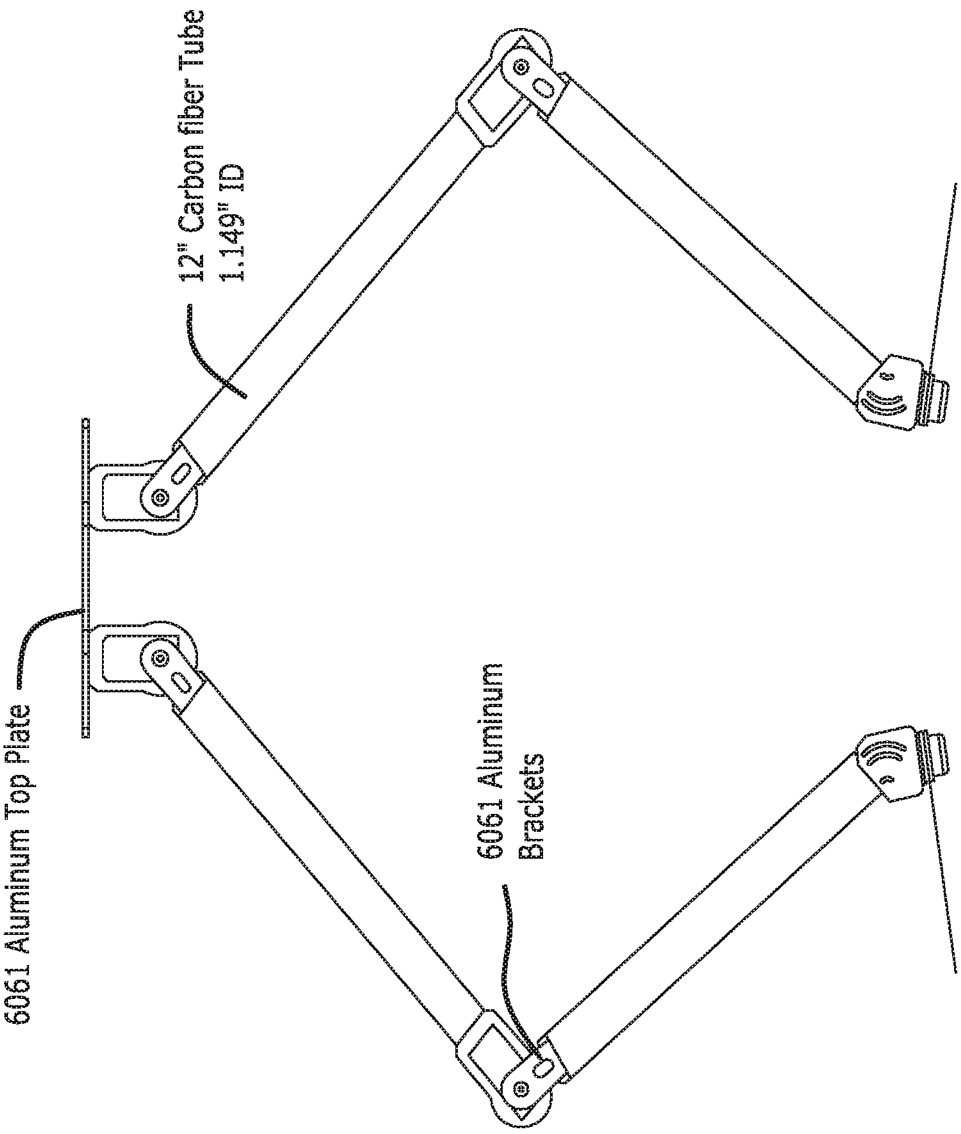


FIG. 11B

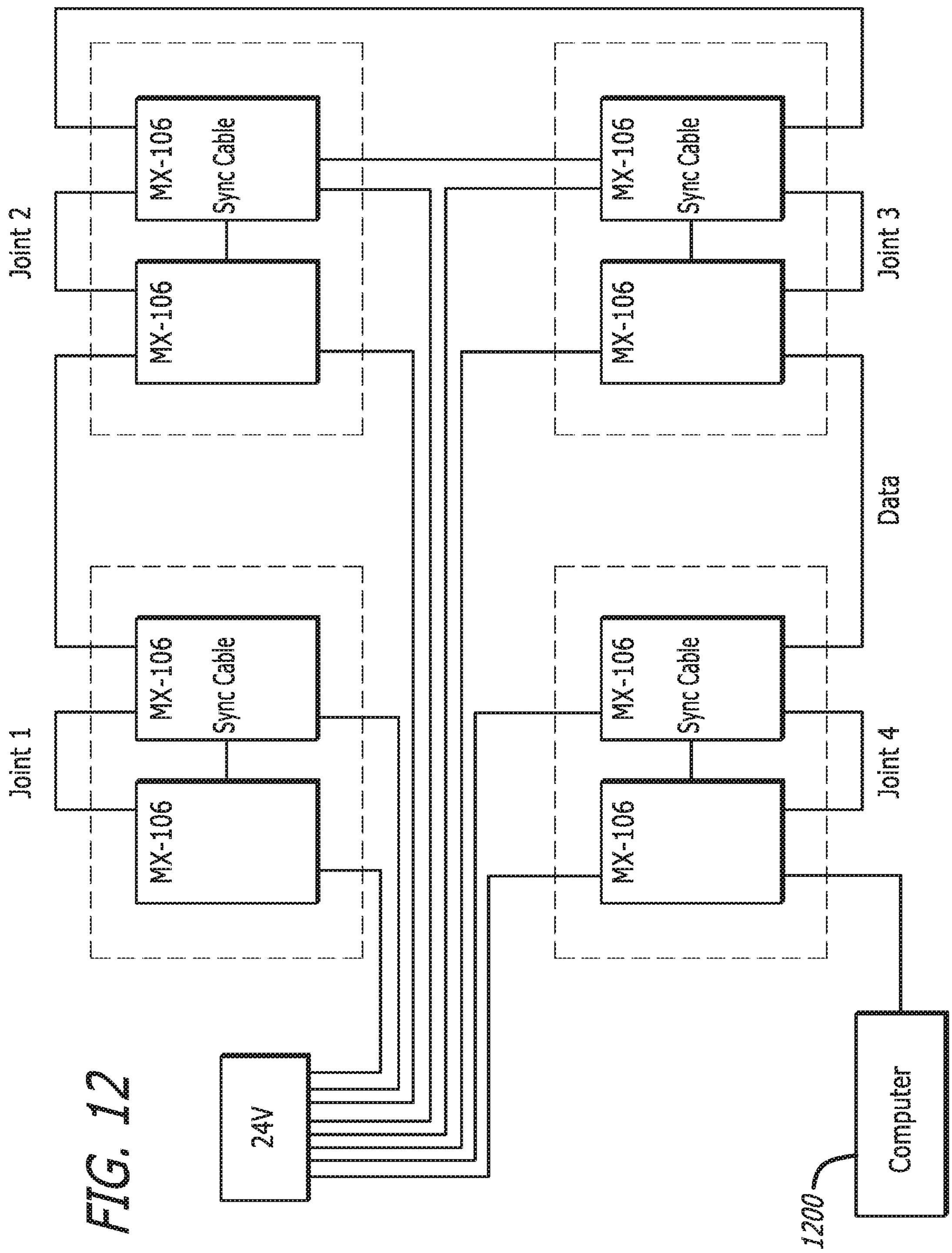

Joint 1
Joint 2
Joint 3
Joint 4
MX-106
Sync Cable
Data
24V
Computer
1200

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/063205

A. CLASSIFICATION OF SUBJECT MATTER

B25J 5/00(2006.01)i, B25J 11/00(2006.01)i, B25J 9/00(2006.01)i, B25J 9/10(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J 5/00; B62D 51/04; B62D 57/028; G06F 19/00; B62D 57/032; F16C 11/00; B25J 11/00; B25J 9/00; B25J 9/10

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: bipedal, anthropomorphic, leg, foot, link, neck, gripper, robot, mobile machine

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A		3,19
Y	US 2008-0135312 A1 (NAKAMURA et al.) 12 June 2008 See paragraphs [0017]-[0033] and figures 1, 2.	1,2,4-18
Y	US 2004-0172164 A1 (HABIBI et al.) 02 September 2004 See paragraph [0016] and figures 1, 2.	4-15
Y	US 2008-0210477 A1 (TAKENAKA et al.) 04 September 2008 See paragraphs [0026]-[0039] and figures 1-3c.	5,6,8
Y	US 2005-0077856 A1 (TAKENAKA et al.) 14 April 2005 See paragraphs [0045]-[0053] and figures 1-3.	18

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 March 2017 (09.03.2017)	**09 March 2017 (09.03.2017)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/063205

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