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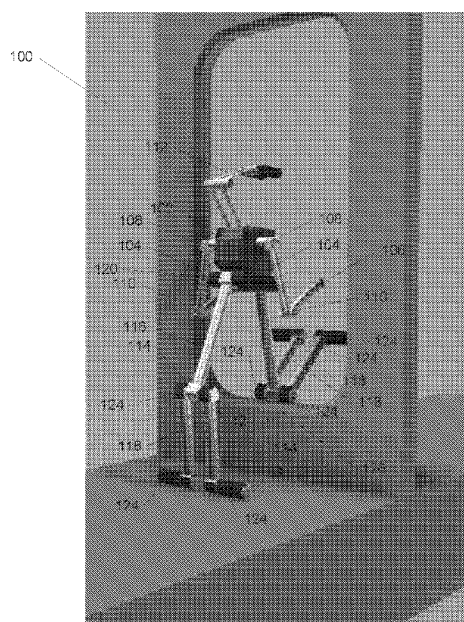


FIG. 1

(57) Abstract: A robotic system where a pair of legs is configured such that a knee joint can rotate continuously 360 degrees around an axis. The upper body connects to a pair of legs each including an upper portion and a lower portion. One end of the lower portion of each leg connects to a hip joint. A knee joint in each leg has one degree of freedom around an axis where the knee joint can rotate 360 degrees around the axis. Control circuitry can be housed in the upper body for providing bipedal movement by activating actuators in hip joints and knee joints.



CONTINUOUS ROBOTIC KNEE JOINT SYSTEM

FIELD OF THE INVENTION

[0001] This invention relates to robotics. More particularly, this invention relates to robotic limb joints.

BACKGROUND

[0002] 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.

[0003] 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.

[0004] 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

[0005] Robotic systems in accordance with embodiments of the invention where a pair of legs is configured such that a knee joint can rotate continuously 360 degrees around an axis. One embodiment includes an upper body; 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 knee joint having one degree of freedom around an axis 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, where the first knee joint can rotate continuously 360 degrees around an axis; a second knee joint having one degree of freedom around an axis 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, where the second knee joint can rotate continuously 360 degrees around an axis; 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.

[0006] In further embodiment, the upper portion of the first leg comprises a single link and at least one lower portion of the first leg comprises split links, wherein the split

links can move on either side of the single link when the first knee joint rotates continuously.

[0007] In another embodiment, the upper portion of the first leg comprises split links and the at least one lower portion of the first leg comprises a single link, wherein the single link can move between the split links when the first knee joint rotates continuously.

[0008] In a still further embodiment, bipedal movement further comprises placing the foot of the first leg onto an object in a first foot position.

[0009] In a yet further embodiment, the control circuitry further provides bipedal movement by activating at least the actuators in the first hip joint.

[0010] In a further embodiment again, the control circuitry further provides bipedal movement by activating at least actuators in the first knee joint.

[0011] In a further additional embodiment, bipedal movement further comprises moving the first knee joint onto the object while keeping the foot of the first leg in substantially the same first foot position on the object.

[0012] In a still yet further additional embodiment, bipedal movement further comprises rotating the at least one lower portion of the first leg away from the first foot position while keeping the first knee joint in substantially the same position.

[0013] In still another embodiment again, bipedal movement further comprises continuing to rotate the at least one lower portion of the first leg away from first foot position until the foot of the first leg makes contact with the object in a second foot position while keeping the first knee joint in substantially the same position.

[0014] Still another further embodiment includes: bipedal movement further comprises lifting the first knee joint off the object into a walking position while keeping the foot of the first leg in substantially the same second foot position.

[0015] In yet another embodiment, the object is a raised object.

[0016] In a further embodiment again, the robot further comprises a first and second set of wheels proximate to the first and second knee joints.

[0017] In another embodiment again, the control circuitry further provides wheeled movement using the first and second legs by activating at least actuators in the first and second set of wheels.

[0018] In a still further embodiment again, wheeled movement further comprises placing the first knee joint and the first set of wheels onto the ground and placing the second knee joint and second set of wheels onto the ground.

[0019] In still another embodiment again, the first knee joint on an object is an additional end-effector.

[0020] In yet another embodiment, the bipedal movement using the first and second legs further comprises placing the first knee joint on an object and rotating the lower portion of the first leg on top of the object.

[0021] In a yet further embodiment, 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; and a second hip joint connected to a second end of the upper body distal from first end substantially along the sagittal plan 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.

[0022] In a further embodiment again, the axis of the first knee joint is substantially parallel to the coronal plane.

[0023] In a further additional embodiment, the axis the first knee joint rotates continuously 360 degrees around is substantially parallel to the coronal plane.

[0024] In a still yet further additional embodiment, the axis of the second knee joint is substantially parallel to the coronal plane.

[0025] In still another embodiment again, the axis the second knee joint rotates continuously 360 degrees around is substantially parallel to the coronal plane.

[0026] Still another further embodiment includes:

[0027] A robot in accordance with an embodiment of the invention comprising:

[0028] A robot comprising: an upper body having a sagittal plane and a coronal plane where 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, where the first knee joint can rotate continuously 360 degrees around an axis substantially parallel to the coronal plane; 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, where the second knee joint can rotate continuously 360 degrees around an axis substantially parallel to the coronal plane; 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.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIG. 1 illustrates a bipedal robot with a continuous knee joint configuration in accordance with an embodiment of the invention.

[0030] FIG. 2 illustrates a bipedal robot prototype with a continuous knee joint configuration in accordance with an embodiment of the invention.

[0031] FIG. 3 illustrates scenes of a bipedal robot utilizing a continuous knee joint to climb over an object in accordance with an embodiment of the invention.

[0032] FIGS. 4A – 4B illustrate scenes of a bipedal robot prototype utilizing a continuous knee joint to climb over an object in accordance with an embodiment of the invention.

[0033] FIG. 5 illustrates scenes of a bipedal robot prototype utilizing a continuous knee joint to climb over a different object in accordance with an embodiment of the invention.

[0034] FIG. 6 is a schematic diagram of the electrical system and actuators of a bipedal robot in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

[0035] Turning now to the drawings, a robotic system that utilizes a continuous limb joint for locomotion in accordance with some embodiments of this invention is described. For purposes of this discussion, a robotic system with a continuous limb joint can rotate that joint a full and continuous 360 degrees. Additionally, a robotic system that uses bipedal locomotion at least some of the time is referred to as a bipedal robot.

[0036] In accordance with many embodiments of this invention, a highly stable yet mobile robot that can be used in a variety of environments including (but not limited to) extreme and unstructured environments is provided. In accordance with various embodiments, a robotic system utilizing one or more continuous limb joints can be particularly adept at (but not limited to) taking large steps, climbing over obstacles, walking on uneven terrain, and/or climbing stairs.

[0037] Limbed locomotion of humans, animals, and most modern day robots have many physical limitations. One of these limitations is the range of motion of their joints. Often times, joint limits directly determine the type of locomotion possible. Due to the non-organic architecture of machines, it is possible to replace traditional joints with continuously rotating ones. Various embodiments of the invention focus on the use of a continuous joint (as opposed to traditional robotic knee joints that mimic human knees), and applying this to new innovative methods for locomotion.

[0038] By removing the joint limit and applying new processes and locomotion gates, the limbs are able to traverse over higher obstacles, easily climb steps, and rapidly move through rough terrain. In accordance with several embodiments of the invention, a continuously rotating knee is incorporated within humanoid robotic systems. In addition to letting the joint rotate a full continuous 360 degrees, a well-designed system allows the joint to act as an additional stability point. In many embodiments of the invention such as a humanoid robotic system, the knee can become an additional end-effector (or foot). This additional balancing point can aid the locomotion by allowing the robotic system to be statically balanced.

[0039] A bipedal robot usually walks by lifting each foot and placing it down quickly. While the robot is taking a step it is only balancing on one point of contact (the other end-effector i.e. the other foot). This makes taking large steps and going over obstacles very difficult. Several embodiments of the invention can allow the bipedal robot to take a step by placing its knee on the ground. Once the knee is in contact with the ground, the robotic system can continue to rotate the link thus bringing the end-effector (foot) off the ground. Once the joint has rotated far enough, the end-effector (foot) can again make contact with the ground on the opposite side of the knee. If the motion is continued, the knee can then be lifted off the ground and walking can resume. In several embodiments, at no point during this step does the robotic system rely on only one point of contact with the ground. This can significantly increase the stability of the robotic system, especially in rough terrain and slanted environments. Additionally, the knee can be at a higher level from the ground than the main foot. This allows the robotic system to place the knee on taller objects such as large steps or other obstacles and rotate the leg around it. Once the rotation is complete, the robotic system will have successfully stepped on or over the obstacle using less energy with minimal sacrifice in stability.

[0040] In various embodiments, the knee is a very rigid joint. In addition, the rotating link is able to do a full 360 degree rotation without colliding with the rest of the robotic system. In several embodiments, the link can be attached with an offset so that it is not on the same plane as the previous link. This allows for rotation without collision, but the lack of symmetry can cause a lot of stress on the joint. Alternatively, many embodiments can utilize a symmetric configuration. The link prior to the knee joint can be a single link, but the link after the knee joint is split. The two split links can go around the single link allowing for a continuous rotation. Additionally, several embodiments are just the opposite. The link prior to the knee is split (as compared to the link after the knee being split) and the link after the knee is a single link. Different configurations of embodiments of the invention have different mechanical advantages and disadvantages.

[0041] In several embodiments, bipedal locomotion of the robot can be augmented by providing wheels so that a 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.

[0042] 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 can be 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 during 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 a 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.

[0043] In accordance with some embodiments, the robotic system 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 of the invention. The same foldable attributes can 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 as appropriate to the requirements of specific applications in accordance with various embodiments of the invention. Bipedal robots and methods of walking using a continuous knee joint in accordance with many embodiments of the invention are discussed further below.

Robot Configuration

[0044] The body of a bipedal robot utilizing a continuous knee joint in accordance with an embodiment of this invention is shown in FIG. 1. Various aspects of the bipedal robot are discussed separately below.

Upper Body

[0045] The upper body 102 of bipedal robot 100 houses the majority of the sensing and manipulation equipment for the robot. In many embodiments, upper body 102 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/or a radiation sensor. As can readily be appreciated, the specific sensors incorporated within a continuous knee joint robotics platform implemented in accordance with an embodiment of the invention are largely dependent upon the requirements of specific applications.

[0046] The two arm manipulators are mounted on upper body 102 on opposite sides of the bipedal robot 100. Each arm includes an upper arm 104 and a lower arm 106. 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 108, one degree of freedom at the elbow 110, and one degree of freedom at the wrist. 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, in various embodiments the ends of each of the arms will 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 of the arms may be retractable in order to prevent damage while they are being used to assist in limbed locomotion in accordance with a number of embodiments of the invention. As can readily be appreciated, the specific characteristics of manipulators utilized on limbed locomotion robotics platforms in accordance with various embodiments of the invention are largely dependent upon the requirements of a given operating environment.

[0047] The neck 112 is mounted to the upper body 102 on the sagittal plane. The neck 112 has a high definition camera and a Lidar mounted at the end of the neck 112 to allow inspection above obstacles and in tight spaces in accordance with many embodiments. It should be readily appreciated that configuration of upper body 102 is merely illustrative and a variety of other upper body elements can be utilized as appropriate to the requirements of specific applications. Furthermore, the combination of arms and/or legs in bipedal robot 100 are merely illustrative and a variety of other combinations can be utilized as appropriate to specific applications including (but not limited to) additional arms, no arms, additional legs, limbs that are used as both arms and legs, a variety of end-effectors attached to a limb, and/or a variety of numbers of joints and/or segments within a limb. Additionally, end-effectors attached to limbs can include (but are not limited to) clamps, forks, vacuums, hands, grippers, jaws, claws, and/or tool tips. In addition, the sensor system

Legs

[0048] In accordance with some embodiments of the invention, the mechanical design of bipedal robot 100 utilizes continuous limb joints to traverse over higher obstacles, easily climb steps, and rapidly move through rough terrain etc. In order to achieve limbed locomotion, the legs of bipedal robot 100 utilize a continuously rotating knee joint 114.

[0049] In the illustrated embodiment, a first leg and a second leg are mounted to upper body 102 on opposing ends of upper body 102. Each leg includes an upper portion 116 and two lower portions 118. In various embodiments, the orientation of

these portions can be reversed with two upper portions and one lower portion as appropriate to specific applications. The upper and lower portions 116 and 118 of the legs can be 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. In addition, the specific materials utilized in the construction of a bipedal robotics platform in accordance with various embodiments of the invention are typically dependent upon the specific applications for which a given robot is designed.

[0050] In many embodiments, the upper portion 116 of each leg is connected to upper body 102 by hip joint 120 and to the two lower portions 118 by continuous knee joint 114. A pair of wheels 122 can be affixed to each leg at knee joint 114 for use in wheeled locomotion. One skilled in the art can appreciate that the wheels 122 may be affixed to other portions of bipedal robot 100 in accordance with some various other embodiments of the invention. By manipulating knee joints such that wheels touch the ground, a bipedal robot in accordance with various embodiments can easily change from a walking mode to a driving mode. In several embodiments, a bipedal robot can use wheels on the first leg to move across raised obstacles before performing continuous joint rotation. This can for example (but is not limited to) provide the bipedal robot with superior foot placement after continuous joint rotation by slightly moving the leg along the obstacle, and in several embodiments this foot placement can be calculated using sensing equipment in the upper body of the bipedal robot. In several additional embodiments, foot placement can additionally be controlled by motorized wheels which can make small adjustments in the leg position before continuous joint rotation. In further embodiments of the invention, a breaking mechanism can be utilized to prevent continuous joint rotation while wheels are in motion and/or to hold the bipedal robot wheels stationary during continuous joint rotation.

[0051] The hip joint 120 has one degree of freedom around an axis substantially parallel to the coronal plane. The knee joint 114 has one degree of freedom 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. It should readily be appreciated that hip joint 120 is merely illustrative and a variety of other hip joints can be utilized as appropriate to specific robotic applications including (but not limited to) hip joints with additional degrees of freedom and/or hip joints with a degree of freedom around an axis substantially parallel to alternative and/or additional planes.

[0052] 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, feet 124 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.

[0053] In many embodiments, a robotic system can step over a raised obstacle such as raised door threshold 126. Knee joint 114 is positioned on top of the raised door threshold. It should readily be appreciated that the raised door threshold is only an illustrative example, and bipedal robot 100 can position knee joint 114 on other various obstacles including (but not limited to) stairs, rough terrain, sloped floors, and other obstacles.

[0054] Although a variety of bipedal robots are described above with reference to FIG. 1, any of a variety of robot systems that provide locomotion through continuous joint rotation as appropriate to the requirements of specific applications in accordance with embodiments of the invention. A prototype robot in accordance with an embodiment of the invention is discussed below.

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

[0055] A bipedal robot prototype in accordance with an embodiment of the invention includes of a pair of two degree of freedom legs with feet and one waist motor with arms for turning in the method described above.

[0056] 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, and climbing over various obstacles.

[0057] The bipedal robot prototype uses an open loop walking algorithm that is based on the 3D Linear Inverted Pendulum Mode (3D-LIPM), described in Shuuji Kajita et al., *The 3D Linear Inverted Pendulum Mode: A simple modeling for a biped walking pattern generation*, Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems, 29 Oct – 03 Nov 2001, which is hereby incorporated by reference in its entirety. 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, and the bipedal robot body design.

[0058] A bipedal robot prototype in accordance with an embodiment of the invention is illustrated in FIG. 2. The bipedal robot 200 can climb over a stationary object 202 when continuous knee joint 114 comes into contact with top 204 of stationary object 202. Bipedal robot prototype 200 can utilize many components described above with respect to FIG. 1 including (but not limited to) upper body 102, upper leg portion 116, lower leg portions 118, and feet 124.

[0059] In various embodiments, bipedal robot 200 can be divided by a sagittal plane, which can run substantially parallel to a plane formed by the intersection of lines x 206 and y 208. Additionally, bipedal robot 200 can be divided by a coronal plane, which can run substantially parallel to a plane formed by the intersection of lines y 208 and z 210.

[0060] Scenes of robotic systems in accordance with many embodiments of the invention utilizing continuous knee joints to climb over objects are illustrated in FIGS. 3 – 5. Bipedal robot 100 can be seen approaching a raised door threshold in scene 302. The knee joint of a first leg makes contact with the top of the door threshold in scene 304. Lower leg segments of the first leg swing approximately 360 degrees up and over the door threshold in scenes 306 – 314. Once the foot of the first leg has made contact on the ground, the knee joint of the first leg can push off the door threshold as illustrated in scene 316. The second leg can then move into position next to the raised door

threshold in preparation to perform a similar 360 degree knee joint rotation movement as illustrated in scene 318.

[0061] A similar sequence of bipedal robot prototype 200 utilizing a continuous knee to step over an obstacle is shown in scenes 402 – 424 of FIGS. 4A – 4B and scenes 502 – 518 of FIG. 5. A schematic diagram of the electrical system and motors of the robotics platform is shown in FIG. 6. As can readily be appreciated, the motors of the bipedal robot are controlled by signals provided by a computer system that includes a processor executing robot control software.

Control Circuitry of Bipedal Robots

[0062] Control circuitry including an electrical system and actuators of a bipedal robot system in accordance with an embodiment of the invention is shown in FIG. 6. In various embodiments, the legs of a bipedal robot are controlled by one or more joints. In several embodiments, a first leg can contain joint 1 (602) and joint 2 (604). Similarly, a second leg can contain joint 3 (606) and joint 4 (608). It should be readily apparent to one having ordinary skill that this distribution of joints is merely illustrative, and each leg can have a variety of combinations of joints (including but not limited to asymmetrically distributed numbers of joints in each leg), and/or joints can be used with other portions of the bipedal robot including (but not limited to) a head, an upper body, one or more arms, and/or additional legs.

[0063] Joint 1, joint 2, joint 3, and joint 4 can contain one or more actuators 610. In many embodiments, actuators can include (but are not limited to) electrical, hydraulic and/or pneumatic actuators. Electrical actuators can further include (but are not limited to) a variety of electric motors such as DC motors, AC motors, servomotors, and/or stepper motors. It should be readily apparent that these example actuators are merely illustrative and any of a variety of actuators can be utilized as appropriate to control joint movement in a bipedal robot in accordance with many embodiments of the invention.

[0064] A computing system 612 can be utilized to control components of the bipedal robot including (but not limited to) legs, joints, and/or actuators. In several embodiments, a control signal can be transmitted from the computing system to one or more joints through link 614. It should be readily apparent to one having ordinary skill

that a variety of joints can be connected to a computing system in a variety of configurations as appropriate to specific applications.

[0065] A power supply 616 can provide a source of energy to the actuators. Power supplies can include (but are not limited to) a local battery, a tethered power source such as power from an electrical outlet, as well as alternating current and/or direct current. Although many different systems are described above with reference to FIG. 6, any of a variety of control circuitry may be utilized to control bipedal robots as appropriate to the requirements of specific applications in accordance with various embodiments of the invention.

[0066] 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. Depending on the environment, there may be some hardware constraints on robotic systems designed in accordance to some of the embodiments of the invention. Nonetheless, further knee joint 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.

[0067] 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;
 - 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 knee joint having one degree of freedom around an axis 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, where the first knee joint can rotate continuously 360 degrees around an axis;
 - a second knee joint having one degree of freedom around an axis 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, where the second knee joint can rotate continuously 360 degrees around an axis;
 - 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, wherein the upper portion of the first leg comprises a single link and at least one lower portion of the first leg comprises split links, wherein the split links can move on either side of the single link when the first knee joint rotates continuously.
3. The robot of claim 1, wherein the upper portion of the first leg comprises split links and the at least one lower portion of the first leg comprises a single link, wherein the single link can move between the split links when the first knee joint rotates continuously.

4. The robot of claim 1, wherein the plurality of feet are fixed.
5. The robot of claim 1, wherein bipedal movement further comprises placing the foot of the first leg onto an object in a first foot position.
6. The robot of claim 5, wherein the control circuitry further provides bipedal movement by activating at least the actuators in the first hip joint.
7. The robot of claim 5, wherein the control circuitry further provides bipedal movement by activating at least actuators in the first knee joint.
8. The robot of claim 5, wherein bipedal movement further comprises moving the first knee joint onto the object while keeping the foot of the first leg in substantially the same first foot position on the object.
9. The robot of claim 8, wherein the control circuitry further provides bipedal movement by activating at least the actuator in the first hip joint.
10. The robot of claim 8, wherein bipedal movement further comprises rotating the at least one lower portion of the first leg away from the first foot position while keeping the first knee joint in substantially the same position.
11. The robot of claim 10, wherein the control circuitry further provides bipedal movement by activating at least the actuator in the first knee joint.
12. The robot of claim 10, wherein bipedal movement further comprises continuing to rotate the at least one lower portion of the first leg away from first foot position until the foot of the first leg makes contact with the object in a second foot position while keeping the first knee joint in substantially the same position.

13. The robot of claim 12, wherein the control circuitry further provides bipedal movement by activating at least the actuator in the first knee joint.
14. The robot of claim 12, wherein bipedal movement further comprises: lifting the first knee joint off the object into a walking position while keeping the foot of the first leg in substantially the same second foot position.
15. The robot of claim 14, wherein the control circuitry further provides bipedal movement by activating at least the actuator in the first hip joint.
16. The robot of claim 14, wherein the object is a raised object.
17. The robot of claim 1, wherein the robot further comprises a first and second set of wheels proximate to the first and second knee joints.
18. The robot of claim 17, wherein the control circuitry further provides wheeled movement using the first and second legs by activating at least actuators in the first and second set of wheels.
19. The robot of claim 18, wherein wheeled movement further comprises placing the first knee joint and the first set of wheels onto the ground and placing the second knee joint and second set of wheels onto the ground.
20. The robot of claim 1, wherein the first knee joint on an object is an additional end-effector.
21. The robot of claim 1, wherein the bipedal movement using the first and second legs further comprises placing the first knee joint on an object and rotating the lower portion of the first leg on top of the object.

22. The robot of claim 1, wherein the upper body further comprises a sagittal plane and a coronal plane, wherein the sagittal plane and the coronal plane are substantially perpendicular.

23. The robot of claim 2, further comprising:

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;

and a second hip joint connected to a second end of the upper body distal from 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.

24. The robot of claim 2, wherein the axis of the first knee joint is substantially parallel to the coronal plane.

25. The robot of claim 2, wherein the axis the first knee joint rotates continuously 360 degrees around is substantially parallel to the coronal plane.

26. The robot of claim 2, wherein the axis of the second knee joint is substantially parallel to the coronal plane.

27. The robot of claim 2, wherein the axis the second knee joint rotates continuously 360 degrees around is substantially parallel to the coronal plane.

28. A robot comprising:

an upper body having a sagittal plane and a coronal plane where 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, where the first knee joint can rotate continuously 360 degrees around an axis substantially parallel to the coronal plane;

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, where the second knee joint can rotate continuously 360 degrees around an axis substantially parallel to the coronal plane;

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.

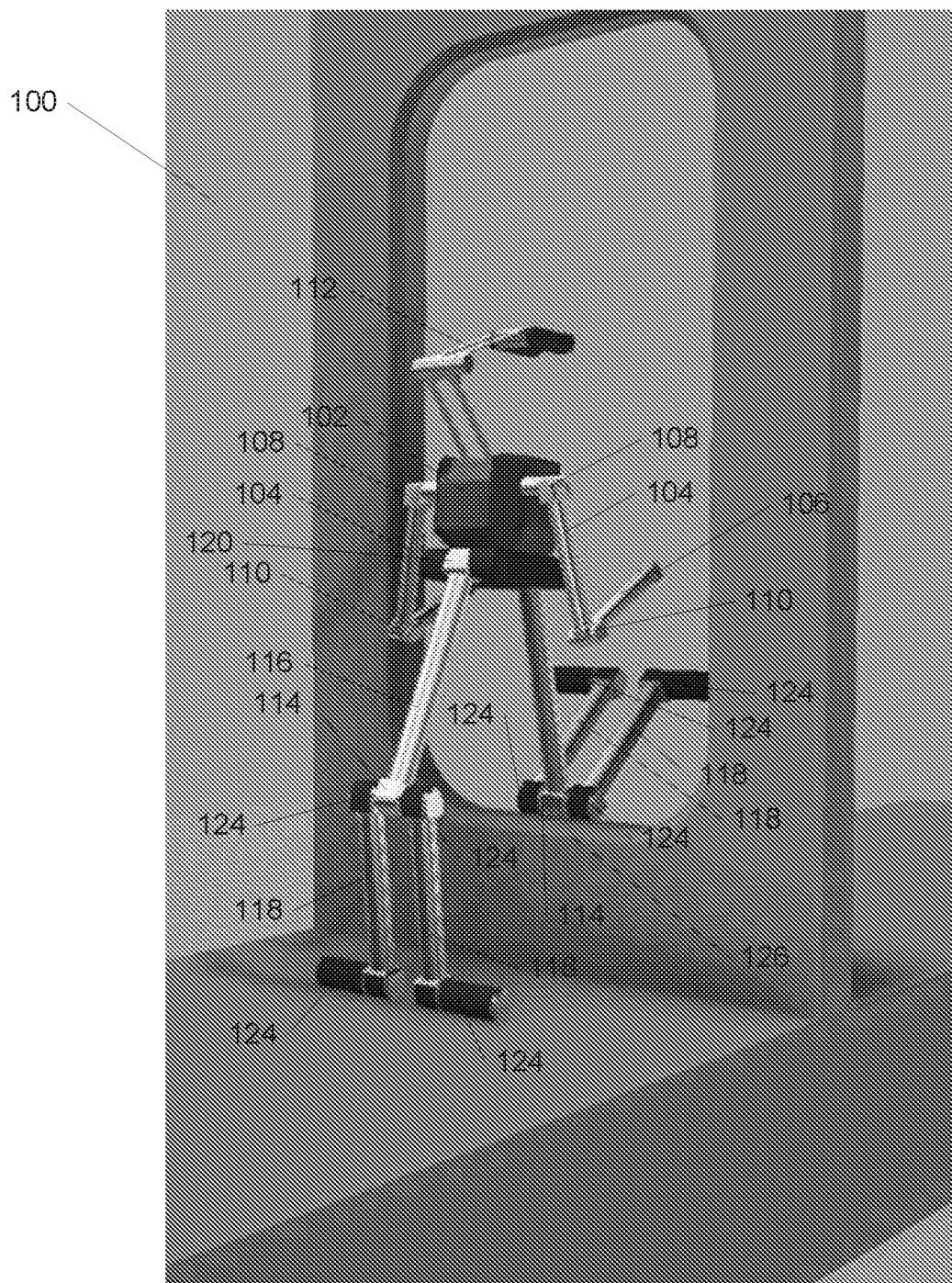


FIG. 1

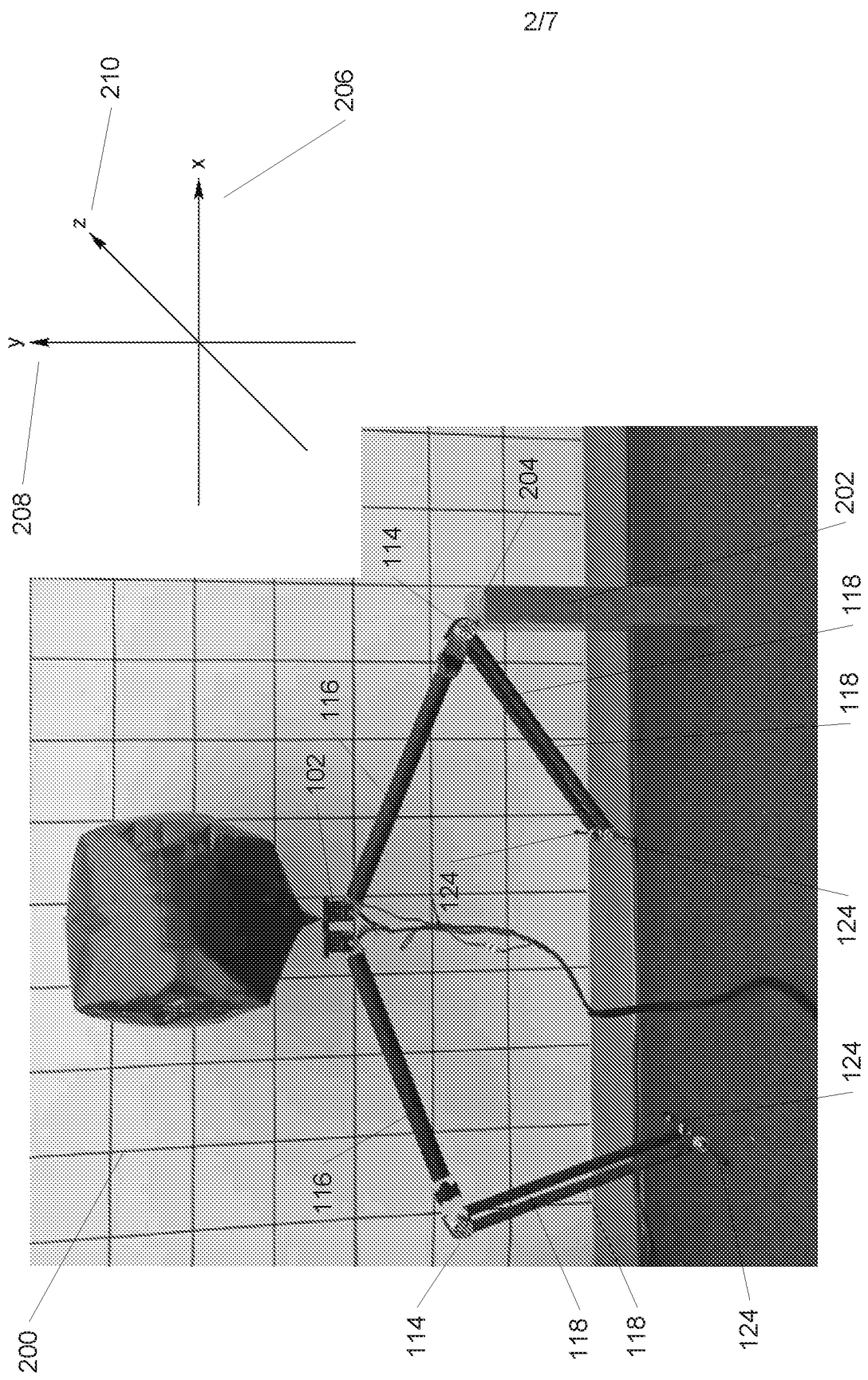


FIG. 2

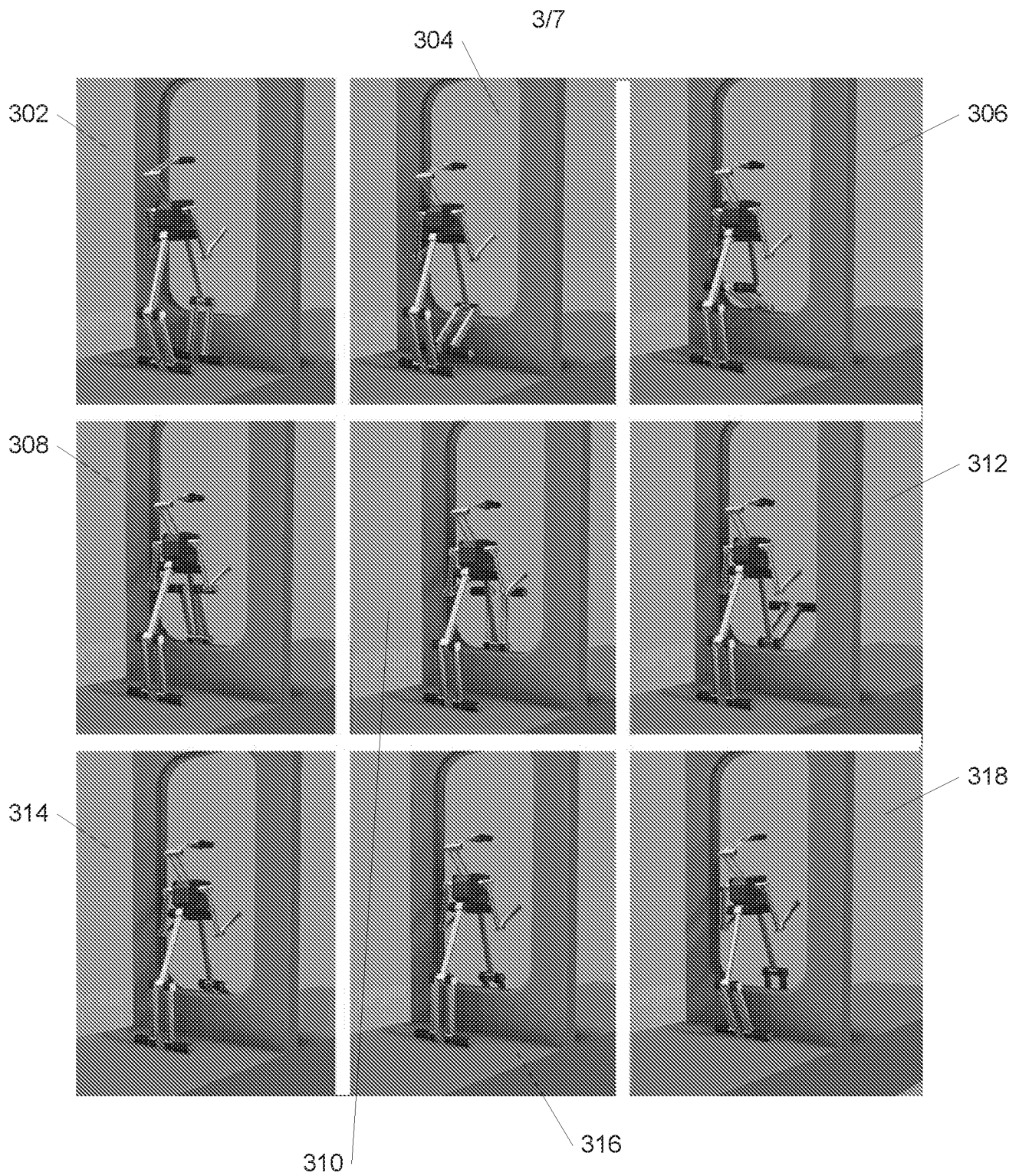


FIG. 3

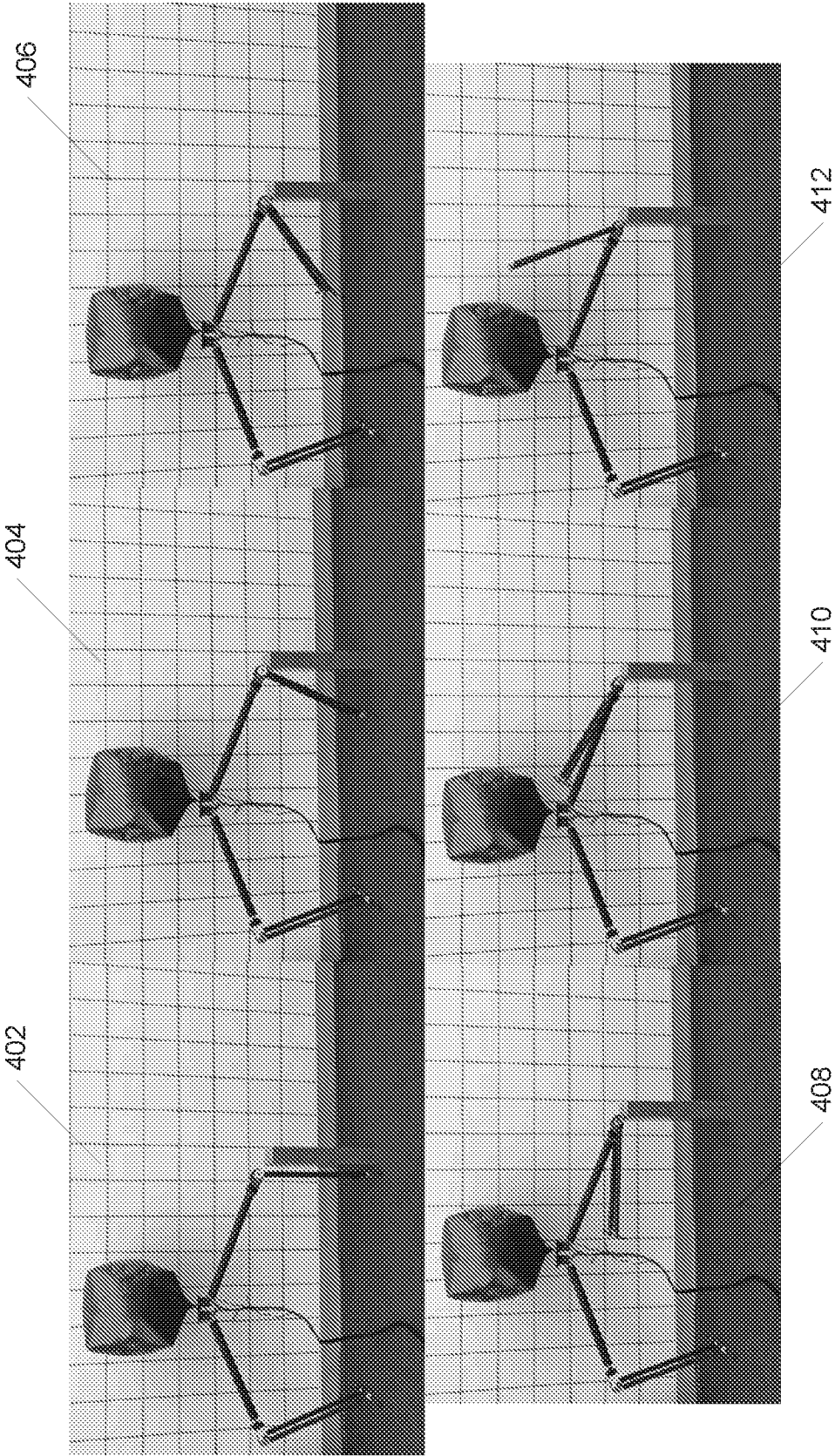


FIG. 4A

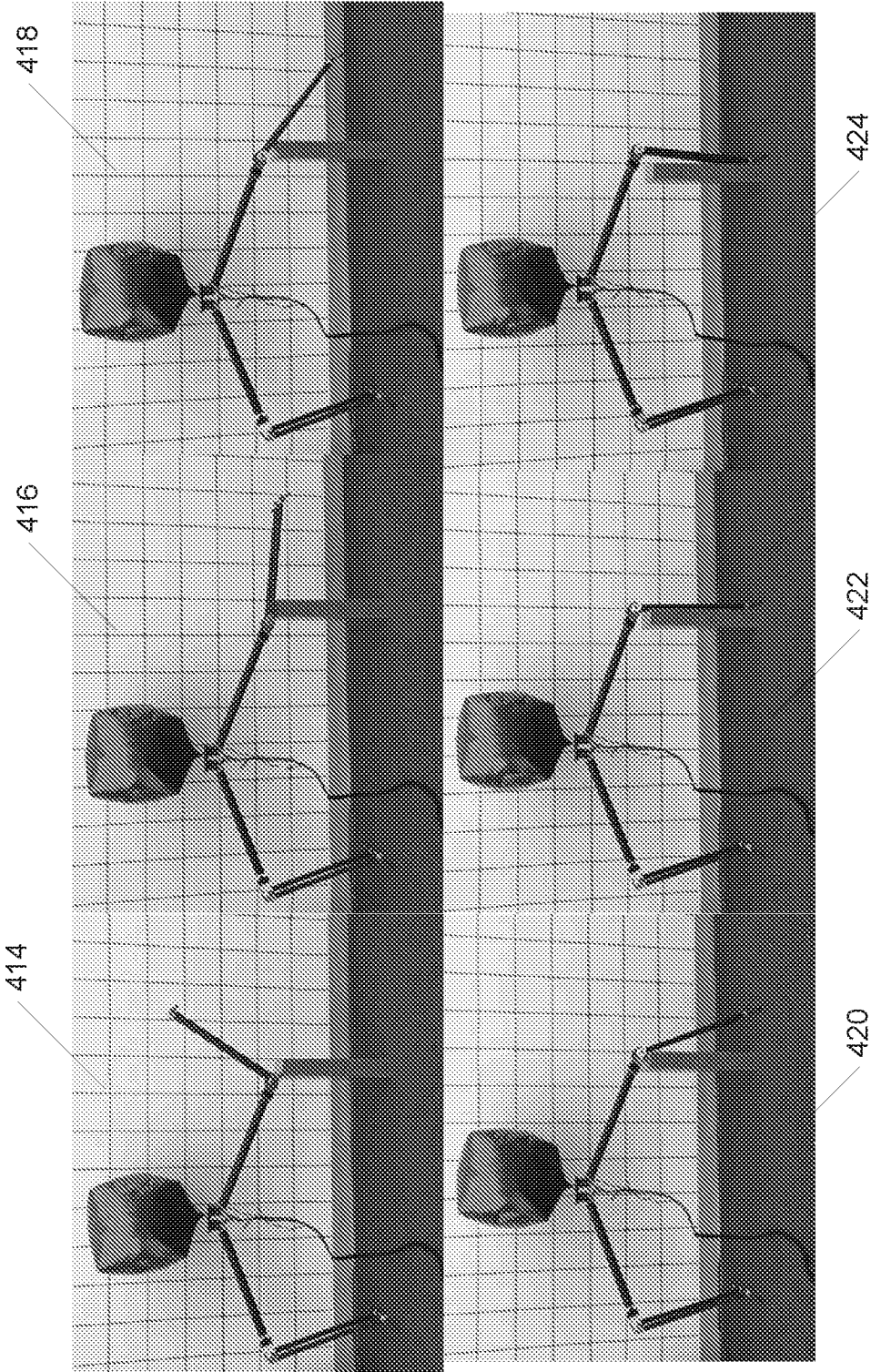


FIG. 4B

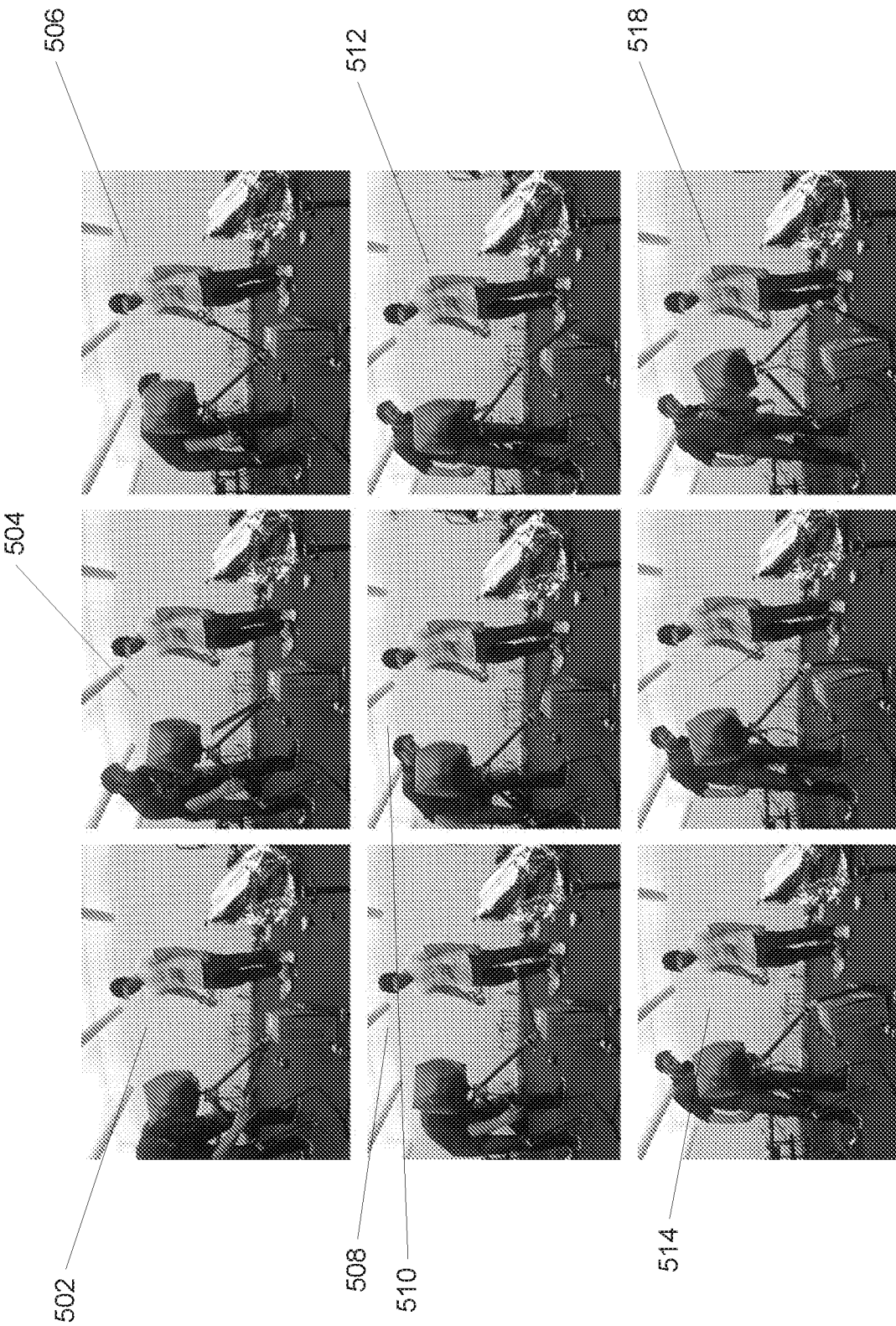


FIG. 5

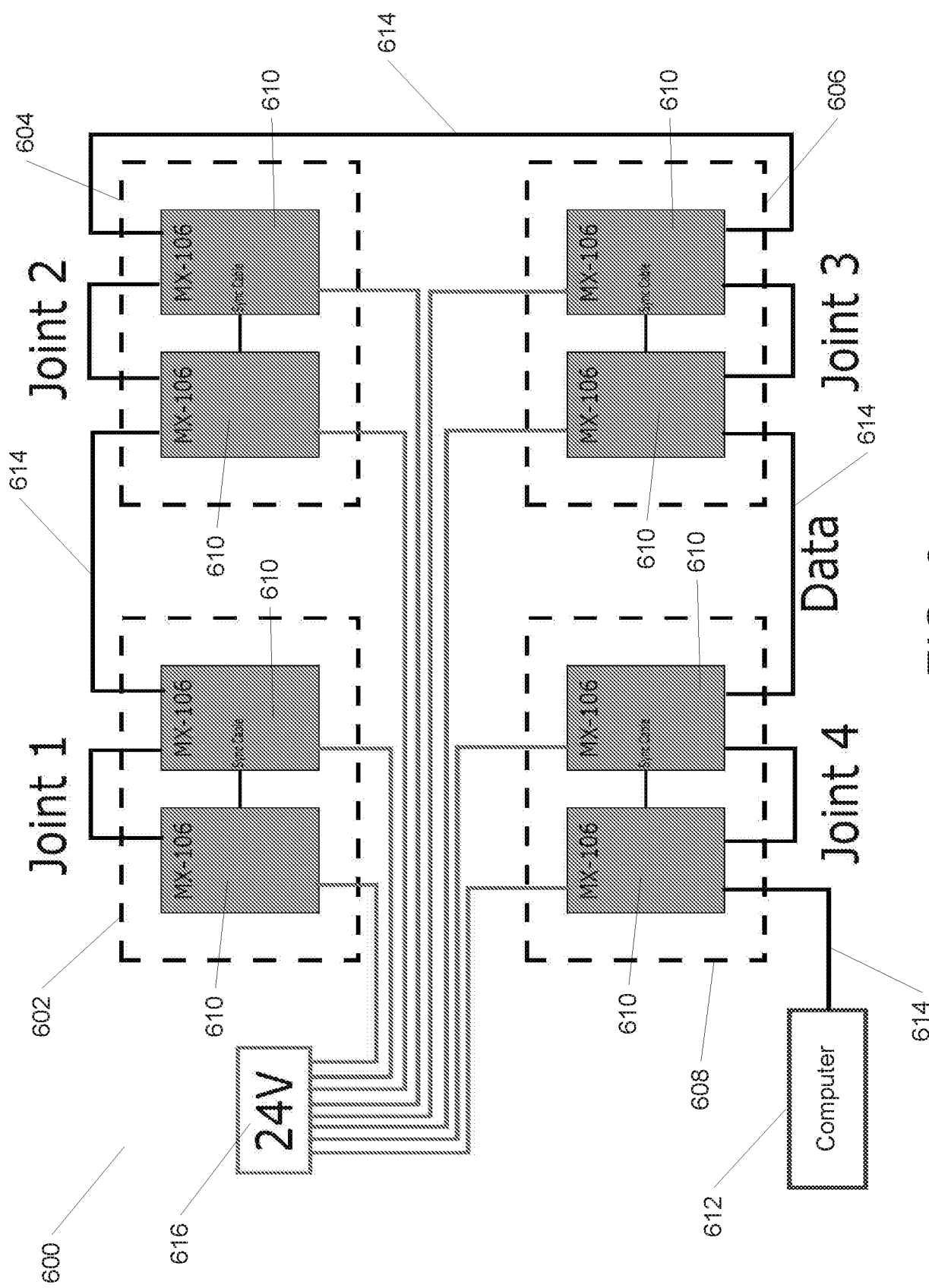


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/033140

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - B62D 57/032; B62D 57/02; B62D 57/028 (2017.01)

CPC - B62D 57/032; B62D 57/02; B62D 57/028 (2017.05)

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)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 180/8.1; 180/8.2; 180/8.3; 180/8.6; 180/8.7; 318/568.12; 700/245; 700/247; 901/1; 901/30 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,842,533 A (TAKEUCHI) 01 December 1998 (01.12.1998) entire document	1-28
A	US 2004/0255711 A1 (TAKENAKA et al) 23 December 2004 (23.12.2004) entire document	1-28
A	WO 2010/142044 A1 (ROBOTINC.CH AG et al) 16 December 2010 (16.12.2010) entire document	1-28
A	US 2009/0301798 A1 (YANG et al) 10 December 2009 (10.12.2009) entire document	1-28

☐ 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

23 July 2017

Date of mailing of the international search report

14 AUG 2017

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