



- (51) International Patent Classification:  
A61B 34/30 (2016.01)
- (21) International Application Number:  
PCT/US2017/018393
- (22) International Filing Date:  
17 February 2017 (17.02.2017)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:  
62/296,212 17 February 2016 (17.02.2016) 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, KH, 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))

[Continued on next page]

- (54) Title: ROBOTIC SYSTEMS AND METHODS FOR MINIMALLY INVASIVE ORTHOPEDIC SURGERIES

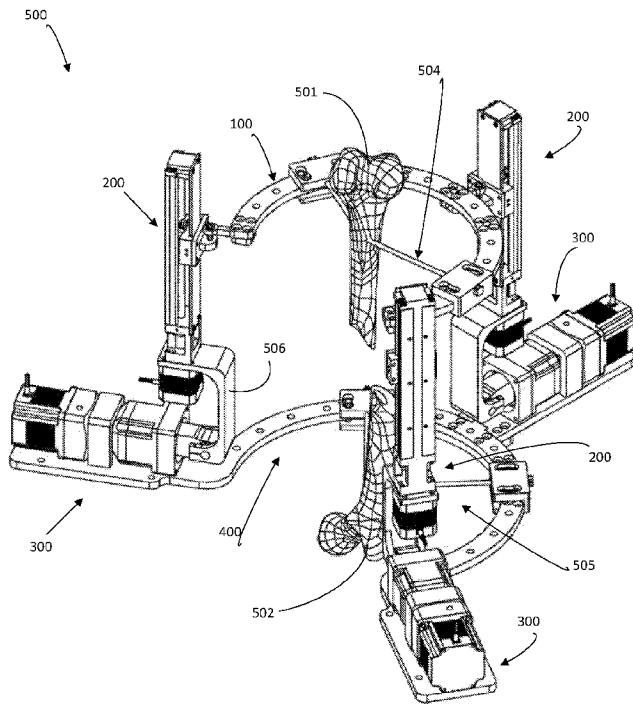


FIG. 1

(57) Abstract: A surgical robot includes a fixed frame and a moving frame, each having an open space in a center region and may be formed as a partially open ring. The robot also includes three leg structures connecting the fixed frame and the moving frame, and enabling the moving frame to move relative to the fixed frame. The robot also includes a stabilizer for holding an anatomical structure in the open space of each frame. Each leg structure may include a linear component coupled to the moving frame, a rotary component mounted to the fixed frame, and a connector connecting between the two. Each of the linear component and the rotary component may have a rotary actuator that can be controlled by a computer. The robot may be controllable by a computer to assist a reduction procedure of long bone fractures or pelvis surgery.

WO 2017/143204 A1

- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

## ROBOTIC SYSTEMS AND METHODS FOR MINIMALLY INVASIVE ORTHOPEDIC SURGERIES

### RELATED APPLICATION

5           This application claims the benefit of priority of U.S. Provisional Patent Application No. 62/296,212, filed February 17, 2016, the disclosure of which is incorporated herein by reference in its entirety.

### BACKGROUND

10           This disclosure relates to robotic systems and in particular to robotic systems for treatment of bone fractures.

          Lower limb fractures account for nearly a third of all fractures, and the ratio is still growing, due to the ageing of the population. A large number of lower limb fractures, that are very common in trauma centers, are those associated with long bones. The treatment of long bone fractures includes two main steps. First, the fracture is reduced, and then the bone  
15           fragments are fixed by external or internal fixation systems, e.g., plates and intramedullary nails. Due to its minimally invasive nature, intramedullary nailing technique is the treatment of choice of many surgeons for femoral and tibial shaft fractures.

          However, accurate reduction of long bone fractures is difficult to achieve using the conventional surgical techniques. High radiation exposure, to both the patient and the  
20           operating team, and malalignment of the bony fragments frequently occur; the latter can dramatically affect the course of healing, leading to nonunion complications. Also, soft tissue damages, due to large manipulation forces and repeated reduction attempts, are common. As such, there is a need to develop systems that can effectively improve clinical outcomes in patients undergoing bone reduction surgery.

25           This document describes systems and methods to address the shortcomings in the art.

### SUMMARY

          The present invention is directed to robotic systems and method of using such systems to perform orthopedic surgeries, such as bone long bone reduction, pelvic surgery,  
30           joint reconstructions, foot and ankle surgery, and arthroscopy. At least one aspect of the present invention is directed to methods of performing a guided orthopedic surgery by

attaching proximal fragments of a fractured bone to a fixed frame of a robot; attaching a distal fragment of the fractured bone to a moving frame of the robot; and align these fragments to a desired position for optimal patient outcome.

In some embodiments, a surgical robot may include a fixed frame and a moving  
5 frame. Each of the fixed frame and moving frame defines a respective plane, and includes an open space in a center region. Each frame may also be formed as a partially annular ring having an opening therein. The robot may also include three leg structures connecting the fixed frame and the moving frame, and configured to move the moving frame relative to the fixed frame. The robot may also include a stabilizer configured to hold an anatomical  
10 structure in the open space formed in the center region of each of the moving frame and the fixed frame.

The stabilizer may include at least one rod attached at varying locations along the fixed frame and extending from the fixed frame towards the open space formed in the center region thereof. The at least one rod associated with the fixed frame can be configured to be  
15 positioned to hold a first fragment of the anatomical structure in place relative to the fixed frame. Similarly, the stabilizer may also include at least one rod attached at varying locations along the moving frame and extending from the moving frame towards the open space formed in the center region thereof. The at least one rod associated with the moving frame can be configured to be positioned to hold a second fragment of the anatomical structure in  
20 place relative to the moving frame.

In some embodiments, each of the three leg structures may include a linear component that facilitates a sliding component to travel in a linear motion longitudinally along the leg structure, in which the sliding component is coupled to the moving frame at a mounting location. The linear component of each leg structure may also be coupled to a first  
25 actuator to move the sliding component longitudinally along the leg structure. The first actuator of each leg structure may be a rotary actuator. Each leg structure may also include a screw shaft coupled to the first actuator to transfer rotational motion from the first actuator to the linear motion of the sliding component. Further, each leg structure may also include a rotary component mounted to the fixed frame at a mounting location, and a connector  
30 connecting the linear component to the rotary component. The connector can be of a U-shape.

In some embodiments, the rotary component may include a shaft couplable to a shaft of a second rotary actuator to transfer rotation of the rotary actuator to the connector. The rotary component may include a shaft connector positioned to be coupled to the shaft of the rotary component and also to pivotally connect to the connector of each leg structure. The rotary component may also include a key positioned to lock the shaft connector to the shaft of the rotary component. Each of the first and second rotary actuators for each leg structure can be configured to rotate using a servo or stepper motor.

In some embodiments, the mounting locations at which the sliding components for the three leg structures are coupled to the moving frame can be equally spaced, and the mounting locations at which the rotary component for the three leg structures are mounted to the fixed frame can also be equally spaced. In some embodiments, the mounting locations can be adjustable along the partially annular ring of the moving frame and/or fixed frame. In some embodiments, the fixed frame may have an extended plate at each mounting location to enable a rotary component to be mounted thereon. Each extended plate may lie in the same plane formed by the fixed frame.

In some embodiments, the fixed frame can be movably mounted to a stand that is configured to support the robot. The robot may also include an attachment device for attaching an image capturing device to the robot, the image capturing device is capable of capture one or more images in real-time during a surgery. The image capturing device can be an ultrasound device, an x-ray scanner or a combination thereof. In some embodiments, the robot may have an additional leg structure similar to the structure of other leg structures described above. The additional leg structure may connect a first additional element attachable to the fixed frame and a second additional element attachable to the moving frame. Each additional element may be attached to and close the opening of the respective frame.

In some embodiments, a robotic system may include the surgical robot described above, a processing device in communication with the first and second rotary actuators of each leg structure, and computer software stored in a non-transitory computer-readable storage medium to control each of the actuators during a reduction procedure of long bone fractures or pelvic surgeries. In the robotic system, each of the moving frame and the fixed frame are formed as a partially annular ring having an opening therein, and the opening of

the moving frame and the opening of the fixed frame can be positioned around the long bone to reach a position for the procedure.

In some embodiments, a method for controlling a robot for use in a reduction procedure of a long bone fracture or pelvis surgery may include the steps of: attaching a proximal fragment of a fractured bone to a fixed frame of a robot; attaching a distal fragment of the fractured bone to a moving frame of the robot; by a processing device, moving the moving frame of the robot to a desired position; by the processing device, rotating the moving frame to allow parallel alignment to a shaft of the proximal fragment; by the processing device, translating the moving frame in a plane transverse to an axis of the proximal fragment to enable the axis of the distal fragment to align with an axis of the proximal fragment; and by the processing device, moving the moving frame to a target pose for a fracture end of the distal fragment to align with an opposing fracture end of the proximal fragment. In some embodiments, the moving frame may move in 6 degree of freedom in relation to the fixed frame.

The various steps of the method may also include receiving a position instruction from a user, such as a user command via a graphical user interface. The method may further include receiving, using a processing device, the position instruction; generating, using the processing device, one or more control parameters for one or more actuators of the robot based on the received position instruction; transmitting, using the processing device, control signals representing the one or more parameters to the one or more actuators. The position instruction may include one or more of a x position, a y position, a z position, an alpha, a beta, a gamma, a delta  $T_m$ , a time interval, a step ratio, a delta Rot, and a sample time. The method may also include using an image-capturing device to capture in real-time one or more images during the procedure, where the one or more captured images include the fracture end of the distal fragment and the opposing fracture end of the proximal fragment, or a pelvis. In one embodiment, the method may include generating preoperative or intraoperative images at the surgical site and determining desired trajectories to align fractured fragments.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts a perspective view of a robot according to some embodiments.

FIG. 2A is an exploded view of the moving frame of a robot according to some embodiments.

FIG. 2B depicts an example of a moving frame with sliding tracks for adjusting the location of leg structures according to some embodiments.

5 FIG. 3A is an exploded view of some components of the leg structure according to some embodiments.

FIG. 3B depicts an example of a screw shaft according to some embodiments.

FIG. 4 is an exploded view of some components of a gear box according to some embodiments.

10 FIG. 5 is an exploded view of the fixed frame of a robot according to some embodiments.

FIG. 6 depicts a perspective view of a robot attached to a movable stand according to some embodiments.

FIG. 7 depicts an exploded view of the stand of embodiments in FIG. 6.

15 FIG. 8 depicts a perspective view of a robot with an additional leg structure according to some embodiments.

FIG. 9 depicts a perspective view of a robot with an additional leg structure according to some embodiments.

FIG. 10 depicts an example of a control panel as part of a user interface.

20 FIG. 11 depicts an example of a robotic system for use in a reduction procedure for large bone fractures.

FIG. 12 shows a diagram of a process for controlling a robotic system according to some embodiments.

25 FIG. 13 shows a schematic 6-degree-of-freedom robot with three legs and coordinates for an evaluation.

FIG. 14 shows a workspace analysis of some illustrated embodiments compared to the known Gough-Stewart platform.

FIG. 15. shows experimental verification of robot movements according to some embodiments.

30 FIG. 16 depicts an example of internal hardware that may be included in any of the electronic components of the robotic system.

## DETAILED DESCRIPTION

As used in this document, the singular forms “a,” “an,” and “the” include plural references unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art. As used in this document, the term “comprising” means  
5 “including, but not limited to.”

The term “leg” or “leg structure” as used herein refers to any structure that supports a moving frame on a fixed frame.

The term “frame” as used herein refers to any structure that comprises one or more  
10 fixed components and provides support for or positioning of a surgical instrument. The “frame” may form a two-dimensional (2D) plane or may be of any three-dimensional (3D) structure.

In FIG. 1, in some embodiments, a surgical robot **500** may include a fixed frame **400** and a moving frame **100**, which will be described in detail later. The robot may also include  
15 multiple leg structures, which connect the fixed frame **400** and the moving frame **100**. The leg structures may also be configured to enable the moving frame **100** to move relative to the fixed frame **400**. In some embodiments, there may be three leg structures (FIG 1). The robot **500** may also include a stabilizer **504**, **505** that is configured to hold an anatomical structure **501**, **502** during a reduction procedure for long bone fractures. In some  
20 embodiments, the stabilizer **504**, **505** may also be configured to move a part of the anatomical structure to align with another part. For example, in the reduction procedure for long bone fractures, the stabilizer **504**, **505** may be configured to align a distal fragment **501** of a long bone to a proximal fragment **502** of the long bone. In some embodiments, the stabilizer may contain a gripping member to grip, carry, hold or maintain the anatomical  
25 structure undergoing surgery.

In some embodiments, each leg structure may include a linear component **200**, which facilitates a sliding component to travel in a linear motion longitudinally along the leg structure, and the sliding component may be coupled to the moving frame **100** at a mounting location. Additionally, and/or alternatively, each leg structure may include a gear box **300**,  
30 which can be mounted to the fixed frame **400**. In some embodiments, each leg structure may include a connector **506** to couple the linear component **200** with the gear box **300**.

The illustrated embodiments will enable the moving frame to move in 6-degrees-of-freedom.

In FIG. 2A, the moving frame is further explained in detail. In some embodiments, the moving frame **100** may include an open space formed in the center region of the moving frame. The moving frame may be of any suitable shape. For example, the moving frame  
5 may form as a partially annular moving ring **101**. In some embodiments, the moving frame can be at least a half-ring, can be a  $\frac{3}{4}$  ring, with some variations, such as, for example, with  $\pm 25\%$ . The moving frame can also be a full ring. The moving ring can also be adopted in other shapes such as square, partial square, ellipse, partial ellipse, oval or U-shape, partial  
10 oval, triangle, partial triangle, L-shape.

In some embodiments, the moving ring may be made of various suitable materials. For example, it can be metallic, aluminum, titanium alloys, stainless steel, hard plastic, polyolyphen or hard plastic alike, or anything capable of holding or supporting bone up to 400 Newton on an object without significant deflection (e.g. less than 5% deformity or  
15 bending or displaced more than 5%), or any material that can be sterilized and be used in a clean room environment. In some embodiments, the moving ring **101** may contain multiple holes of various types. For example, the hole **102** may be for fixing, adding or attaching other components to the moving ring; the hole **103** may be used for fastening the stabilizer to the frame. The thickness of the moving frame can range from 0.1 mm to 7.5 cm,  
20 preferably 0.5 mm to 2 cm, 10 mm to 1 cm, depending on the material used and the stiffness of the material.

In some embodiments, the stabilizer may include at least a grip, such as a rod **106** that is attached at varying locations along the moving frame and extending from the moving frame towards the open space formed in the center region of the moving frame, wherein the  
25 at least one rod is configured to be positioned to hold a bone fragment of the anatomical structure in place relative to the moving frame. The grip **106** may provide direct or indirect gripping of the anatomy under the surgery. It can pick up, hold, carry or guide a bone gripping mechanism.

In some embodiments, the moving frame may also include a fastener or bracket **104**,  
30 which fastens the rod **106** to the moving frame. The fastener **104** may also be used to attach an instrument to the moving frame, such as an image sensor, a drug delivery component, a surgical instrument or other ancillary components required to perform the surgery. In some

embodiments, the stabilizer rod **106** can be configured to secure a bone fragment in place relative to the moving ring. The stabilizer may be in contact with a bone fragment using simple screws, or clamped, mounted, or suctioned to the bone, forceps, modified scalpel, or it can be cuffs, braces to hold or connect to the bone or the soft tissue containing the bone,  
5 or can be other grips.

In some embodiments, the fastener **104** may contain one or two holes for attaching to the moving ring. It can be rotated to be aligned to the moving ring. It may be made of same material as moving ring. The fastener may also have a hole that allows passing through any grip, such as a rod **106** or pins, surgical needle, surgical instruments, laprascopic hands  
10 or device, drill, hollow cylinder to insert or guide other surgical instruments such as catheterization tubes. The fastener **104** may also contain grooves **105** positioned to fit in the moving frame **101**. The fastener **104** may also change orientation, and facilitate the rotation of the grip on the moving ring.

In some embodiments, the moving frame **101** may have one or more holes **102** for  
15 attaching a joint, e.g. a ball and socket joint for coupling to the linear component (**200** in FIG. 1) of the leg structure. The moving platform may optionally have a fastener **107** for attaching the ball and socket joint to the moving ring **101**. The fastener **107** can be screwed to the moving ring, welded, glued, or include a sliding component to facilitate flexibility of movement for ball and socket joint. To facilitate six-degrees-freedom of the moving frame,  
20 the coupling between the moving frame and the leg structure may further use a ball and socket joint **108** that provides or has three-degrees-of-freedom which connects the moving platform to the leg structure.

In FIG. 3A, in some embodiments, the linear component **200** of the leg structure may have an upper housing **205**. The linear component **200** may also have a connector **201**  
25 that facilitates the coupling of the leg structure to the moving frame by receiving the ball and socket joint of the moving frame (**108** in FIG. 2A) into a hole thereon. In some embodiments, the linear component may be configured to move a sliding component, e.g. **204**, longitudinally along the leg structure. In some embodiments, the linear component **200** may be configured to be coupled to an actuator **209** to provide one-degree freedom to  
30 the leg structure. The actuator can be of various types, e.g. a linear actuator or a rotary actuator. In some embodiments, the actuator can be a rotary actuator. The rotary actuator may use a servo or stepper motor. In some embodiments, the rotary actuator **209** can be an

electric actuator motor. It may be controlled by computer software commands, or a processing device or a microcontroller, automatically or manually, hinged on the operator platform or surgeon console. The housing of the actuator can be made of the same material as indicated above, aluminum, steel, titanium, or any material that can be sterilized in clean room environment.

Each leg structure may also include a screw shaft **206** configured to be coupled to the actuator **209** and to transfer a rotational motion from the actuator to a linear motion of the sliding component **204**. An exploded view of the screw shaft is also shown in FIG. 3B. The sliding component can be a nut on the screw that moves in a linear fashion longitudinally along the linear component. The linear component may also have a coupling housing **207** attached thereto from underneath the upper housing **205** and that allows coupling of the shaft of the rotary actuator **211** and the transmission of the rotation of the rotary actuator to the rotation of the shaft of the screw **206**. The leg structure may also include a lower extremity **210**, e.g. a connector, which facilitates the attachment of the rotary actuator **209** to the coupling housing **207** at one end. The leg structure may also be configured to couple to a rotary component such as a rotary gear box (**300** in FIG. 1) at an opposing end, which will be explained later.

Alternatively, the coupling housing **207** may be positioned in the vicinity of the upper housing **200**, for example, on top of the upper housing or below it, or behind the upper housing. The coupling housing **207** may include a coupler **208** positioned to fit between the lower part of the upper housing **212** and upper part of the shaft of the rotary actuator **211** to align the respective shafts and facilitate transmission of rotary force. The coupler **208** can be flexible coupling made of metal, aluminum, alloy or combination with plastic. It can be a closed, open or semi open housing.

In some embodiments, the upper housing **205** may be a nut screw assembly. It may have an optional cover **203** to close the screw and avoid dust accumulation inside the box. The sliding component **204** may be made of a screw shaft **206** and a nut, the nut itself may contain ball bearings to allow smooth movement of the nut on the screw shaft **206**. The upper housing **205** may be configured to hold the screw shaft **206**. The screw shaft **206** may have a groove thereon longitudinally to allow nut **204** (which contains a ball for moving in the groove and the screw connector **202**) to move up and down the screw in a linear fashion.

The housing **205** itself may also include back wall, side walls, an upper ceiling or a lower base (now shown).

In some embodiments, the connector **201** may be used to attach or connect the moving frame to the leg structure, which may be the only point of attachment between the upper part of the leg structure and the moving frame. The connector **201** may contain a back plate which can be directly attached to the sliding nut **204** or indirectly through the middle connector **202** in cases where a cover is used. The connector **202** can be a U-shape connector that embraces the cover and allow movement of the connector **201** moveable up and down along the cover while being engaged with the nut and the screw shaft **206**.

In some embodiments, the coupling housing **207** may include a coupler **208**, upper part of the rotary shaft **211** and a lower part **212** that may extend from the screw shaft through the base of the upper housing **205** and through the ceiling of the coupling housing to meet within the coupling house space. In some embodiments, the lower extremity **210** may include a U-shaped and semi-U-shaped connector having three surfaces, an arm and two surfaces perpendicular to the arm to allow fastening of the lower extremities to other component of the robot. In some embodiments, the lower extremity may be a semi-U-shaped structural part that facilitates coupling of the upper housing to the rotary gear box system **300**. In some embodiments, the coupling of the upper housing **205** and the rotary gear box may be directly through the coupling housing **207** without using a connector. In some embodiments, the connector **210** may have receptive holes **215** that receive a rod pin **213** to facilitate connecting to the rotary gear box system **300**, which will be further explained with reference to FIG. 4.

With reference to FIG. 3 and FIG. 4, in some embodiments, the rotary gear box system **300** may be mounted to the fixed frame at a mounting location, such as shown in FIG. 1. The rotary gear box system may include a shaft couplable to a shaft of a second rotary actuator and configured to transfer rotation of the rotary actuator to the connector **210**. The second rotary actuator may use a servo or stepper motor. The rotary gear box system **300** may also include a shaft connector **301** positioned to be coupled to the shaft of the rotary gear box **308** and also to pivotally connect to the connector of each leg structure, e.g. connector **210**. The rotary gear box system **300** may also include a key **304** positioned to lock the shaft connector **301** to the shaft of the rotary gear box **308**. In some embodiments, the rod **213** may pass through the holes **215** of the lower extremities and a hollow space **305**

of the shaft connector **301**, where the hollow space **305** is aligned in between the receptive holes **215**, coupling the lower extremities to a rotary gear box **303** optionally in its respective housing.

Optionally, the coupling between the rotary gear box system **300** and the linear component **200** (or connector **210**) may use thrust lower bearing **214** to smoothen the connection and minimize the friction between the connector **211** and the outer surface of the gear box shaft connector **301**. The shaft connector **301** can also optionally contain roller bearings **302** inside its hollow space **305**, which allows smooth rotating of the rod **213** when inside the connector **301**. The shaft connector **301** can optionally contain hollow pathway **307** to allow a screw to be fastened to the gearbox shaft of **308** and at the same time permit a gearbox shaft key **304** to lock into the connector with little or no axial movement or compression.

In some embodiments, the rotary gear box system **300** may also have a gear box housing **303** and a rotary actuator **306**. The gear box housing **303** can be one- or two-stage gear box or has more than two stages, to enhance the torque generated by the rotary actuator, reduce the speed of the rotary actuator and further transmit the force and rotation of the rotary actuator **306** to the linear component **200** through the shaft connector **301**. The rotary gear box system **300** may also include connectors **309**, **310** configured to mount the rotary gear box assembly to the fixed frame, which will be further explained.

In FIG. 5, the fixed frame is explained in detail. In some embodiments, the fixed frame may have similar structure of the moving frame (as shown in FIG. 2A). With reference to FIGs. 2 and 5 together, the mounting locations at which the sliding components for the three leg structures are coupled to the moving frame may be equally spaced or spaced variably. The mounting locations at which the rotary gear box systems for the three leg structures are mounted to the fixed frame may also be equally spaced or spaced variably. For example, the mounting location at which the sliding component for a middle leg structure of the three leg structures is coupled to the moving frame may be adjustable along the partially annular ring of the moving frame, so that the middle leg structure can slide towards the other two proximal legs within the movable ring. In some embodiments, the adjustment of the leg structures along the frames can be possible by using one or more mounting holes **102**. In other embodiments, the adjustment can be possible by using a frame

that has one or more tracks along the arc of the ring (FIG. 2B) that facilitate a movement of a slider on the frame.

Similarly, the mounting location at which the rotary gear box system for a middle leg structure of the three leg structures is mounted to the fixed frame may also be adjustable  
5 along the partially annular ring of the fixed frame. Alternatively, and/or additionally, the location of any of the other leg structures may also be adjustable. In some embodiments, the body of the fixed and movable rings may include a railing to facilitate movement of the leg structure(s). Alternatively, at least one actuator may be attached to the frames or the middle legs to allow automatic movement or sliding of the middle leg structure thought out the  
10 frames.

In FIG. 5, in some embodiments, the fixed frame **400** may include an open space formed in the center region of the fixed frame. The fixed frame may be of any suitable shape. For example, the fixed frame may form as a partially annular fixed ring **401**. In some  
15 embodiments, the fixed frame can be at least a half-ring, can be a  $\frac{3}{4}$  ring, with some variations, such as, for example, with  $\pm 25\%$ . The fixed frame can also be a full ring. The fixed ring can also be adopted in other shapes such as square, partial square, ellipse, partial ellipse, oval or U-shape, partial oval, triangle, partial triangle, L-shape.

In some embodiments, the fixed ring may be made of various suitable materials. For example, it can be metallic, aluminum, titanium alloys, stainless steel, hard plastic,  
20 polyolyphen or hard plastic alike, or anything capable of holding or supporting bone up to 400 Newton on an object without significant deflection (e.g. less than 5% deformity or bending or displaced more than 5%), or any material that can be sterilized and be used in a clean room environment. In some embodiments, the fixed ring **401** may contain multiple holes of various types. For example, the holes **402** may be for mounting a rotary gear box  
25 system to the fixed ring; the holes **403** may be used for fastening the stabilizer to the frame or adding or attaching other components to the fixed ring. The thickness of the fixed frame can range from 0.1 mm to 7.5 cm, preferably 0.5 mm to 2 cm, 10 mm to 1 cm, depending on the material used and the stiffness of the material.

In some embodiments, the stabilizer may include at least a grip, such as a rod **406**  
30 that is attached at varying locations along the fixed frame and extending from the fixed frame towards the open space formed in the center region of the fixed frame, wherein the at least one rod is configured to be positioned to hold a bone fragment of the anatomical

structure in place relative to the fixed frame. The grip **406** may provide direct or indirect gripping of the anatomy under the surgery. It can pick up, hold, carry or guide a bone gripping mechanism.

In some embodiments, the fixed frame may also include a fastener or bracket **404**,  
5 which fastens the rod **406** to the fixed frame. The fastener **404** may also be used to attach an instrument to the fixed frame, such as an image sensor, a drug delivery component, a surgical instrument or other ancillary components required to perform the surgery. In some embodiments, the stabilizer rod **406** can be configured to secure a bone fragment in place relative to the fixed ring. The stabilizer may be in contact with a bone fragment using simple  
10 screws, or clamped, mounted, or suctioned to the bone, or it can be cuffs, braces to hold or connect to the bone or the soft tissue containing the bone, or can be other grips.

In some embodiments, the fastener **404** may contain one or two holes for attaching to the fixed ring. It can be rotated to be aligned to the fixed ring. It may be made of same material as fixed ring. The fastener may also have a hole that allows passing through any  
15 grip, such as a rod **406** or a pin, a surgical needle, surgical instruments, laparoscopic hands or device, drill, hollow cylinder to insert or guide other surgical instruments such as catheterization tubes. The fastener **404** may also contain grooves **405** positioned to fit in the fixed frame **401**. The fastener **404** may also change orientation, and facilitate the rotation of the grip on the fixed ring.

In some embodiments, the fixed frame **401** may have one or more holes **402** for  
20 attaching a bone grip, such as a fastener **404** to the fixed ring **401** via holes **403**, or fixing, adding or attaching other components to the fixed ring **401** via holes **402**. In some embodiments, the holes **403** can be used for fixing or attaching image sensors or drug delivery components, surgical instrument or other ancillary components required to perform  
25 the surgery.

Returning to FIG. 5, in some embodiments, the fixed frame **400** may include an extended plate at each mounting location, wherein each extended plate is configured to enable a rotary gear box system to be mounted thereon. In some embodiments, each extended plate may lie in the same plane as that formed by the fixed frame, or the fixed ring  
30 **401**. In some embodiments, a middle base plate for mounting a middle rotary gear box and actuator may be a single or multiple plate structure **407**, **408**, either directly or indirectly connected to the fixed ring through holes **402**, which may be a single or double adjacent

holes. The middle base plate(s) may contain a plurality of holes **409** to allow mounting of the rotary gear box system to the fixed ring.

In some embodiments, an open fixed ring **401** can contain a flat surface **411**, **412** proximate to an end of the open fixed ring to allow resting of the rotary gear box system (the rotary gear box– actuator assembly) of the leg structures. These plates may contain  
5 various sets of holes. For example, the plates may include holes **409** used to mount the rotary gear box system to the surface of the plate. The plates may also include holes **410** used to connect the robot to a movable stand which will be explained hereinbelow.

In FIG. 6 and FIG. 7, a robotic system for a reduction procedure of large bone  
10 fractures may include the robot as described above, and additionally a stand **601**. In some embodiments, the fixed frame is movably mounted to a stand that is configured to support the robot and enable the robot to be moved freely to a position for a reduction procedure of a long bone fracture. In some embodiments, the stand **600** may include a movable base **601** optionally containing locking wheels and an upper extension **602** containing one or more  
15 surfaces **603** that allow the mounting of one or more leg structures, e.g. **411**, **412** (in FIG. 5) of the robot thereto.

In some embodiments, the system provides generating preoperative or intraoperative images at the surgical site and determining desired trajectories to align fractured fragments. As such, the robot further comprises an attachment device (now shown) configured for  
20 attaching an image capturing device to the robot, wherein the image capturing device is capable of being positioned to capture one or more images of the long bone fracture in real-time during the reduction procedure. In some embodiments, the image capturing device may be an x-ray scanner, a camera or other ultrasound imaging devices in mobile or stationary form. In other embodiments, the robot may have additional sensor attachments such as force  
25 sensors, position sensors, tracking sensor, vision tracking sensor, infrared sensor or the like to regulate respective parameters during the surgery such as haptic feedback through the work of the surgeon.

As shown in FIG. 8 and FIG. 9, the robot **800** may optionally contain an additional removable leg structure. In some embodiments, the robot **800** may include a first additional  
30 element attachable to the fixed frame **832** to close the opening of the fixed frame. The robot **800** may also include a second additional element attachable to the moving frame **830** to close the opening of the moving frame. The robot **800** may also include an additional leg

structure **812** that may be of similar structure of other leg structures **810**. The additional leg structure **812** may also be coupled to the moving frame **830** and mounted to the fixed frame **832** in a similar manner as other leg structures.

In some embodiments, the additional leg **812** may include a linear component that is couplable to an actuator to facilitate a sliding component to travel in a linear motion longitudinally along the additional leg structure, wherein the sliding component is mounted to the second additional element at a mounting location. The additional leg structure may also include a screw shaft configured to be coupled to the first actuator and to transfer rotation of the first actuator to the linear motion of the sliding component, a rotary gear box system mounted to the first additional element, and a connector connecting the linear component to the rotary gear box. The rotary gear box system of the additional leg structure may include a shaft couplable to a shaft of an additional rotary actuator and configured to transfer rotation of the rotary actuator to the connector. The additional leg structure may also include a shaft connector positioned to be coupled to the shaft of the rotary gear box and also pivotally connect to the connector of the additional leg structure.

The robot described in various illustrated embodiments in FIGs. 1-9 may be controlled by one or more processing devices in a robotic system that will allow the moving frame to move in six-degrees-of-freedom with precision in a reduction procedure for large bone fractures or pelvic surgeries. In some embodiments, the system may include the above described robot, and additionally include a processing device installable on the robot or remotely, and computer-readable storage medium or memory that contain programming instructions configured to cause the processing device to control each of the actuators during a reduction procedure of a long bone fracture or pelvic surgeries. In a computer assisted procedure, the robot may be movably mounted to a stand that is configured to support the robot and enable the robot to move freely to suitable position during a surgery, such as the reduction procedure of the long bone fracture or pelvic surgeries.

In some embodiments, the robotic system may further include an image capturing device positioned to capture one or more images of the surgical area, such as the long bone fracture or the pelvis, in real-time during the procedure. The image capturing device may be an x-ray scanner, a camera, other ultrasound, CT or MRI imaging devices to facilitate a guided orthopedic environment by generating preoperative or intraoperative images at the surgical site and determining desired trajectories to align fractured fragments.

In some embodiments, the precision control of the movement of the platform is further explained. Each of the actuators of the robot described in this document may require one or more control parameters in order to operate. The robotic system may be configured to receive the control parameters from a microprocessor or a processing device. The microprocessor may be configured to receive trajectory position instructions, convert the position instructions to one or more actuator control parameters and send the one or more control parameters to the one or more actuators via electrical signals. In some embodiments, the microprocessor may implement computer-readable program instructions (e.g. C, C++, Matlab, or any other computer languages) to convert desired trajectory position instructions to actuator control parameters.

As shown in FIG. 10, in some embodiments, the robotic system can be controlled from a user (surgeon) manually or autonomously by receiving the position instruction in various ways. For example, the system may receive position instruction from a user via a control panel **1000**, such as a touch screen control panel. Alternatively and/or additionally, the system may receive a command from a 6-DOF joystick that is connected to the system and operated by the user. The trajectory position instruction may include a multitude of values, such as x, y, z positions, alpha, beta, theta angles, steps and time intervals etc., Translational and rotational increments can be adjusted by “Delta Trn” and “Delta Rot” buttons, respectively. For instance, “Delta Trn” may range from 1 to 10 (mm), while “Delta Rot” may range from 0.1 to 1 (deg). “Sample time” ranges between 0.001 and 0.01 (s), and “Time interval” from 1 to 10 (s). “Step ratio” is dependent to the driver adjustments and may range from 1 to 250. The actuator control parameters may include the values for displacements and rotations of each actuator.

In some embodiments, in the robotic system that is to be used for a reduction procedure of large bone fractures, as shown in FIG. 11, the robotic system may have a circular fixed and moving frames, with g (radius of the fixed ring) = 15.6 (cm) and h (radius of the moving ring) = 15.3 (cm), respectively. Each of the three leg structures may be equipped with a rotary actuator located on the fixed frame. This rotary actuator may include a 260 Watt stepper motor with a nominal torque of 0.83 N.m followed by a 10:1 low-ratio Apex gearbox, with a low clearance of  $0.13^\circ$ , such as the motor made by Autonics, to enlarge the shaft torque. The rotary gear box shaft may be connected to the lower part of the linear component of the leg structure using a revolute joint. The revolute joint may be made of a

miniature needle bearing. Linear actuation at each leg structure may be provided using a ball screw system. The linear actuation may be powered by an 80 Watt stepper motor with a nominal torque of 0.24 N.m to provide sufficient torques, such as the stepper motor made by Autonics. The system may also include a spherical joint to connect the linear component  
5 or upper housing of the leg structure to the moving frame. The total mass of each of the three leg structure may be about 1.76 (kg) and that of the moving frame may be about 0.68 (kg). A graphical user interface, such as shown in FIG. 10, may also be included in the system to assist the user to perform the reduction procedure.

In at least some embodiments one of ordinary skill in the art may input suitable  
10 parameters to maximize clinical outcome based on population data. Such parameters may include x, y, and z as translational movements; alpha, beta, and gamma as rotational movements; translational resolution ( $\Delta$  Trn); rotational resolution ( $\Delta$  Rot); a time interval to reach to a target point; a Step ratio to signify the precision of the movement of the moving ring; and a Sample time of controlling signals from the computer to actuator.  
15 The control panel may further contain a start and stop button to regulate the movements and/or interrupt the movements in an emergency. As such, population data may be employed to designate the rotational workspace with dimensionless parameters.

In at least one aspect, method for controlling a robot is described during an orthopedic bone surgery. In some embodiments, a method of treating a single or complex  
20 long bone structure is described including the steps of: (a) attaching a proximal fragment of a fractured bone to a fixed frame of a robot; (b) attaching a distal fragment of the fractured bone to a moving frame of the robot; (c) by a processing device, moving the moving frame of the robot to a desired position, (d) by the processing device, rotating the moving frame to allow parallel alignment to a shaft of the proximal fragment, (e) by the processing device,  
25 translating the moving frame in a plane transverse to an axis of the proximal fragment to enable the axis of the distal fragment to align with an axis of the proximal fragment; and optionally (f) by the processing device, moving the moving frame to a target pose for a fracture end of the distal fragment to align with an opposing fracture end of the proximal fragment.

30 With reference to FIG. 12, in some embodiments, a method may be implemented using the various illustrated embodiments in FIG. 1-11 for a reduction procedure of large bone fractures. The method may include attaching a proximal fragment of a fractured bone

to a fixed frame of a robot **1202**, attaching a distal fragment of the fractured bone to a moving frame of the robot **1204**. The method may additionally use a computer to control the robotic system. In some embodiments, the method may include moving the moving frame of the robot to stretch the distal fragment **1206** so that the distal fragment is separated from the proximal fragment. The method may also include rotating the moving frame to cause the distal fragment subject to varus-valgus rotation **1208** so that a shaft of the distal fragment lies parallel to a shaft of the proximal fragment. The method may further include translating the moving frame in a plane transverse to an axis of the proximal fragment to enable the axis of the distal fragment to align with an axis of the proximal fragment **1210**, and moving the moving frame to shorten the distal fragment to obtain a target pose for a fracture end of the distal fragment to align with an opposing fracture end of the proximal fragment **1212**.

In some embodiments, the steps of moving, rotating, translating and moving the moving frame may include receiving a position instruction from a user, e.g. via a graphical user interface. The method may additionally include using the computer to generate one or more control parameters for one or more actuators of the robot based on the received position instruction, and to operate the one or more actuators based on the one or more control parameters. Alternatively, and/or additionally, the method for performing the reduction procedure may also include using an image capturing device to capture in real-time one or more images during the surgery such as the reduction procedure, wherein the one or more captured images include the fracture end of the distal fragment and the opposing fracture end of the proximal fragment.

The various illustrated embodiments are advantageous over conventional surgical robots, such as the Stewart mechanism that has six legs with passive universal joints. The illustrated embodiments that have three or four leg structures are particularly suitable for computer assisted long-bone fracture reduction procedure in that the reduced number of legs make the robotic system lighter, since the rotary actuators are resting on the fixed frame, which allows for higher accelerations to be available due to smaller inertial effects. The leg structures in the illustrated system are also configured non-symmetrically on a semicircle on the base and moving platforms. This frontally wide open architecture, enables the mechanism to embrace and manipulate column-shape objects. The applications of such mechanism are versatile, from fracture reduction of long bones in surgical robotics to column climber robots in industrial robotics.

A kinematic analysis has been conducted on the illustrated embodiments above to verify the applicability of the system to the fracture reduction of long bones. As shown in the FIG. 13, coordinate  $C_i(A_i, x_i, y_i, z_i)$  is attached to the base platform with its  $x_i$  axis aligned with the rotary actuator in the  $x_i$  direction, and its  $z_i$  axis perpendicular to the fixed platform.  $x_i$  is rotated by  $y_i$  from the X direction of fixed platform coordinate  $A(O, X, Y, Z)$ . The rotary actuators are located at the positions  $A_i$  (for  $i = 1, 2, 3, 4$ ) on the base platform and each shaft is connected to the lower part of the linear actuators through a universal joint. The upper parts of linear actuators are connected to the moving platform,  $B_i$  points, through spherical joints.

Cartesian coordinates  $A(O, x, y, z)$  and  $B(P, u, v, w)$  represented by  $\{A\}$  and  $\{B\}$  are attached to the base and moving platforms, respectively. In FIG. 13,  $s_i$  represents the unit vector along the axes of  $i$ -th rotary actuator and  $d_i$  is the vector along  $A_iB_i$  with the length of  $d_i$ . Assuming that each limb is connected to the fixed base by a universal joint, the orientation of  $i$ -th limb with respect to the fixed base can be described by two successive rotations, rotation  $\theta_i$  around the axis  $s_i$ , followed by rotation  $\psi_i$  around  $n_i$ , which is itself perpendicular to both  $d_i$  and  $s_i$ . It is to be noted that  $\theta_i$  and  $d_i$  are active joints, actuated by the rotary and linear actuators, respectively, while,  $\psi_i$  is an inactive joint.

In FIG. 13,  $a_i$  which represents  $OA_i$  can be written as  $a_i = g[\cos \gamma_i \quad \sin \gamma_i \quad 0]^T$ , where  $g$  and  $h$  are the radius of the fixed and moving platforms, respectively,  ${}^B b_i$  represents the position of the  $i$ -th joint on the platform in the moving frame  $\{B\}$ ,  ${}^B b_i = PB_i)_B$ .  ${}^B b_i$  is constant and is equal to  ${}^B b_i = a_i = h[\cos \gamma_i \quad \sin \gamma_i \quad 0]^T$ . We can represent  ${}^A_B R = [r_{ij}]$ , the rotation matrix from A to B, using Euler angles as

$${}^A_B R = \begin{bmatrix} c\alpha_2 c\alpha_3 & -c\alpha_2 c\alpha_3 & s\alpha_2 \\ c\alpha_3 s\alpha_2 s\alpha_1 + s\alpha_3 c\alpha_1 & -s\alpha_3 s\alpha_2 s\alpha_1 + c\alpha_3 c\alpha_1 & -c\alpha_2 c\alpha_1 \\ -c\alpha_3 s\alpha_2 c\alpha_1 + s\alpha_3 s\alpha_1 & s\alpha_3 s\alpha_2 c\alpha_1 + c\alpha_3 s\alpha_1 & c\alpha_2 c\alpha_1 \end{bmatrix} \quad (1)$$

where  $s\alpha_1 = \sin\alpha_1$  and  $c\alpha_1 = \cos\alpha_1$ , and so on.  $\alpha_1, \alpha_2$ , and  $\alpha_3$  are three Euler angles defined according to the  $x - y - z$  convention. Thus, the vector  ${}^B b_i$  would be expressed in the fixed frame  $\{A\}$  as

$$b_i = {}^A_B R P B_i)_B \quad (2)$$

Let  $p$  and  $r_i$  denote the position vectors for  $P$  and  $B_i$  in the reference frame  $\{A\}$ , respectively. From the geometry,

$$r_i = p + b_i \quad (3)$$

Subtracting vector  $a_i$  from both sides of (3) one obtains

5

$$r_i - a_i = p + b_i - a_i \quad (4)$$

Left hand side of (4) is the definition of  $d_i$ , therefore

$$d_i^2 = (p + b_i - a_i) \cdot (p + b_i - a_i) \quad (5)$$

10 Using Euclidean norm  $d_i$  can be expressed as

$$d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \quad (6)$$

in which

$$15 \quad \begin{cases} x_i = -h(\cos \gamma_i r_{11} + \sin \gamma_i r_{21}) + g \cos \gamma_i \\ y_i = -h(\cos \gamma_i r_{12} + \sin \gamma_i r_{22}) + g \sin \gamma_i \\ z_i = -h(\cos \gamma_i r_{13} + \sin \gamma_i r_{23}) \end{cases} \quad (7)$$

Coordinates  $C_i(A_i, x_i, y_i, z_i)$  are connected to the base platform with their  $x_i$  axes aligned with the rotary actuators in the  $s_i$  directions, with their  $z_i$  axes perpendicular to the fixed platform. Thus, one can express vector  $d_i$  in  $\{C_i\}$  as

$$20 \quad {}^{C_i}d_i = d_i \begin{bmatrix} \sin \psi_i \\ \sin \theta_i \cos \psi_i \\ \cos \theta_i \cos \psi_i \end{bmatrix} \quad (8)$$

From the geometry,

$$r_i = a_i + {}_{C_i}^A R {}^{C_i}d_i \quad (9)$$

where  ${}_{C_i}^A R$  is the rotation matrix from  $\{C_i\}$  to  $\{A\}$ ,

25

$${}_{C_i}^A R = \begin{bmatrix} \cos \gamma_i & -\sin \gamma_i & 0 \\ \sin \gamma_i & \cos \gamma_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (10)$$

By equating the right sides of (3) and (4), and solving the resultant equation,  $\psi_i$  and  $\theta_i$  can be calculated as follows:

$$5 \quad \psi_i = \sin^{-1} \left( \frac{\cos \gamma_i (x-x_i) + \sin \gamma_i (y-y_i)}{d_i} \right) \quad (11)$$

and

$$\theta_i = \sin^{-1} \left( \frac{\sin \gamma_i (x-x_i) - \cos \gamma_i (y-y_i)}{d_i \cos \psi_i} \right) \quad (12)$$

and

The kinematic performance of the system has been compared to a known Gough-  
10 Stewart platform in terms of reachability. Consider the two mechanisms with  $g = 1(\text{m})$  and  $h = 0.5(\text{m})$ , respectively; where  $g$  and  $h$  are the radii of the fixed and moving platforms, respectively. By assuming a cubic with  $1\text{m}$  length,  $1(\text{m})$  width and  $1(\text{m})$  height located  $0.25(\text{m})$  above the base platform, we are interested in determining the volume percentage in which the mechanism can successfully reach the locations within this cubic space.

15 As shown in FIG. 14, the reachable space in the Stewart platform is much smaller than that of the wide-open mechanism. This is due to the fact that, in the 6-legged Stewart-like UPS mechanisms, the workspace is constructed by intersection of six spheres. However, in the illustrated embodiments that have three leg structures, the workspace is constructed by intersection of only three spheres.

20 The performance of the robot was evaluated in an experimental study on a prototype of the illustrated embodiments. During the experiments, an optical stereoscopic vision system such as a system made by Claron Technology Inc., Ontario, Canada, was used as an external observer to track the robots end-effector, i.e., the center of the moving platform. In the illustrated system shown in FIG. 11, a 3D camera was used to detect a set of markers  
25 attached to the moving platform to find its position and orientation with respect to a fixed Cartesian coordinate system, defined using another set of markers attached to the frame.

In the experiments, at first, the workspace of an example of a robotic system was measured by running its actuators in different directions to the end of the moving range, and recording the end-effector position by the optical tracker. The results indicated a circular

truncated workspace, which was sufficiently large for fracture reduction maneuvers in spite of the fact that the spherical joints used in the prototype could rotate only up to  $\pm 25$  deg.

In the next stage, trajectory tracking experiments were performed to verify the robots kinematical model and assess the effects of the friction and backlash. As shown in FIG. 15  
5 in each test, a desired trajectory, e.g., an offset circle, was defined for the end-effector to be followed and the corresponding joint trajectory for each actuator was computed, using the inverse kinematics equations, to generate the position data of the actuators. The top figure illustrates a planar circular motion. The maximum error is  $\%8$  in two spots, due to an existing joint clearance. The bottom figure illustrates the vertical movements. The robot  
10 follows the prescribed path. The experiments revealed reasonably acceptable results. The example robot that was used in the experiments, according to some embodiments, was capable of moving the end-effector on a 100 (mm) radius circle co-centered with a virtual point with a maximum deviation from the reference trajectory of about 8 mm.

The above illustrated embodiments described in FIGs. 1-12 can be implemented in  
15 various configurations. For example, the system may implement the control functions by a processor installable on the robot, a processor of the robotic system or a processor on a cloud. FIG. 16 depicts an example of internal hardware that may be included in any of the electronic components of the system, such as the processing device, the robot, or the robotic system. An electrical bus **1500** serves as an information highway interconnecting the other  
20 illustrated components of the hardware. Processor **1505** is a central processing device of the system, configured to perform calculations and logic operations required to execute programming instructions. As used in this document and in the claims, the terms “processor” and “processing device” may refer to a single processor or any number of processors in a set of processors, whether a central processing unit (CPU) or a graphics  
25 processing unit (GPU) or a combination of the two. Read only memory (ROM) **1510**, random access memory (RAM) **1515**, flash memory, hard drives and other devices capable of storing electronic data constitute examples of memory devices **1525**. A memory device, also referred to as a computer-readable medium, may include a single device or a collection of devices across which data and/or instructions are stored.

30 An optional display interface **1530** may permit information from the bus **1500** to be displayed on a display device **1535** in visual, graphic or alphanumeric format. An audio interface and audio output (such as a speaker) also may be provided. Communication with

external devices may occur using various communication devices **1540** such as a transmitter and/or receiver, antenna, an RFID tag and/or short-range or near-field communication circuitry. A communication device **1540** may be attached to a communications network, such as the Internet, a local area network or a cellular telephone data network.

5           The hardware may also include a user interface sensor **1545** that allows for receipt of data from input devices **1550** such as a keyboard, a mouse, a joystick, a touchscreen display **1530**, a remote control, a pointing device, a video input device and/or an audio input device. Digital image frames also may be received from an imaging capturing device **1555** such as an x-ray scanner to capture one or more images of the bone fractures during the  
10 reduction procedure.

          Optionally, the hardware may not need to include a memory, but instead programming instructions are running on one or more virtual machines or one or more containers on a cloud. For example, the processing device may be a server on a cloud that includes multiple virtual machines, each virtual machine having an OS, a virtual disk, virtual  
15 network and Apps, and the programming instructions for implementing various functions in the print system may be stored on one or more of those virtual machines on the cloud.

          Reduction is a crucial step in the surgical treatment of bone fractures to achieve anatomical alignment and facilitate healing. The illustrated embodiments provide a 6-degree-of-freedom wide-open parallel mechanism for computer assisted fracture reduction  
20 of long bones, and are advantageous over known Gough-Stewart platform. As a result, a larger workspace is achieved, sufficient for surgical maneuvers. The system could provide the fine adjustments easily as its force capacity was sufficiently higher than the counteracting forces and torques produced by rubber bands.

          The moving frame of the system is lighter than the conventional counterpart as the  
25 rotary actuators are resting on the fixed platform, which allows for higher accelerations to be available due to the smaller inertial effects. Further, the legs of the mechanism are configured non-symmetrically on semicircles on the base and moving platforms, enabling the mechanism to embrace and manipulate column-shape objects such as long bones easily.

          In some embodiments, the system may also be used clinically in order to improve  
30 the quality of fracture reduction with no need to repetitive manipulations, and reduce the amount of radiation exposure to the operating staff and patients. The initial configuration of the bone fragments can be found from the CT data and the desired target configuration

from the morphological features of the bone, as well as the geometry of the fracture ends. An optimal path from the initial to the desired target configuration would enable a closed reduction procedure with improved accuracy and less soft tissue damage.

In one preferred embodiment, methods of performing a long bone surgery are  
5 describe using a surgical robot that provides 6-degrees-of-freedom to empower the surgical team. In some embodiments, the method employs the robot that includes a fixed frame defining a first plane, wherein the fixed frame includes an open space formed in a center region thereof; a moving frame defining a second plane, wherein the moving frame includes an open space in a center region thereof; three leg structures connecting the fixed frame and  
10 the moving frame, and configured to move the moving frame relative to the fixed frame; and a stabilizer configured to hold an anatomical structure in the open space formed in the center region of each of the moving frame and the fixed frame.

In at least another embodiment, the method may include attaching a proximal fragment of a fractured bone to a fixed frame of a robot, attaching a distal fragment of the  
15 fractured bone to a moving frame of the robot, moving the moving frame of the robot to stretch or align the distal fragment so that the distal fragment is positioned to the proximal fragment to maximize recovery time. The method may also include rotating the moving frame to cause the distal fragment subject to varus-valgus rotations so that a shaft of the distal fragment lies parallel to a shaft of the proximal fragment.

The presently described surgical methodologies may include treating complex  
20 fractures by translating the moving frame in a plane transverse to an axis of the proximal fragment to enable the axis of the distal fragment to align with an axis of the proximal fragment, and moving the moving frame to shorten the distal fragment to obtain a target pose for a fracture end of the distal fragment to align with an opposing fracture end of the  
25 proximal fragment.

In some embodiments, the steps of moving, rotating, translating and moving the moving frame may include using an ultrasonic or x-ray image capturing device to capture in real-time one or more, 2D or 3D images during the surgery, wherein the one or more captured images include the fracture end of the distal fragment and the opposing fracture  
30 end of the proximal fragment.

The various illustrated embodiments facilitate increased surgical workspace, while allowing precise alignment of fractured bones. Above-disclosed features and functions, as

well as alternatives, may be combined into many other different systems or applications. Various components may be implemented in hardware or software or embedded software. Various presently unforeseen or unanticipated alternatives, modifications, variations or improvements may be made by those skilled in the art, each of which is also intended to be  
5 encompassed by the disclosed embodiments.

## CLAIMS

1. A surgical robot comprising:
  - a fixed frame defining a first plane, wherein the fixed frame includes an open space formed in a center region thereof;
  - 5 a moving frame defining a second plane, wherein the moving frame includes an open space formed in a center region thereof;
  - three leg structures connecting the fixed frame and the moving frame, and configured to move the moving frame relative to the fixed frame; and
  - a stabilizer configured to hold an anatomical structure in the open space formed in  
10 the center region of each of the moving frame and the fixed frame.
2. The robot of claim 1, wherein the stabilizer comprises:
  - at least one rod attached at varying locations along the fixed frame and extending from the fixed frame towards the open space formed in the center region thereof, wherein the at least one rod is configured to be positioned to hold a first fragment of the anatomical  
15 structure in place relative to the fixed frame; and
  - at least one rod attached at varying locations along the moving frame and extending from the moving frame towards the open space formed in the center region thereof, wherein the at least one rod is configured to be positioned to hold a second fragment of the anatomical structure in place relative to the moving frame.
- 20 3. The robot of claim 1, wherein each of the moving frame and the fixed frame are formed as a partially annular ring having an opening therein.
4. The robot of claim 1, wherein each of the three leg structures comprises a linear component that facilitates a sliding component to travel in a linear motion longitudinally along the leg structure, wherein the sliding component is coupled to the moving frame at a  
25 mounting location.
5. The robot of claim 4, wherein the linear component of each leg structure is configured to be coupled to a first actuator to move the sliding component longitudinally along the leg structure.
6. The robot of claim 5, wherein the first actuator of each leg structure is a rotary  
30 actuator, and each leg structure further comprises a screw shaft configured to be coupled to the first actuator and to transfer rotational motion from the first actuator to the linear motion of the sliding component.

7. The robot of claim 4, wherein each leg structure further comprises:  
a rotary component mounted to the fixed frame at a mounting location; and  
a connector connecting the linear component to the rotary component.
- 5 8. The robot of claim 7, wherein the connector is of a U-shape.
9. The robot of claim 7, wherein the rotary component comprises a shaft couplable to  
a shaft of a second rotary actuator and configured to transfer rotation of the second rotary  
actuator to the connector.
10. The robot of claim 9, wherein the rotary component further comprises a shaft  
10 connector positioned to be coupled to the shaft of the rotary component and also to  
pivotally connect to the connector of each leg structure.
11. The robot of claim 10, wherein the rotary component further comprises a key  
positioned to lock the shaft connector to the shaft of the rotary component.
12. The robot of claim 7, wherein:  
15 the mounting locations at which the sliding components for the three leg structures  
are coupled to the moving frame are equally spaced; and  
the mounting locations at which the rotary component for the three leg structures  
are mounted to the fixed frame are also equally spaced.
13. The robot of claim 7, wherein:  
20 each of the moving frame and the fixed frame are formed as a partially annular ring  
having an opening therein;  
the mounting location at which the sliding component for a middle leg structure of  
the three leg structures is coupled to the moving frame is adjustable along the partially  
annular ring of the moving frame; and  
25 the mounting location at which the rotary component for a middle leg structure of  
the three leg structures is mounted to the fixed frame is adjustable along the partially  
annular ring of the fixed frame.
14. The robot of claim 7, wherein the fixed frame comprises an extended plate at each  
mounting location, wherein each extended plate is configured to enable a rotary  
30 component to be mounted thereon, and further wherein each extended plate lies in the first  
plane.

15. The robot of claim 1, wherein the fixed frame is movably mounted to a stand that is configured to support the robot.

16. The robot of claim 15, wherein the robot further comprises an attachment device configured for attaching an image capturing device to the robot, wherein the image  
5 capturing device is capable of being positioned to capture one or more images in real-time during a surgery.

17. The robot of claim 16, wherein the image capturing device is selected from a group consisting of an ultrasound device and an x-ray scanner or a combination thereof.

18. The robot of claim 9, wherein the first and second rotary actuators for each leg  
10 structure is configured to rotate using a servo or stepper motor.

19. The robot of claim 1, further comprising:

a first additional element attachable to the fixed frame to close the opening of the fixed frame;

a second additional element attachable to the moving frame to close the opening of  
15 the moving frame; and

an additional leg structure comprising:

a linear component that is couplable to a first actuator to facilitate a sliding  
component to travel in a linear motion longitudinally along the additional leg  
structure, wherein the sliding component is mounted to the second additional  
20 element at a mounting location,

a screw shaft configured to be coupled to the first actuator and to transfer  
rotation of the first actuator to the linear motion of the sliding component,

a rotary component mounted to the first additional element, and

a connector connecting the linear component to the rotary component;

25 wherein the rotary component is a rotary gear box comprising:

a shaft couplable to a shaft of a second rotary actuator and configured to  
transfer rotation of the second rotary actuator to the connector, and

a shaft connector positioned to be coupled to the shaft of the rotary  
component and also pivotally connect to the connector of the additional leg  
30 structure.

20. The robot of claim 1, wherein the rotary component is a rotary gear box.

21. A robotic system for use in reduction procedure of long bone fractures or pelvic surgeries, comprising:

a robot according to claim 9;

a processing device in communication with the first and second rotary actuators of  
5 each leg structure; and

a non-transitory computer-readable storage medium containing programming instructions configured to cause the processing device to control each of the first and second actuators during the procedure.

22. The robotic system of claim 21, wherein:

10 each of the moving frame and the fixed frame are formed as a partially annular ring having an opening therein; and

the opening of the moving frame and the opening of the fixed frame are positionable around the long bone to reach a position for the procedure.

23. The robotic system of claim 21, wherein the fixed frame is movably mounted to a  
15 stand that is configured to support the robot and enable the robot to move freely to the position for the procedure.

24. The robotic system of claim 21, further comprising an image capturing device positioned to capture one or more images of the long bone fracture or pelvis in real-time during the procedure.

20 25. The robotic system of claim 24, wherein the image capturing device is selected from the group consisting of an ultrasound device, an x-ray scanner or a combination thereof.

26. A method for controlling a robot for use in a reduction procedure of a long bone fracture, comprising the steps of:

25 attaching a proximal fragment of a fractured bone to a fixed frame of a robot;  
attaching a distal fragment of the fractured bone to a moving frame of the robot;  
by a processing device, moving the moving frame of the robot to a desired  
position;

30 by the processing device, rotating the moving frame to allow parallel alignment to a shaft of the proximal fragment;

by the processing device, translating the moving frame in a plane transverse to an axis of the proximal fragment to enable the axis of the distal fragment to align with an axis of the proximal fragment; and

5 by the processing device, moving the moving frame to a target pose for a fracture end of the distal fragment to align with an opposing fracture end of the proximal fragment.

27. The method of claim 26, wherein the steps of moving, rotating, translating and moving the moving frame comprise receiving a position instruction from a user.

28. The method of claim 27, wherein receiving the position instruction comprises receiving, via a processing device, a user command via a graphical user interface.

10 29. The method of claim 27, further comprising:

receiving, using a processing device, the position instruction;

generating, using the processing device, one or more control parameters for one or more actuators of the robot based on the received position instruction;

15 transmitting, using the processing device, control signals representing the one or more parameters to the one or more actuators.

30. The method of claim 27, wherein the position instruction comprises one or more of a x position, a y position, a z position, an alpha, a beta, a gamma, a delta  $T_m$ , a time interval, a step ratio, a delta Rot, and a sample time.

20 31. The method of claim 26, further comprising using an image capturing device configured to capture in real-time one or more images during the reduction procedure, wherein the one or more captured images include the fracture end of the distal fragment and the opposing fracture end of the proximal fragment.

32. The method of claim 26, wherein the moving frame moves in 6 degree of freedom in relation to the fixed frame.

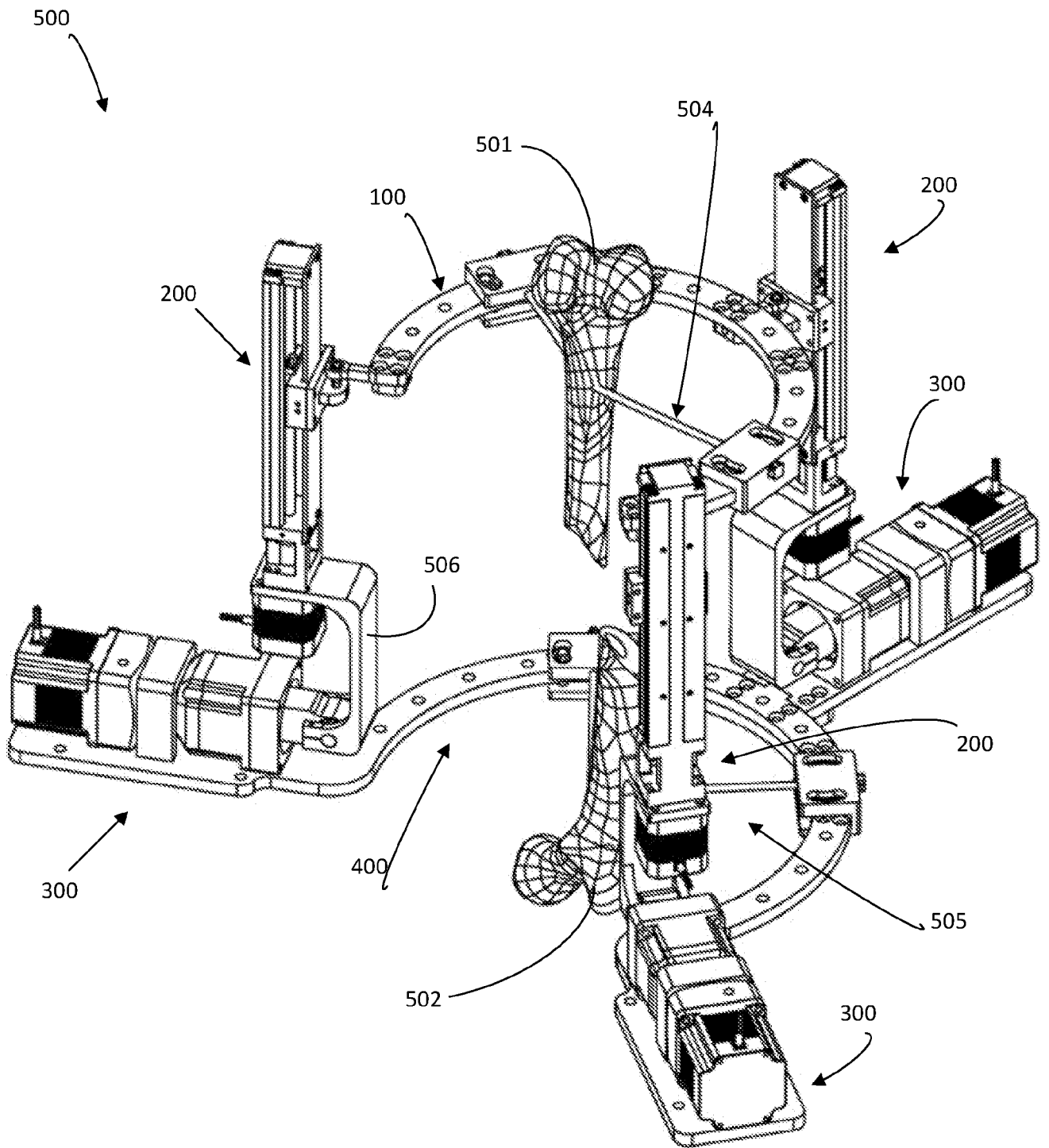


FIG. 1

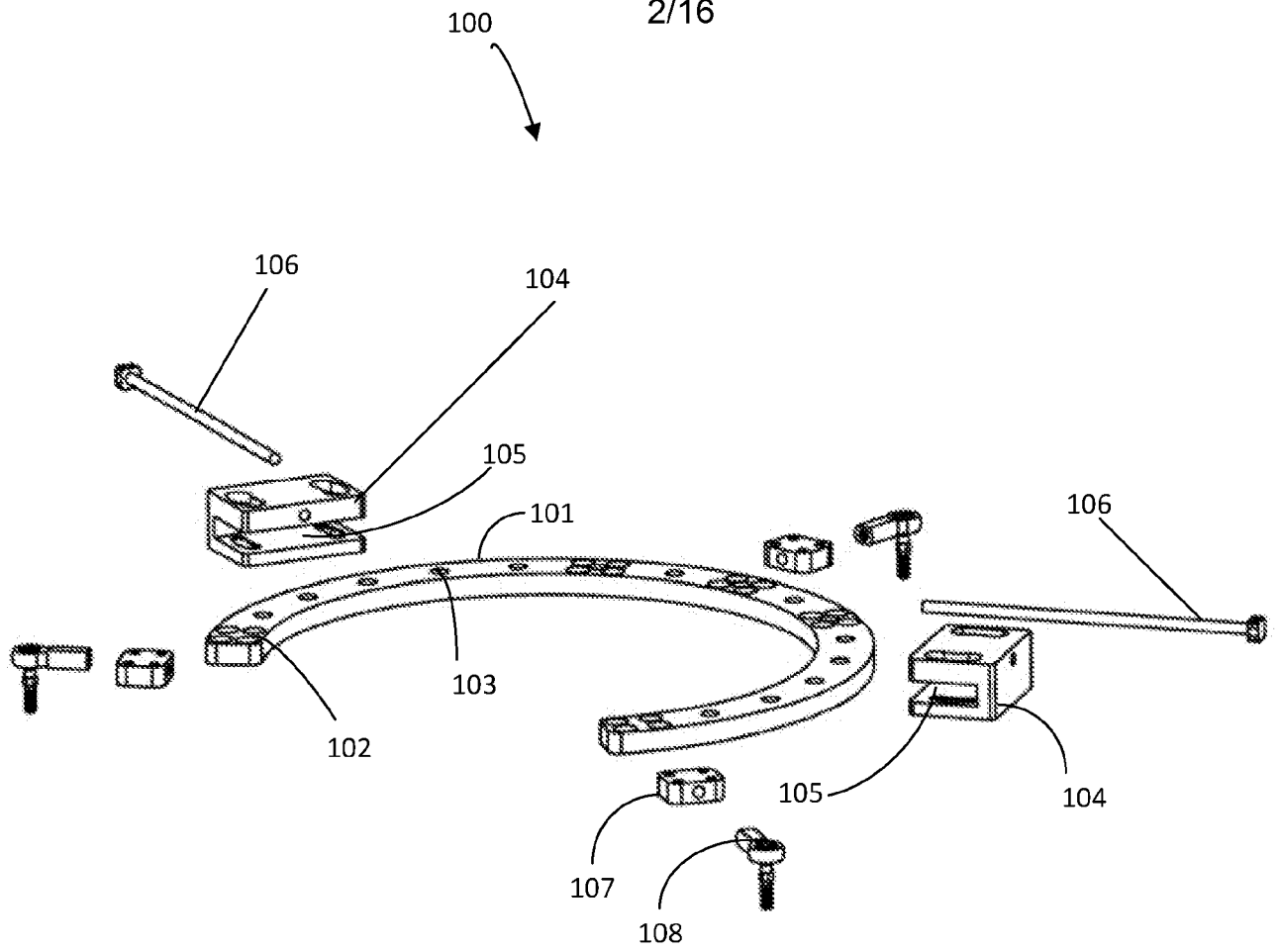


FIG. 2A

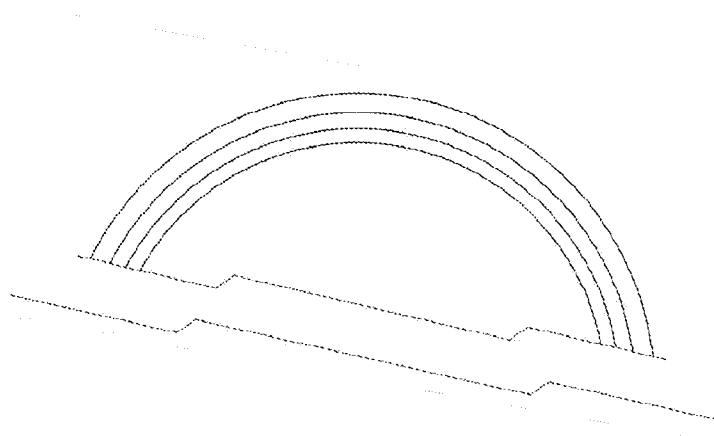


FIG. 2B

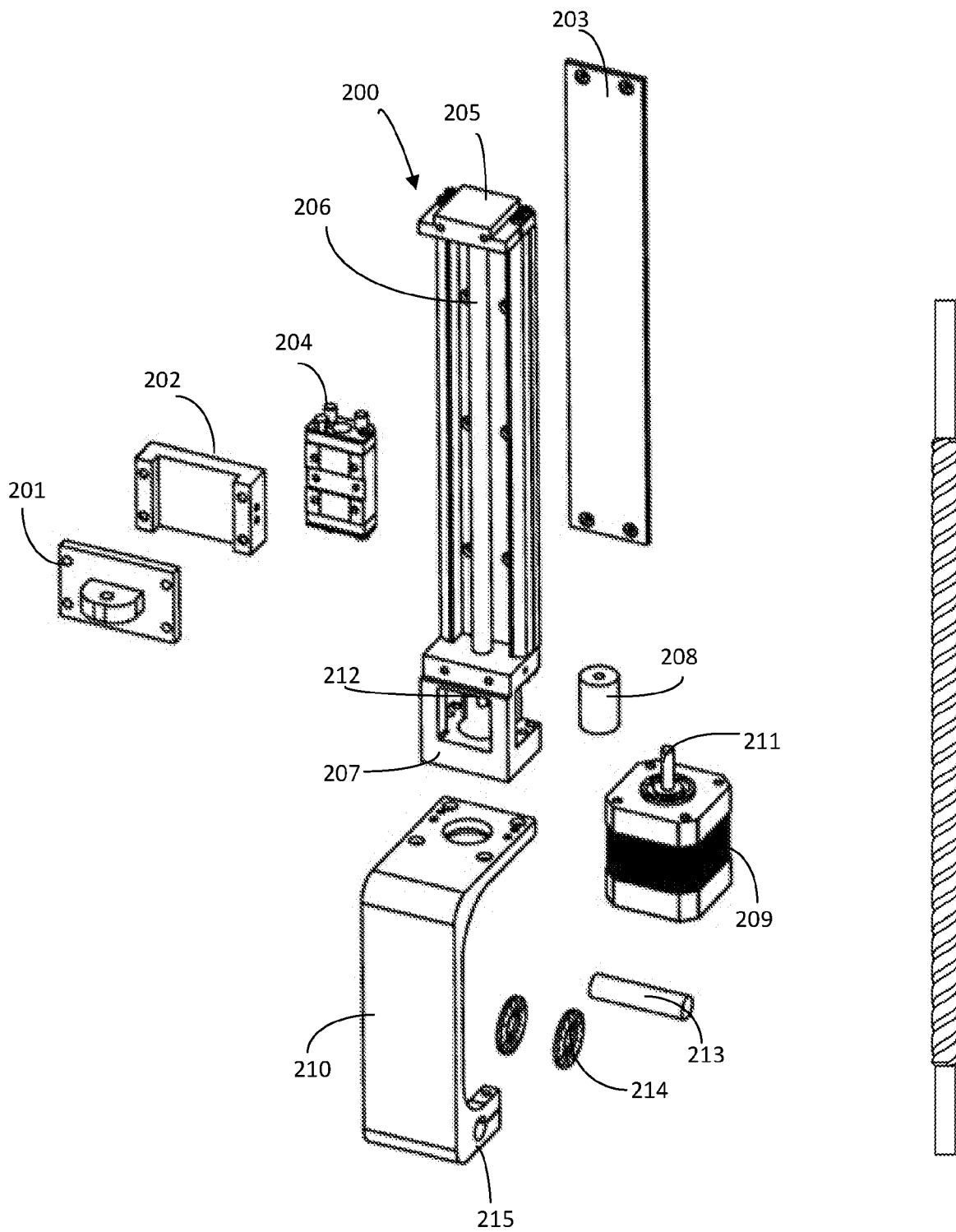


FIG. 3A

FIG. 3B

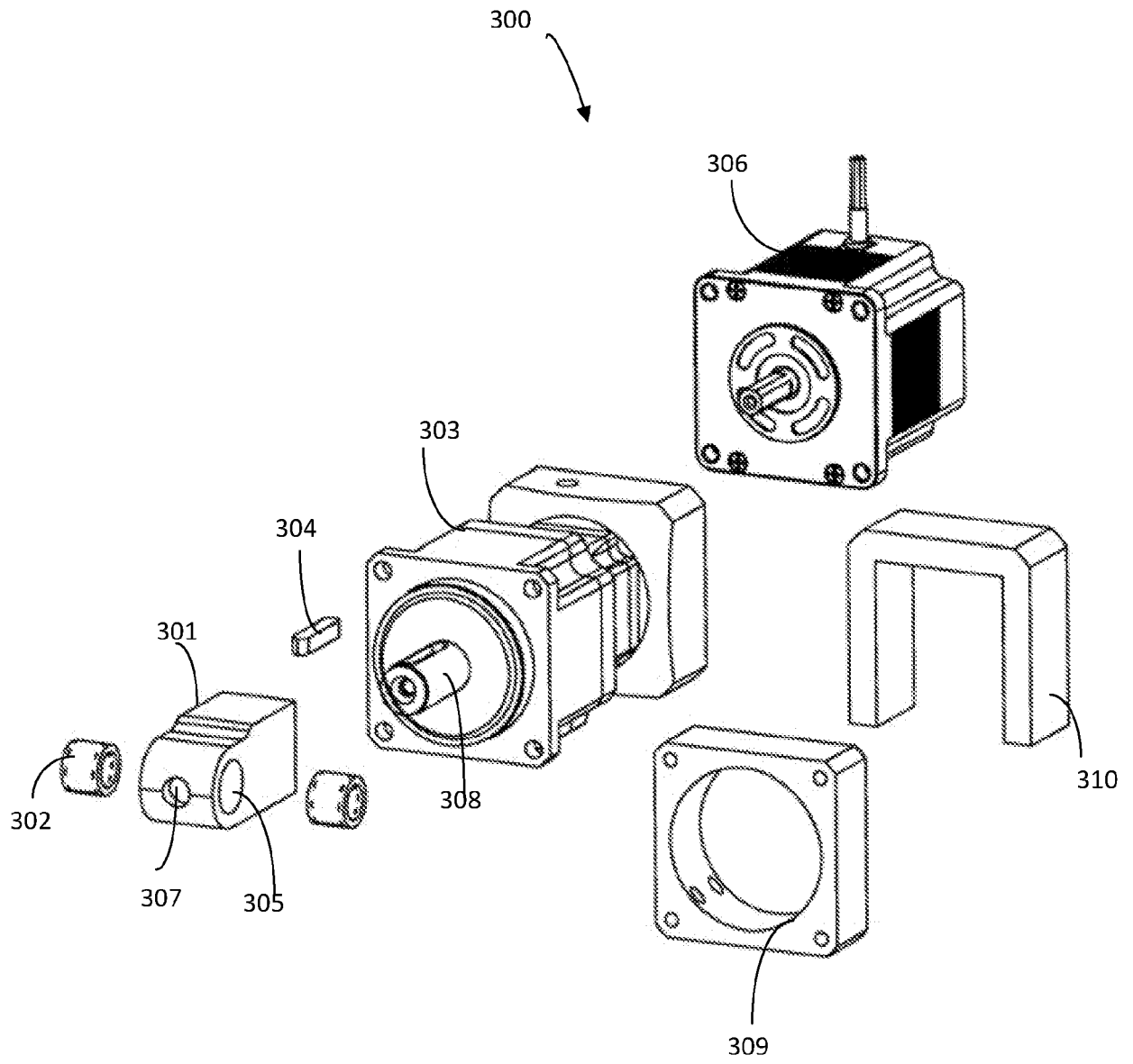


FIG. 4

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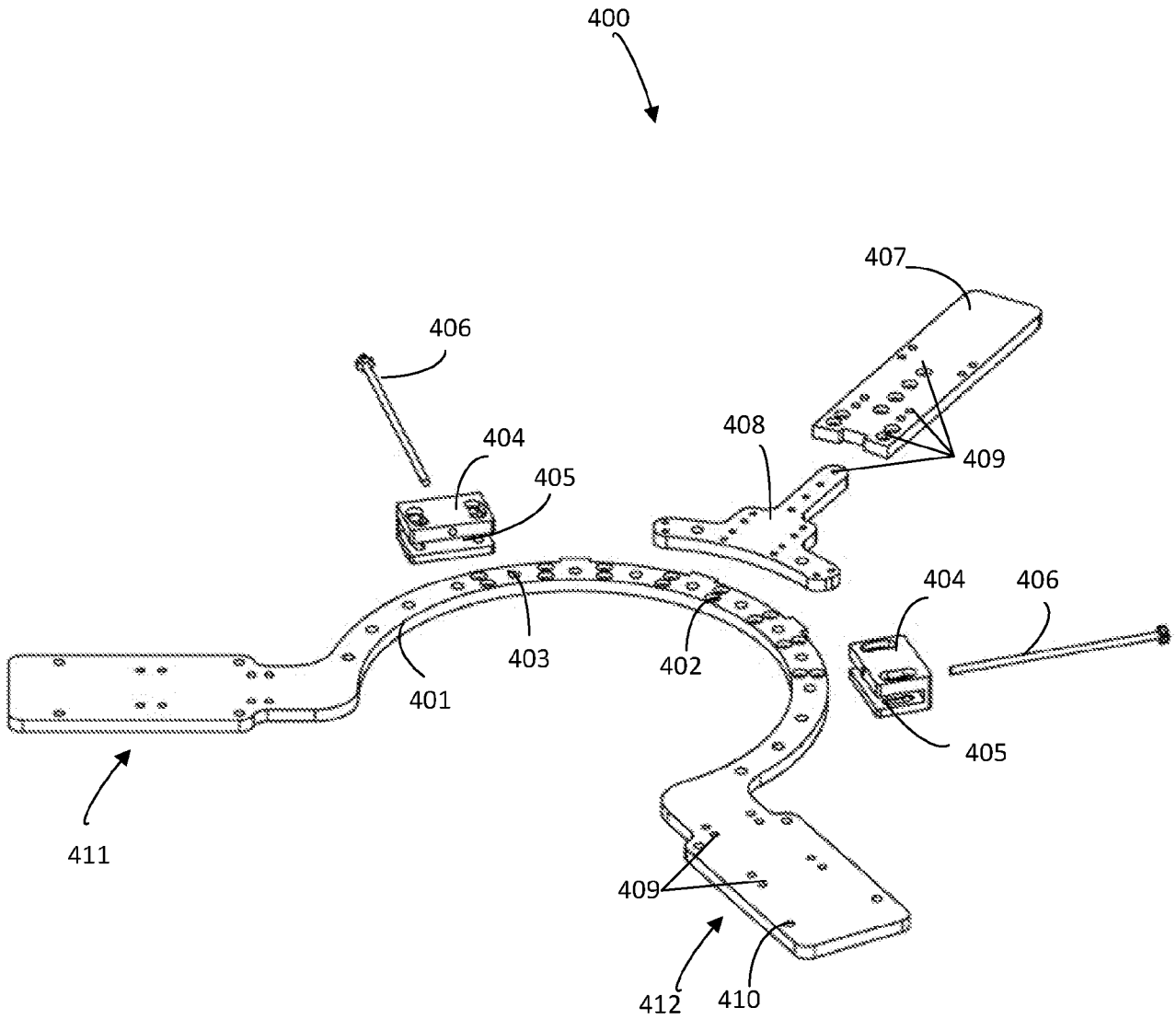


FIG. 5

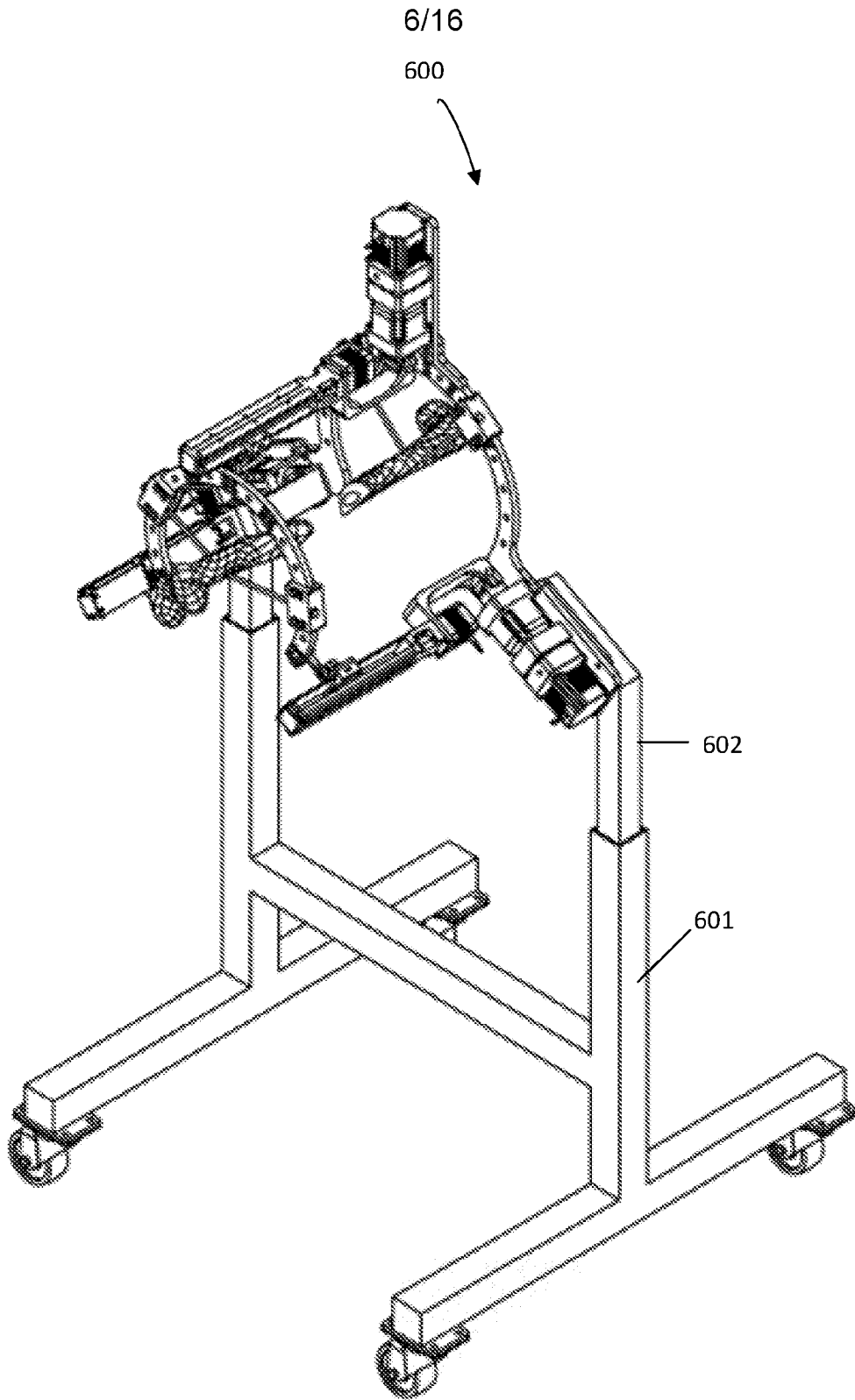


FIG. 6

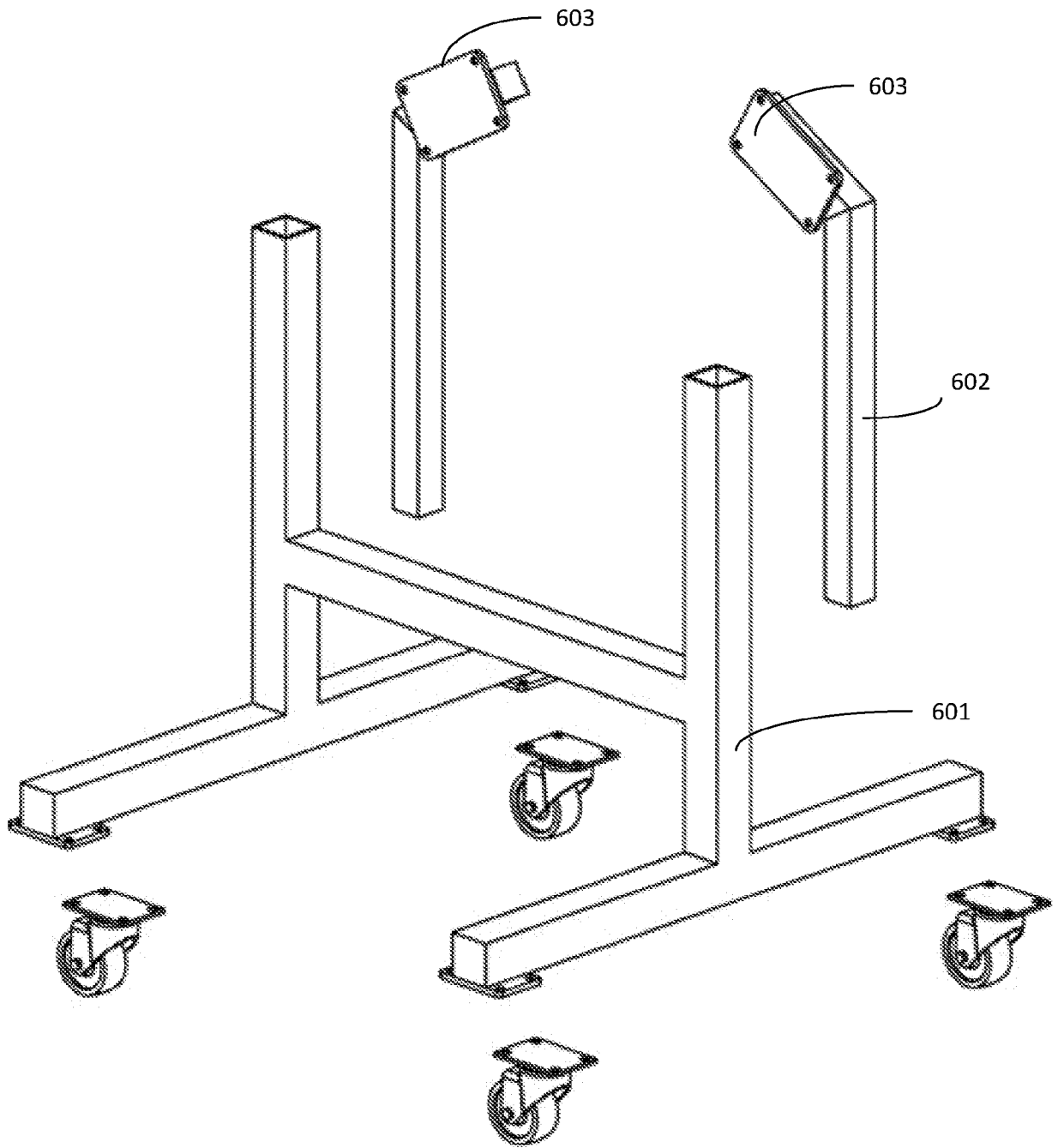


FIG. 7

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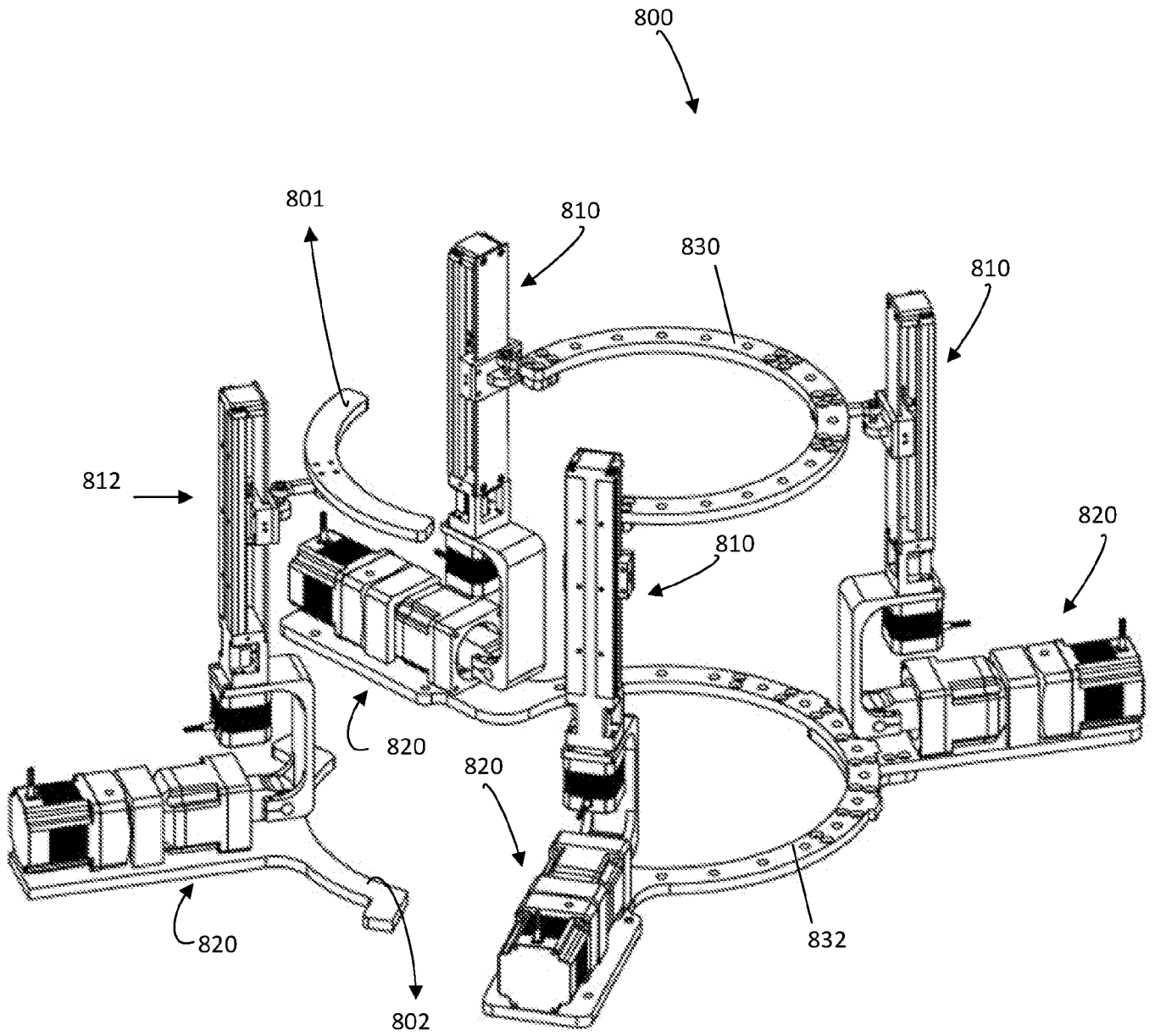


FIG. 8

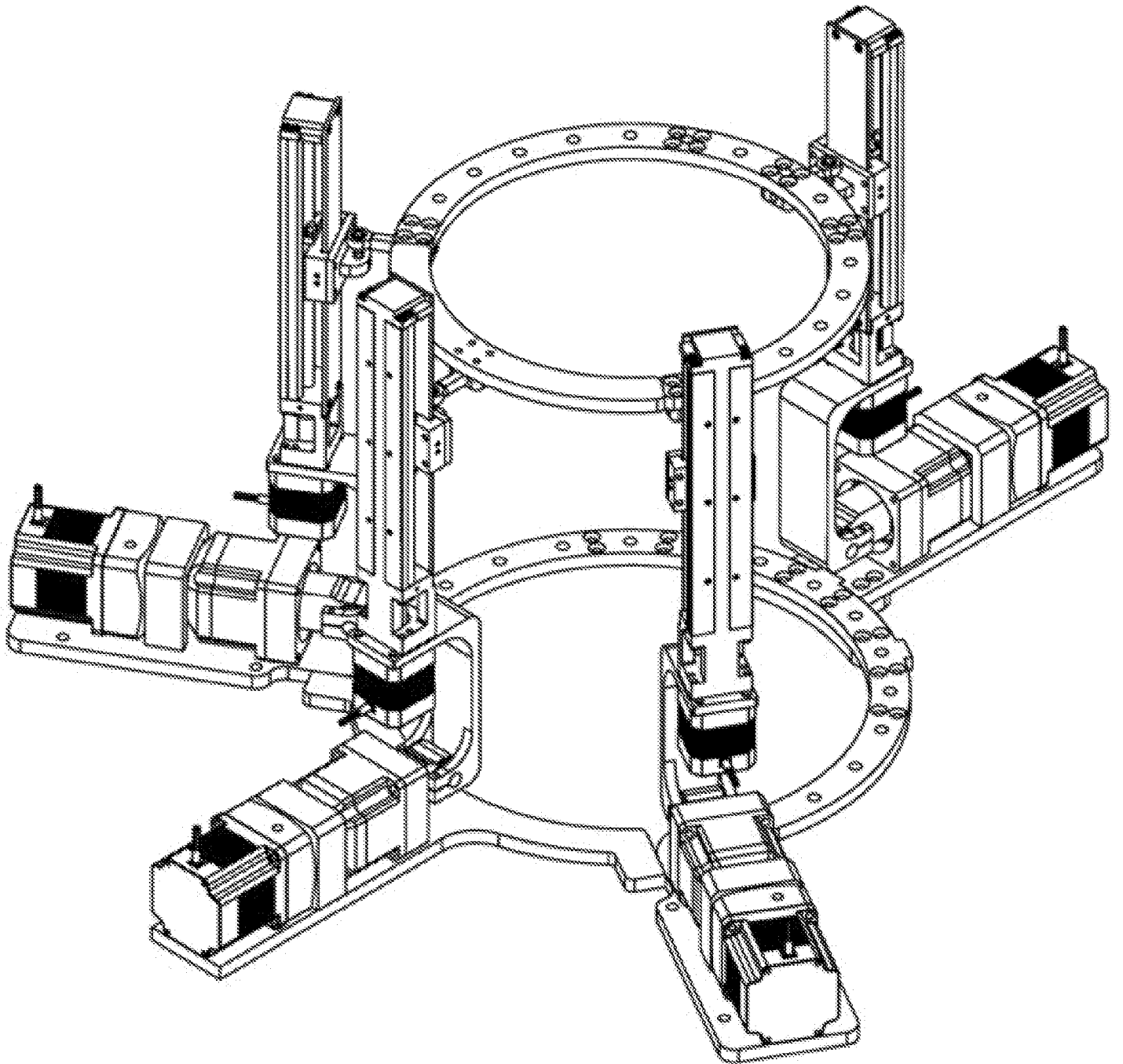


FIG. 9

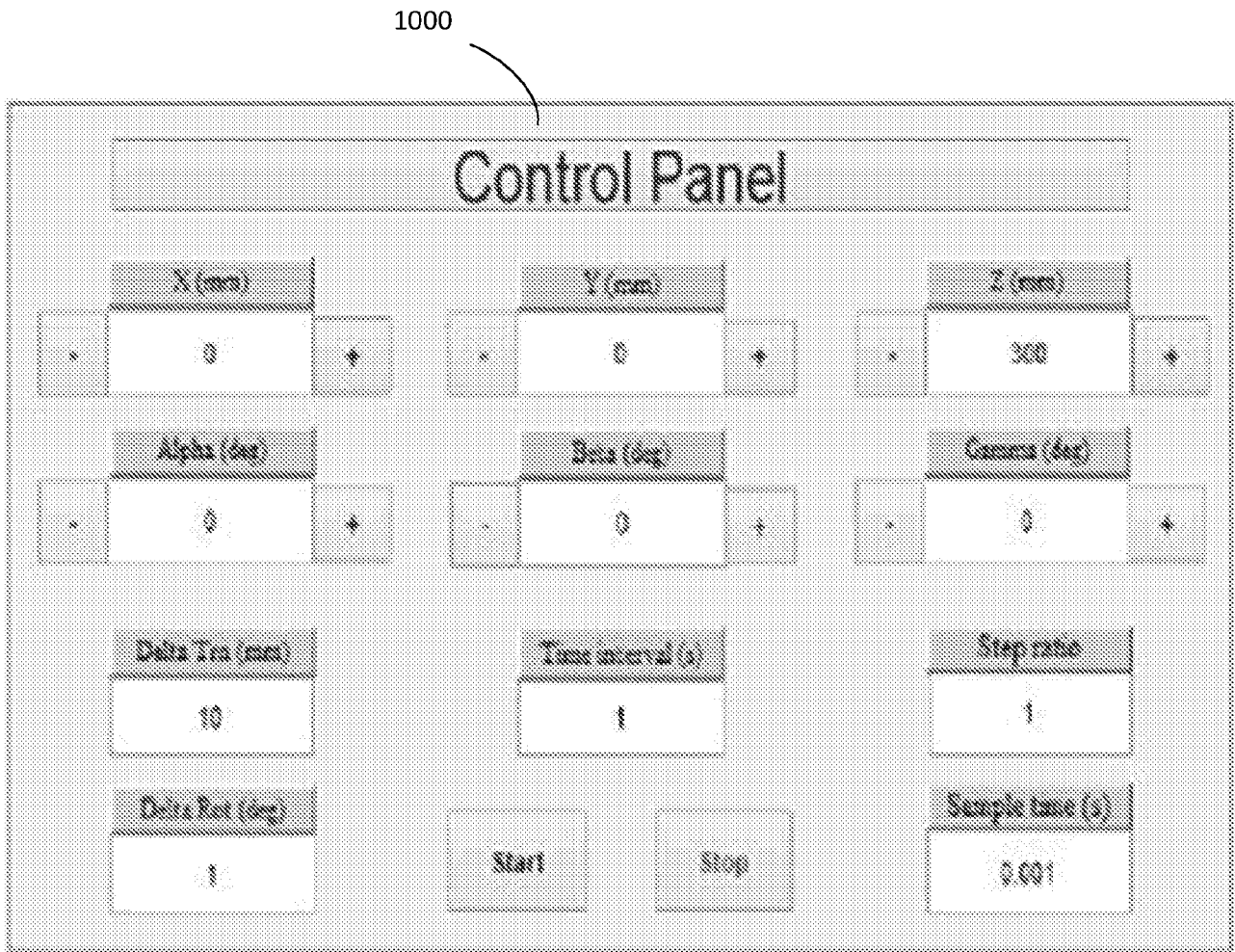


FIG. 10

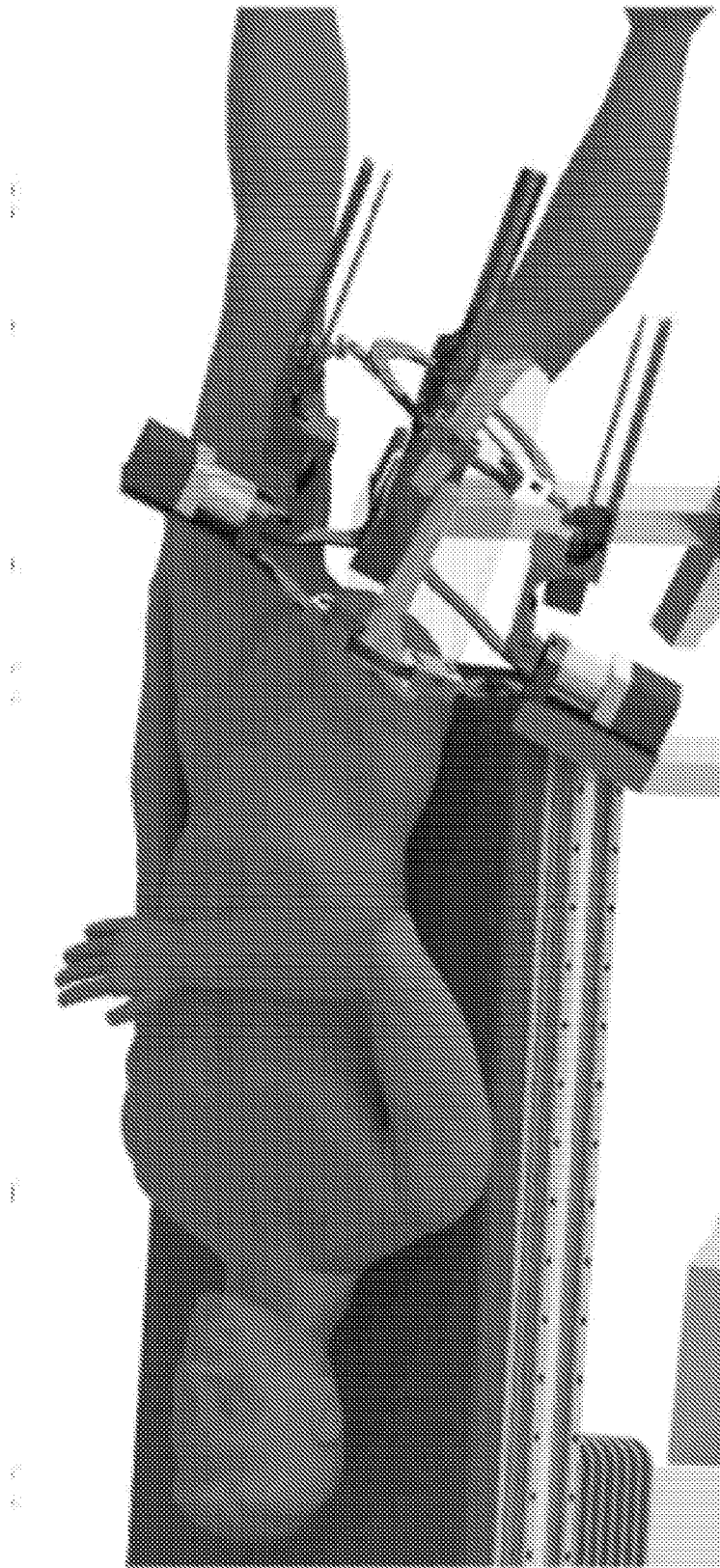


FIG. 11

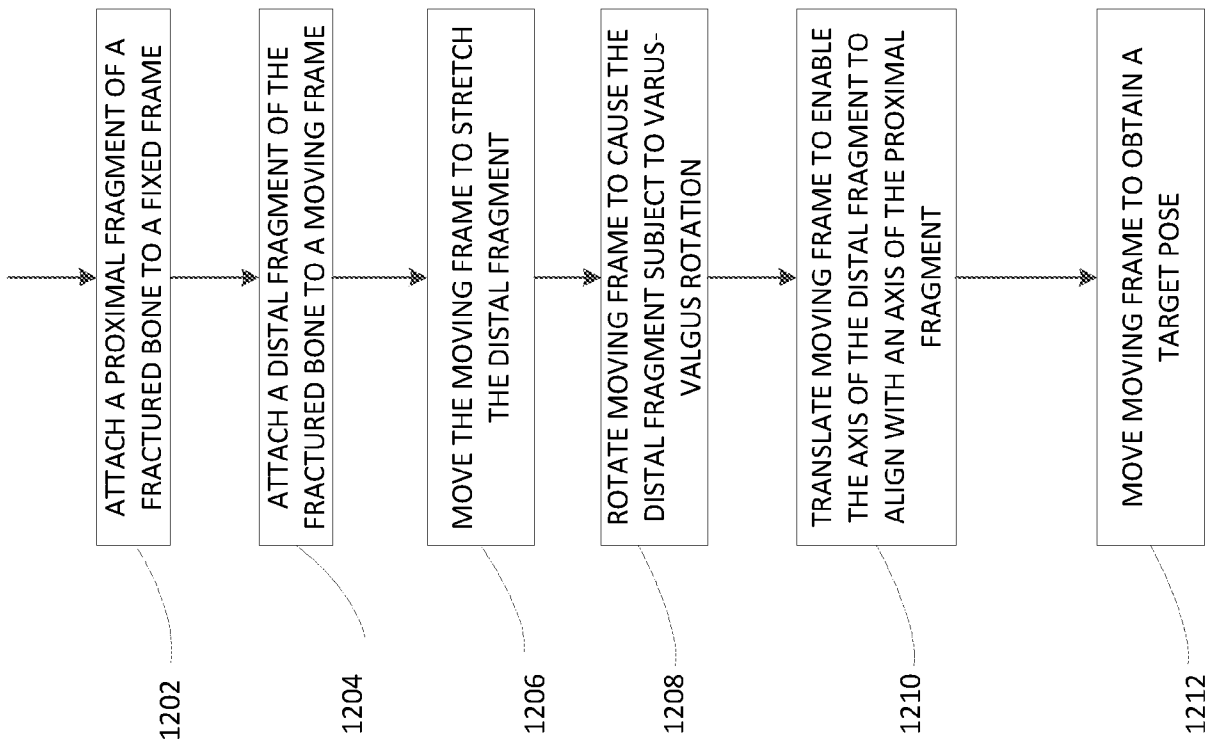


FIG. 12

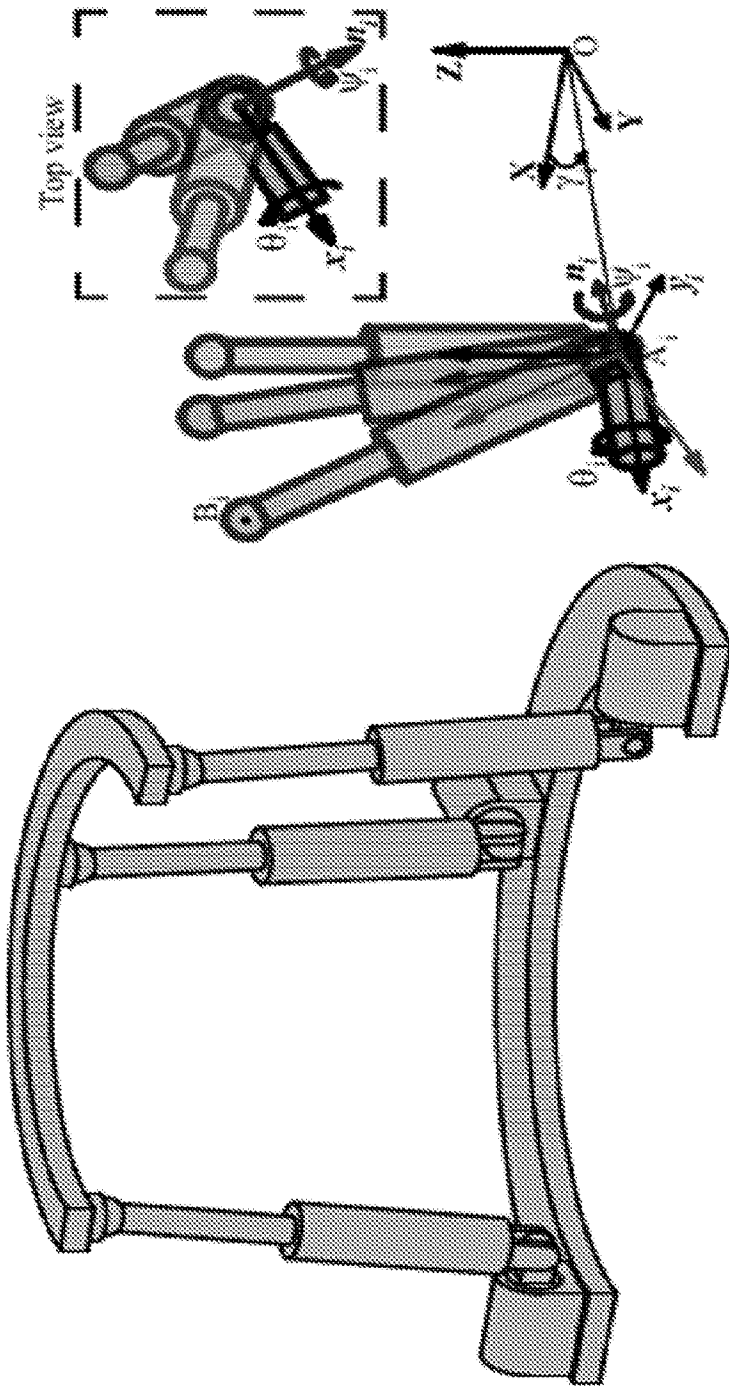


FIG. 13

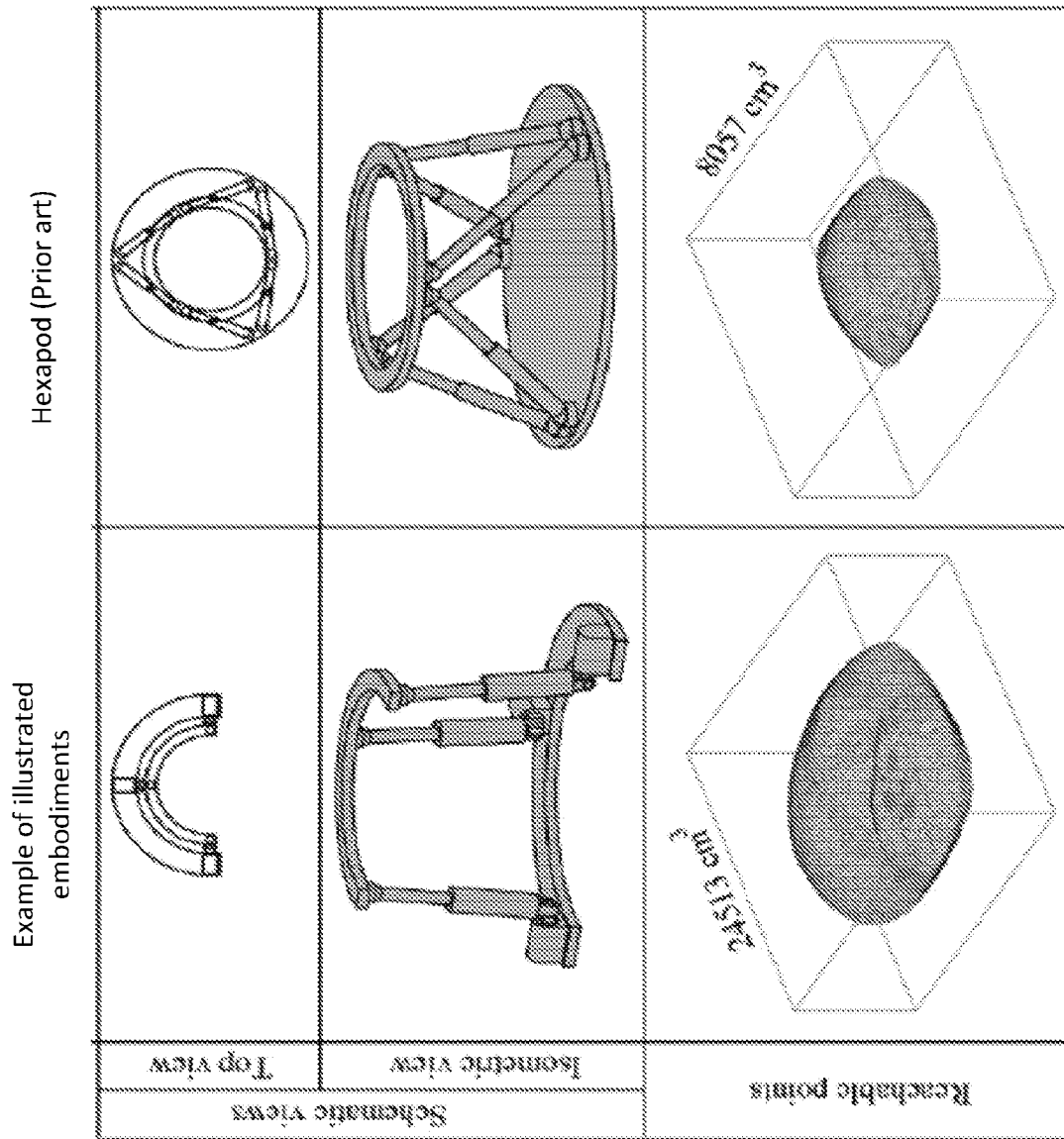


FIG. 14

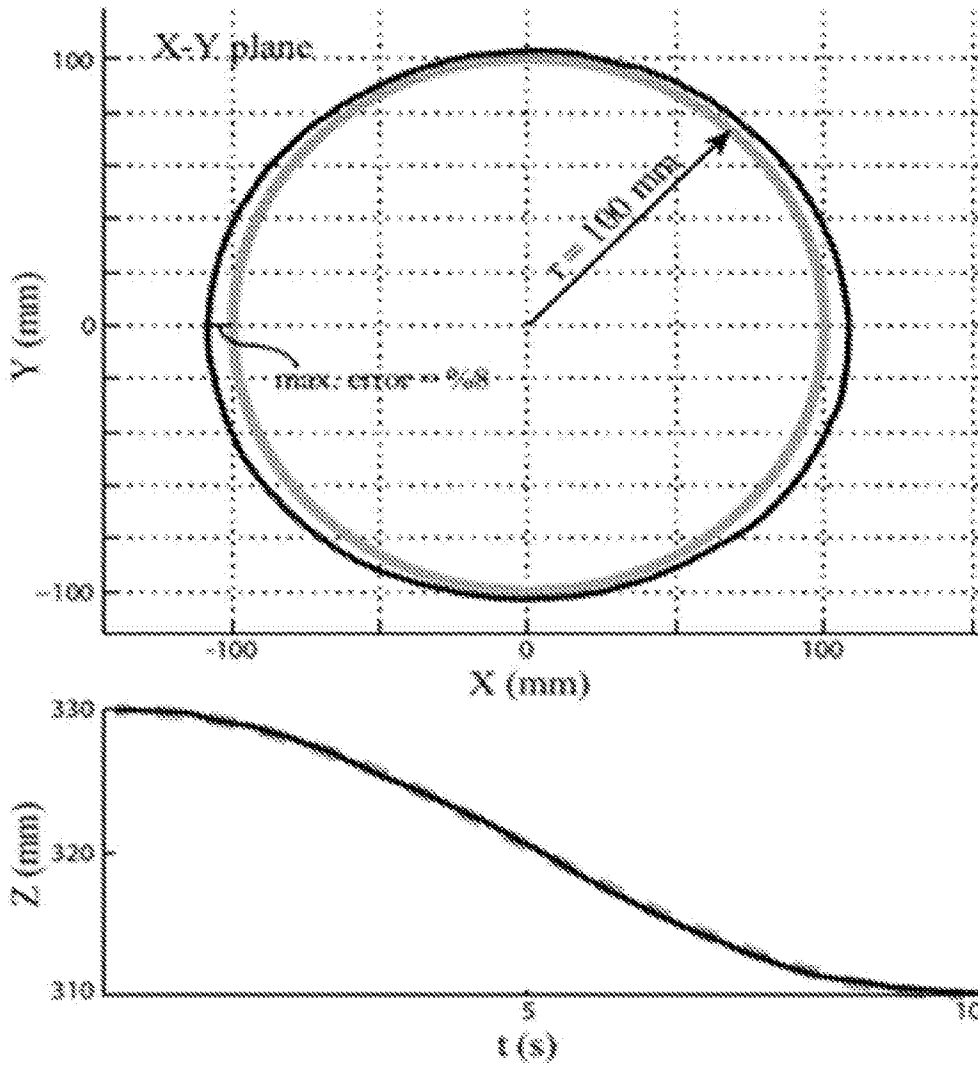


FIG. 15

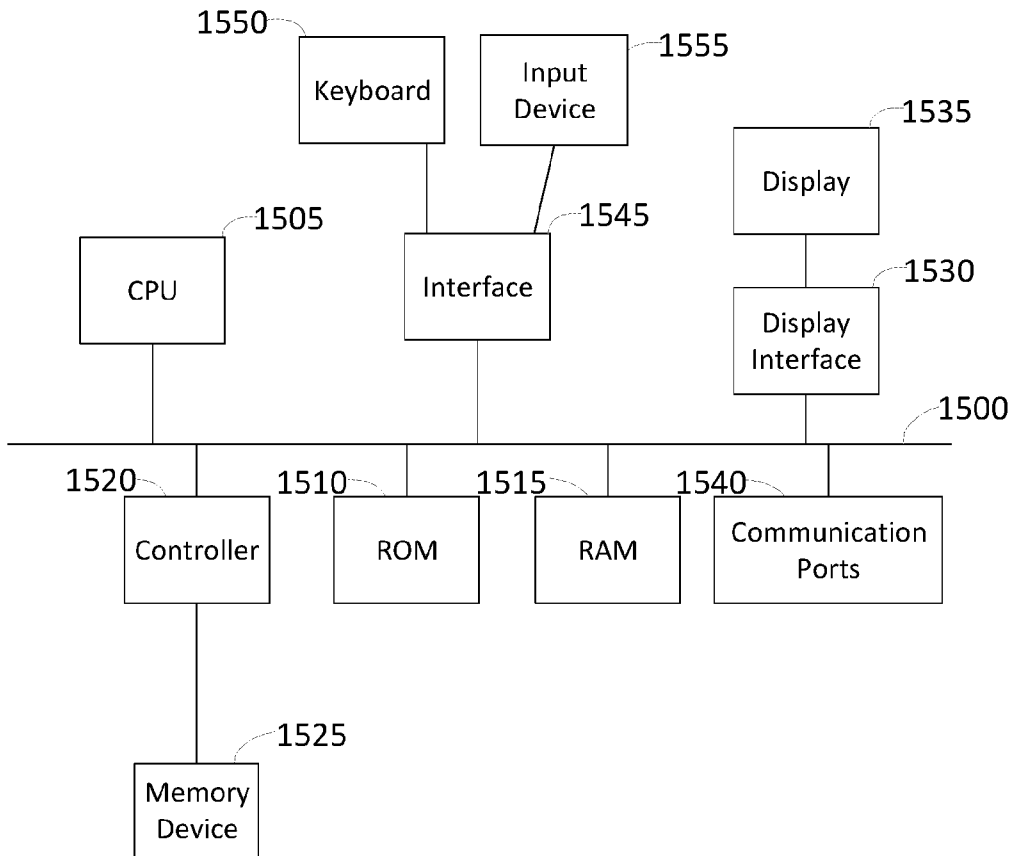


FIG. 16

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/018393

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61B 34/30; A61B 8/00; A61B 8/44; A61B 17/60; A61B 17/62; A61B 17/64; A61B 34/70(2017.01)  
 CPC - A61B 2034/304; A61B 8/4416; A61B 8/4427; A61B 17/6408; A61B 17/6433; A61B 17/645  
 (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 - 128/916; 602/39; 602/40; 606/56 (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.
X	US 8,333,766 B2 (EDELHAUSER et al) 18 December 2012 (18.12.2012) entire document	1-3
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Y		4, 5, 7, 8, 12, 13, 15, 20
Y	WO 2014/201340 A1 (THE BOARD OF TRUSTEES OF THE UNIVERSITY OF ILLINOIS) 18 December 2014 (18.12.2014) entire document	4, 5, 7, 8, 12, 13, 15, 20
A	US 2010/0087819 A1 (MULLANEY) 08 April 2010 (08.04.2010) entire document	1-25
A	US 6,368,330 B1 (HYNES et al) 09 April 2002 (09.04.2002) entire document	1-25
A	US 2015/0112340 A1 (TAMIS OTOGAZ SANAYI TICARET VE MUHENDISLIK HIZMETLERI ITHALAT INHRACAT LIMITED SIRKETI) 23 April 2015 (23.04.2015) entire document	1-25

 Further documents are listed in the continuation of Box C.

 See patent family annex.

\* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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

"&amp;" document member of the same patent family

Date of the actual completion of the international search

21 May 2017

Date of mailing of the international search report

17 JUL 2017

Name and mailing address of the ISA/US

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 Facsimile No. 571-273-8300

Authorized officer

Blaine R. Copenheaver

PCT Helpdesk: 571-272-4300  
 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/018393

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1.  Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2.  Claims Nos.:  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
  
3.  Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:  
See extra sheet(s).

1.  As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2.  As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3.  As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4.  No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:  
1-25

**Remark on Protest**

- The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/018393

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees need to be paid.

Group I, claims 1-25 are drawn to a surgical robot.

Group II, claims 26-32 are drawn to a method for controlling a robot.

The inventions listed in Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1, because under PCT Rule 13.2 they lack the same or corresponding special technical features for the following reasons:

The special technical features of Group I, a surgical robot comprising a fixed frame defining a first plane, wherein the fixed frame includes an open space formed in a center region thereof, a moving frame defining a second plane, wherein the moving frame includes an open space formed in a center region thereof, three leg structures connecting the fixed frame and the moving frame, and a stabilizer configured to hold an anatomical structure in the open space formed in the center region of each of the moving frame and the fixed frame, are not present in Group II; and, the special technical features of Group II, a method for controlling a robot for use in a reduction procedure of a long bone fracture, comprising the steps of attaching a proximal fragment of a fractured bone to a fixed frame of a robot attaching a distal fragment of the fractured bone to a moving frame of the robot, by the processing device, rotating the moving frame to allow parallel alignment to a shaft of the proximal fragment, by the processing device, translating the moving frame in a plane transverse to an axis of the proximal fragment to enable the axis of the distal fragment to align with an axis of the proximal fragment, and by the processing device, moving the moving frame to a target pose for a fracture end of the distal fragment to align with an opposing fracture end of the proximal fragment, are not present in Group I.

Groups I and II share the technical features of a surgical robot comprising a fixed frame, a moving frame, and moving the the moving frame in a plane.

However, these shared technical features do not represent a contribution over the prior art. Specifically, US 2015/0112340 A1 to Tamis Otogaz Sanayi Ticaret Ve Muhendislik Hizmetleri Ithalat Inhracat Limited Sirketi teaches of a surgical robot (fixation robot 20, Fig. 2; Abstract regarding a fixation robot enables alignment of fractured bones in orthopaedic operations) comprising a fixed frame (fixed retainer jaw 31, Fig. 2), a moving frame (moving retainer jaw 30, Fig. 2), and moving the the moving frame in a plane (Para. [0053] regarding moving the retainer jaw (30) is provided on the carrying body (21) and it is capable of multi-axial movement. For example, linear movement in y-plane is provided by the Y-plane advancer (23)).

Since none of the special technical features of the Groups I-II inventions are found in more than one of the inventions, unity is lacking.