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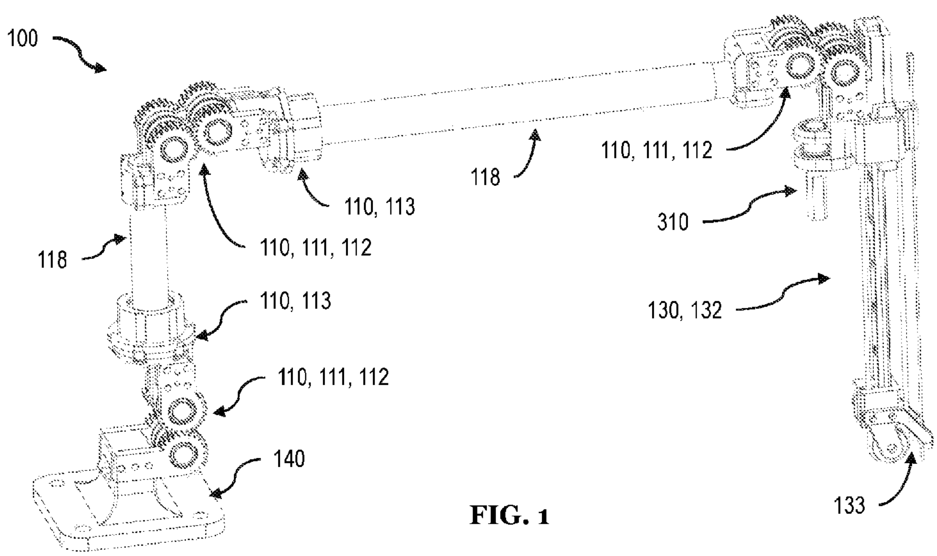

FIG. 1

(57) Abstract: A system for a multi-axis cable routing mechanism usable for actuating an end effector such as a needle insertion end effector that can include: a series of articulating mechanisms interconnected through a set of rigid links, wherein the series of articulating mechanisms includes: a set of pulley hinge joints and a set of roll joints; a set of cables routed through the series of articulating mechanisms, wherein each articulating mechanism is configured to actuate while preserving cable length of the set of cables; an end effector with at least one degree of freedom coupled to the cable.

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SYSTEM FOR A MULTI-AXIS CABLE ROUTING MECHANISM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This Application claims the benefit of U.S. Provisional Application No. 63/508,359, filed on 15-JUN-2023, which is incorporated in its entirety by this reference.

TECHNICAL FIELD

[0002] This invention relates generally to the field of teleoperated medical devices and more specifically to a new and useful system for a multi-axis cable routing mechanism.

BACKGROUND OF THE INVENTION

[0003] Robotic tools have played an increasingly important role in various medical applications, such as surgery, diagnostics, and performing other medical procedures. However, despite their numerous advantages, there are still some challenges and limitations associated with the use of robotic tools especially in the medical space.

[0004] One of the significant challenges in implementing robotic tools for medical applications is the difficulty in achieving reliable and intuitive control over the action of the tool. Drive-by-wire solutions have been employed but are often limited by their lack of haptic feedback, making it difficult for the user to confidently perform delicate operations or procedures without risking damage to tissues or structures. Placing electric actuators (e.g., electric motors) directly at tool ends is often impractical due to various reasons. The size of electrical actuators can be one limiting factor because medical devices must often be compact and operate in small, confined spaces. As another limiting factor, the weight of an electrical actuator can add to the inertia at the end of the device, which may increase risk to a patient.

[0005] Hydraulic actuation systems have been explored as an alternative solution to overcome the limitations of drive-by-wire technologies, aiming to provide more dexterous and precise control. However, the integration of hydraulic actuation within robotic tools can also pose several challenges. For instance, the management of hydraulic lines and actuators and their integration within a devices structure may be challenging for many actuation systems. Hydraulic lines must be mechanically coupled to actuators either directly or indirectly. Additionally, the presence of hydraulic lines or other mechanical couplers can create constraints on the system's range of motion, limiting its ability to access and manipulate certain anatomical structures during procedures.

[0006] Thus, there is a need in the field of teleoperated medical devices field to create a new and useful system and method for a multi-axis cable routing mechanism. This invention provides such a new and useful system and method.

BRIEF DESCRIPTION OF DRAWINGS

[0007] FIG. 1 is a schematic representation of a system variation.

[0008] FIG. 2 is a schematic representation with a cutaway view showing cable routing within structures of one system variation.

[0009] FIG. 3 is a cross-sectional view of a system variation showing pulley joints and roll joint details with a cable routed for substantially fixed cable length within the cross-sectional plan.

[0010] FIG. 4 is a cross-sectional view of the routing mechanism

[0011] FIGs. 5A-5B are detailed views of a pulley hinge joint coupled to a roll joint connected to a rigid joint used to route two cables.

[0012] FIG. 6 is a cross-sectional detail view of the cable routing mechanism engaged with a needle insertion end effector with details of a pulley system used with the needle insertion end effector.

[0013] FIG. 7 is a schematic representation of a system variation with a linear-sliding joint.

[0014] FIG. 8A and FIG. 8B are schematic representations of a variation of a prismatic joint using two pulleys.

[0015] FIG. 9 is a diagram of an exemplary internal pulley system of a prismatic joint variation.

[0016] FIG. 10 is a schematic diagram showing three states of linear-sliding actuation of a variation of a prismatic joint using two pulleys.

[0017] FIGs. 11A-11C are detailed diagrams of alternative variations of internal pulley system variations for a prismatic joint.

[0018] FIG. 12 is a schematic representation of a cable routing mechanism connected to a remote center motion (RCM) actuation system that is actuated by a hydraulic actuation system.

[0019] FIG. 13 is a schematic representation of a cable routing mechanism connected to a remote center motion (RCM) actuation system that is actuated by a hydraulic actuation system and a second actuation system used to actuate an actuation input to control the cable actuation of a needle insertion end effector.

[0020] FIG. 14 is a schematic representation of the cable routing mechanism connected to an articulated robotic arm as an actuation system.

[0021] FIG. 15 is a schematic representation of the cable routing mechanism mounted to a segment of an articulated robotic arm used as an actuation system.

[0022] FIG. 16 is a schematic representation of an exemplary implementation of the system as part of a mobile cart.

[0023] FIG. 17 is a schematic representation of an exemplary implementation of the system used in connection with a medical imaging system.

[0024] FIG. 18 is a schematic representation of an exemplary variation of a cable compensating mechanism used with the system.

[0025] FIG. 19 is a diagram representation of a variation of an RCM actuation mechanism.

[0026] FIG. 20A and FIG. 20B are schematic representations of variations of an RCM actuation mechanism.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0027] The following description of the embodiments of the invention is not intended to limit the invention to these embodiments but rather to enable a person skilled in the art to make and use this invention.

1. Overview

[0028] A system for a multi-axis cable routing mechanism functions to enable a highly maneuverable end effector with one or more degrees of freedoms (DOFs) driven by one or more proximally grounded actuators. The system routes cabling from a proximal input end to a distal output end (e.g., at an end effector or device). The multi-axis cable routing mechanism routes cables through an interconnected series of passively articulating mechanisms establishing a configured number of decoupled DOFs of manipulation of an end effector, the end effector having at least one controlled DOF. The system may be used to decouple actuation of an end effector by one source of manipulation (e.g., a human or robot positioning and orienting the end effector) from actuation of some action of the end effector (e.g., needle insertion) applied by another source of manipulation. The system can be designed for using the routed cables to drive actuation of the action of the end effector.

[0029] The system may be used to mechanically bridge a cable driven end effector over or around a mechanism used to control or drive the actuation of the end effector. The system can achieve this mechanical bridging of space with tightly mechanical coupling that may result in reduced backlash controlling an output and improved transfer of haptic feedback.

[0030] The system may be configured for manipulation with any suitable number of DOFs (e.g., 4, 5, or 6 DOF for positioning an end effector). The system preferably enables cable routing with minimal or no cable length change during actuation and manipulation of the system. The system additionally enables the end effector to be highly maneuverable over a large workspace without interfering with an actuation system.

[0031] The system can uniquely solve a challenge of an end effector being flexibly maneuverable by some translational input while retaining mechanical coupling between an end effector and a controller of the end effector. In some variations, the translational input could be a robotic manipulator like an articulated robotic arm. For example, a 6-axis robotic arm could be moving an end effector into position, and then a doctor safely removed from the robotic arm can have direct mechanically coupled control of the end effector.

[0032] The translational input could also be a human moving and positioning an end effector. For example, having multiple humans crowded around a patient to manipulate a device can present numerous challenges. However, using the system, one medical practitioner could position an end effector in close proximity to a patient, and then a second medical practitioner comfortably standing elsewhere could control the actuation of the end effector through a mechanically coupled mechanism that has direct haptic feedback and highly responsive control of the end effector actuation.

[0033] In some variations, the system may be used with hydraulic actuators, enabling grounding of the actuator components and associated hydraulic tubing. This mitigates challenges arising from actuator inertia and hydraulic tube motion.

[0034] The use of hydraulic control of the end effector may be used to enable haptic feedback in the control of the end effector. The hydraulically controlled DOF of the end effector, may provide haptic feedback which can be useful in many situations. Physical feedback imparted onto the end effector is translated back as haptic feedback delivered back to an input hydraulic manipulator system. The system may enable using a system of cables to interface a hydraulic control input and the end effector. Cables coupled to a hydraulic control input may enable such haptic feedback from the end effector back to an operator.

[0035] The system may include a cable routing mechanism that is made of a series of rigid links connected by passive joints (e.g., rotary or prismatic) through which a cable may be routed such that motion of the cable routing mechanism has very little impact on overall cable length. Maintaining cable length prevents moving the cable routing mechanism from actuating a cable driven end effector and/or straining the cable. The joints of the structure may be passive and designed to be easily manipulated by some external actuating system (e.g., a hydraulic system, a robotic arm, human control, etc.). As discussed, the system functions to allow cabling to leapfrog or bypass integration with a complex actuation system and enable direct actuation at an endpoint of said system with a grounded actuator that controls the cable. In this manner, the cable routing mechanism may be a largely passive mechanism that may then be controlled or articulated by a separate, active mechanism. This passive design of the system enables the system to adapt to a wide variety of active actuation mechanisms (e.g., a robotic arm, hydraulic mechanisms, and the like).

[0036] The system is herein described as it can be applied to the medical space. But the system may have applications in any field of use where hydraulic actuation of one or more degrees of freedom at some actuated end effector may be desirable. In many medical applications, the positioning of a medical device like a needle may have many options for the type of active actuation system used to manipulate the system in space. However, for insertion of the needle, it may be beneficial to have haptic feedback of the needle insertion action. The cable routing mechanism may enable this degree of freedom of the needle end effector to be controlled with direct mechanically coupled haptic feedback. This may, in some variations, even be provided through a hydraulic system that integrates with the cables of the cable routing mechanism of the system.

[0037] In some variations, the system may be implemented to use magnetic resonance imaging (MRI) compatible materials enabling actuation and haptic feedback to medical device operation during use of an MRI machine. In particular, the systems and methods may be used for performing procedures on a patient with live MRI monitoring of the patient. The system and an end effector may be made free of ferreous metals or electronics such that it can be used on a patient within the bore of an MRI machine.

[0038] Such a system variation may include or be used in combination with an MRI-compatible manipulator system. An MRI-compatible manipulator system may similarly be made of MRI-compatible materials. In some variations, the MRI-compatible manipulator system may be a hydraulically-driven system such as one described in published PCT application WO2024086666, titled "System and method for a hydraulic transmission system of teleoperation device with haptic feedback", filed 18-OCT-2023, or published PCT application WO2024086671, titled "System and method for a manipulator of surgical tools" filed 18-OCT-2023, both of which are both incorporated in their entirety by this reference.

[0039] The system may additionally or alternatively be used in combination with other imaging technologies such as CT scans, ultrasound imaging, or other imaging technologies. Such imaging technologies can sometimes limit access to a patient (e.g., a physician can't physically use a tool because a CT scanner is blocking access or there may be a desire to avoid radiation exposure) and so the system may be used to enable remote operation of an end effector. For example, biopsies and ablations performed under CT guidance may use a hydraulically actuated needle integrated with the system. The system may in some variations be actuated into position using some manipulator system to actuate position like a robotic arm. Also, the systems and methods are not limited to being used in combination with such imaging technologies and could be used with other suitable medical applications. The system may additionally have applications in other fields of use outside of the medical field.

[0040] Herein, a system variation involving haptic feedback-enabled hydraulic control of needle insertion is used as an exemplary variation. This enables a broad range of actuation systems to accurately position the needle end effector, followed by the utilization of hydraulics for precise needle insertion. While the needle end effector serves as an exemplary use case for the system, one skilled in the art would appreciate that the system has applications with other types of end effectors and in areas outside the medical space.

[0041] The system and method may provide a number of potential benefits. The system and method are not limited to always providing such benefits and are presented only as exemplary representations for how the system and method may be put to use. The list of benefits is not intended to be exhaustive and other benefits may additionally or alternatively exist.

[0042] As one potential benefit, the system may enable cable length to remain constant or experience limited changes in length when experiencing actuation. This stability in cable length ensures that the end effector moves with high precision and accuracy and with high correspondence to a control input. This can be crucial for delicate medical procedures. Additionally, maintaining a constant cable length helps in providing consistent tension, preventing slippage and ensuring reliable force transmission, which can improve transmission of input to the end effector as well as transmitting haptic feedback from the end effector to a control input. As such, having a mechanism that maintains cable length through the system may enhance safety and the effectiveness of the device during medical operations.

[0043] As another potential benefit, the system may enable an end effector to be highly maneuverable. As a related benefit, the system may additionally be configured to provide maneuverability over a large workspace. This wide range of motion may be crucial for providing flexibility in the use of the device. The ability to move freely within a large workspace may reduce the need for repositioning or additional instruments, leading to more efficient and faster medical procedures.

[0044] As another potential benefit, the system may be largely independent of the type of actuation system used for manipulation. While some variations of the system may include a particular actuation system, the system may additionally be adapted to or used with different systems.

[0045] As another potential benefit, the systems and methods provide a way for remote mechanical actuation of an end effector. The cables can be used to bridge a mechanical input on a proximal end to the end effector on a distal end of a cable routing mechanism. This mechanism, in some variations may be fully passive with all energy coming from the human operator. This may have beneficial implications for medical device regulatory approval.

[0046] As another potential benefit, the systems and methods may provide a solution that offers realistic and useful haptic feedback during hydraulic actuation of an end effector. The hydraulic system can preferably translate haptic feedback from an end effector (i.e., an output manipulator) back to an input manipulator. This can be important to providing a doctor with enhanced control while performing a procedure.

[0047] As another potential benefit, the system may be made of MRI-compatible materials. In other words, the system, as a passive mechanical system, may be made without any active electronics or without any ferromagnetic materials, magnets, or other materials that can interfere with use of an MRI device.

2. System

[0048] As shown in FIG. 1, FIG. 2, and FIG. 3, a system for a multi-axis cable routing mechanism may include: a multi-axis cable routing mechanism 100 that includes a set of articulating mechanisms 110; cable 120 that is routed through the set of articulating mechanisms 110, wherein each articulating mechanism is configured to actuate while substantially preserving cable length routed through the routing mechanism 100; and an end effector 130 with at least one degree of freedom coupled to the cable.

[0049] The system may additionally be included as part of another system and as such may include an input mechanism 200 used to actuate the cables and by extension an action of the end effector, and an actuation system 300 used to manipulate position and/or orientation of the end effector, and/or any other additional component that may be used in combination.

[0050] In particular, the system makes use of a combination of specially designed articulating mechanisms 110 that affords multiple degrees of freedom (e.g., 5 or 6 DOF) for manipulating positioning of an end effector 130, with a cable system 120 integrated through the articulating mechanisms 110 to actuate some action degree of freedom of the end effector 130. In some variations, the system may include articulating mechanisms 110 that include a combination of a hinge joint 111 and a rolling joint 113. The articulating mechanisms 110 may additionally or alternatively include a linear sliding joint 114 such as a prismatic sliding joint 115 described herein. In particular, the hinge joint 111 can be a pulley hinge joint 112. Accordingly, in one variation, the system can include a series of articulating mechanisms 110 interconnected through a set of rigid links 118, wherein the series of articulating mechanisms 110 comprises: a set of pulley hinge joints 111 and a set of roll joints 113; a set of cables 110 routed through the series of articulating mechanisms 110, wherein each articulating mechanism 110 is configured to actuate while preserving cable length of the set of cables; and an end effector 130 with at least one degree of freedom coupled to the cable 110. Preserving cable length of the set of cables preferably includes preserving cable length within some tolerance range.

[0051] A pulley hinge joint 112 can include opposing pulleys that engage in a complimentary manner with the set of cables passing through the pulley hinge joint for conservation of cable length across a defined range of rotational motion. Accordingly, each pulley hinge joint 112 of the set of pulley hinge joints may include opposing pulleys that engage with the set of cables passing through the pulley hinge joint 112, wherein the opposing pulleys may be configured for conservation of cable length across a defined range of rotational motion.

[0052] The system may be used with a variety of types of end effectors. In one particular variation, the end effector 130 is a needle insertion end effector 132 with a linearly actuating degree of freedom, which may be used for actuating longitudinal insertion position of a needle or probe of the needle insertion end effector 132. In this variation, the system may include a set of cables 120 with a first cable and a second cable wherein the first cable and the second cable are mounted to opposing ends of a linearly actuating degree of freedom controlling needle insertion position of the needle insertion end effector 132. Herein, the variation of a needle insertion end effector 132 is used as one exemplary type of end effector, the system and its variations are not limited to a needle insertion end effector 132 and one skilled in the art would recognize that other types of end effectors may alternatively be used.

[0053] The system may be implemented in various configurations depending on desired features, use, and capabilities. In one particular variation, the system is configured with 5 to 6 degrees of freedom of an end effector (e.g., a needle end effector). Such a system variation may include, as shown in FIG. 1, a multi-axis cable routing mechanism that includes a series of articulating mechanisms comprising a first pulley hinge joint coupled of to a first roll joint, the first roll joint coupled to a second pulley joint through a rigid link (e.g., a tube), the second pulley joint coupled to a second roll joint, the second roll joint coupled to a third pulley joint through a second rigid link, and the third pulley joint coupled to the end effector; a cable that is routed through the series of articulating mechanisms, wherein each articulating mechanism is configured to actuate while preserving cable length; and an needle end effector with at least one degree of freedom coupled to the cable. The series of articulating mechanisms may provide five DOF. The system variation may include an actuation interface 310 through which an actuation system may interface with the multi-axis cable routing mechanism 100. The actuator interface 310 may be coupled distal to the third pulley joint (e.g., directly coupled to the end effector). The actuator interface 310 may include a rotational degree of freedom such that the system may effectively experience manipulation of the needle end effector with six DOF.

[0054] In another exemplary variation, the series of articulating mechanisms may be configured to include a linear-sliding joint. For example, a prismatic linear-sliding joint may be used within the set of articulating mechanisms. In such a variation, the system may include, as shown in FIG. 7, a multi-axis cable routing mechanism with a series of articulating mechanisms comprising a first roll joint coupled to a first pulley joint through a rigid link, the pulley joint coupled to a second roll joint, the second roll joint coupled to a prismatic linear-sliding joint, the prismatic linear-sliding joint coupled to a second pulley joint through a second rigid link, and the second pulley joint coupled to the end effector; and a cable that is routed through the series of articulating mechanisms, wherein each articulating mechanism is configured to actuate while preserving cable length; and an needle end effector with at least one degree of freedom coupled to the cable. In a similar manner, the system may include an actuator interface 310 with a rotational degree of freedom, the actuator interface 310 being coupled distal to the second pulley hinge joint (e.g., directly coupled to the end effector 130). This additional degree of freedom may make the end effector movable with six degrees of freedom.

[0055] These sets of articulating mechanisms are provided as exemplary implementations. Other alternative combinations and configurations of articulating mechanisms may be used.

[0056] The multi-axis cable routing mechanism 110 functions as a passive structure that enables manipulation of an end effector while also enabling routing of a cable through or about the routing mechanism while minimizing changes in cable length from motion of the structure. The multi-axis cable routing mechanism 110 may be passive in the sense that its actuation of individual articulating mechanisms 110 results from input from some outside force such as actuation system or a manipulator. In some variations, one or more of the articulating mechanisms 110 may alternatively be actively actuated or driven using a motor or some directly controlled actuator. An actuation system or manipulator can apply its positioning force to the end effector possibly through an actuation interface 310 which may be connected at the distal end at or near the end effector.

[0057] The multi-axis cable routing mechanism additionally serves as a routing conduit for the cable 120. As one aspect, the cable is routed through specifically configured articulating mechanisms designed to substantially preserve cable length over a range of motion through multiple degrees of freedom.

[0058] As another aspect, the cable routing mechanism can provide a suitably sized manipulation workspace while also keeping the cable out of the way. In a way, the cable can be routed around a space used by some actuation system 300 or manipulator thereby keeping the cable out of the space of the mover of the end effector. The structural form of the cable routing mechanism, in some variations, can be in a semi-arced or “bypassing” path. In this variation, a cable routing mechanism with such a circumnavigating path can route the cable around a central region possibly used by an articulating system 300.

[0059] The multi-axis cable routing mechanism preferably includes a set of articulating mechanisms 110 that are interconnected through rigid links 118 along a path of the routing mechanism. The set of articulating mechanisms are configured as a series of interconnecting articulating mechanisms. The set of articulating mechanisms are more particularly configured as a series of articulating mechanisms 110 interconnected through a set of rigid links 118.

[0060] The rigid links 118 function as structural members establishing spacing between degrees of freedom. The rigid links 118 can be substantially static rigid bodies that establish mechanical connections between different points of the articulating mechanism 110. The rigid links 118 may be integrated between any suitable points of cable routing mechanism 100, but in particular may be used between two degrees of freedom. The set of cables 120 may be routed within the rigid link. For example, in one variation, the rigid link 118 may be a tube with a defined internal through channel. However, one or more cable may be routed alongside or otherwise routed between opposing ends of the rigid link 118. The rigid links 118 may be substantially straight linear structures but could alternatively be rigid members with any suitable form. The length of the rigid links 118 may be configured for a desired workspace of the articulating mechanism.

[0061] The articulating mechanisms 110 function as actuating degrees of freedom. The articulating mechanisms 110 are each specially configured and designed so that cables may be routed through them such that the cables experience no or minimal amounts of translational movement. As described, the articulating mechanisms 110 can be interconnected through the set of rigid links 118.

[0062] The set of articulating mechanisms 110 may be decoupled from each other where motion of one articulating mechanism doesn't directly impact motion of another articulating mechanism. Each articulating mechanism functions to provide at least one degree of freedom. The articulating mechanisms 110 may be of different types of articulating mechanisms 110 providing different forms of rotational and/or translational degrees of freedom.

[0063] The articulating mechanisms 110 preferably include defined cavities or recesses to facilitate routing of cable through the articulating mechanisms 110 mechanism. The articulating mechanisms 110 used preferably is a mechanism that enables routing the cable without changes (or significant changes) to the cable length during articulation of a given articulating mechanism 110.

[0064] The articulating mechanisms 110 may include one or more of a different set of variations. In some variations, the set of articulating mechanisms 110 may include a hinge joint 111, a roll joint 113, a linear-sliding joint 114, and/or other types of joints. These different joints can be used in combination to establish the DOFs of the cable routing mechanism. The hinge joint 111 and the roll joint may provide different types of angular degrees of freedom which can be used in combination. In one such variation, the set of articulating mechanisms 110 includes a first hinged joint coupled to a first roll joint coupled to a second hinged joint coupled to a second roll joint coupled to a third hinged joint. The set of articulating mechanisms 110 may alternatively integrate one or more linear-sliding joints. In one variation, the set of articulating mechanisms 110 may include a roll joint coupled to a hinged joint coupled to a second roll joint coupled to a linear-sliding joint, coupled to a second hinged joint.

[0065] In some preferred variations, the routing mechanism 100 includes a series of articulating mechanisms that includes at least a first pulley hinge joint 112 directly coupled to a roll joint 113, wherein the roll joint 113 is connected to another articulating mechanism through a rigid link 118. In this way the pulley hinge joint coupled to a roll joint 113 forms a two degree of freedom compound articulating mechanism. Instances of such a compound articulating mechanism may be repeated multiple times. As shown in an exemplary variation of FIG. 1, there may be two instances of such a compound articulating mechanism in addition to a distal pulley hinge joint 112 used without a connected roll joint 113.

[0066] The routing mechanism 100 or more specifically the articulating mechanisms 110 may use gravity compensation such using counterweights or compressed springs to compensate for gravity such that the routing mechanism can seemingly float at a neutral position, with the effects of gravity being substantially neutralized through the compensation.

[0067] The hinge joint 11 variation functions to establish a rotational degree of freedom between two connected structures that are pivot about a point established by the hinge joint. A hinge joint 111 allows for angular motion in a plane perpendicular to the hinge axis.

[0068] In particular, the hinge joint 111 is a pulley hinge joint 112 (or more simply stated as pulley joint 112 for conciseness). A pulley joint 112 rotates two connected structures about a virtual pivot point. Cables route through the pulley joint 112 so as to maintain substantially constant length through articulation of the pulley joint 112.

[0069] A hinge joint 112 may be designed to provide angular actuation through a range of angular positions. In one variation, the angular range may have a 180° range though other ranges such as greater than 180° or less than 180° (e.g., 135°, 90°, or 45°).

[0070] A pulley joint 112, as shown in FIG. 5A and 5B, can include coupled gears 1210, a coupling link 1230 that connects the coupled gears 1210, and pulleys 1220 aligned with each of the gears 1210 wherein the cable 120 routes through defined grooves of the pulleys 1220. As the pulley joint 112 is rotated, the coupled gears 1210 move about a virtual pivot point between them causing a cable 120 to unravel from one pulley (e.g., 1221) and ravel onto the other opposing pulley (e.g., 1222) thereby maintaining the length of cable 120 within the pulley joint 112.

[0071] The cable 120 may be routed at or near the center of the pulley hinge joint 112. When there is a single cable, the cable may be axially aligned with a defined axial center of the pulley joint 112. When there are two cables, a first cable and second cable may be routed through pulleys 1220 symmetrically positioned offset from a defined axial center. Alternatively, one cable may be axially aligned with a defined center of the axial center of the pulley joint 112 while a second cable is positioned offset. A cable offset from the center may be positioned in near proximity to the defined axial center.

[0072] Multiple instances of each component may be used for structural integrity or to support routing more cables. For example, each side of a pulley joint could have coupled gears with each pair of gears being linked by a coupling link. Multiple pulleys could similarly be aligned with each gear. As shown in FIG. 5A, two pulleys axially aligned with a coupling gear may be used to route two cables through the system. In a variation used to route more than two cables, the pulley hinge joint 112 may include additional sets of pulleys aligned in series like the two sets of pulleys in series shown in FIG. 5A.

[0073] In one variation shown in detail in FIG. 5B, a variation of a pulley joint 112 may include opposing pulleys on either side of a defined rotational axis of the hinge joint. In other words, the pulley joint 112 may include one opposing pulley 1221 on proximal side of a pulley joint 112 and a second opposing pulley 1222 on a distal side of the pulley joint 112. The pulleys may have placement and offset to align a cable passing through the pulley joint with a defined axial center. Each pulley may be aligned with a distinct defined axial center. As shown in FIG. 5B, the first opposing pulley 1221 may be aligned with a first defined axial center and the second opposing pulley 1222 may be aligned with a second defined axial center, where the first defined axial center is no aligned with the second defined axial center. In this example they are perpendicular, but any suitable alignment may be used. Being aligned can be where a defined tangent of the pulley where a cable would come off the pulley aligns the cable substantially with the defined axis.

[0074] Accordingly, the pulley joint 112 may more particularly include: a first set of pulleys 1221 on a first side having an edge 1223 of the first set of pulleys aligned tangentially with a defined linear path of cable through a first adjacent link 1218, and a second set of pulleys 1222 on a second side have an edge 1224 aligned tangentially with a second linear path of the cable through a second adjacent link 1219. The first set of pulleys 1221 may be offset to one side of the linear path, and the second set of pulleys 1222 are offset to one side of the second linear path.

[0075] The roll joint (or "rotational joint") variation 113 functions to enable axial rotation about a central defined axis running through some component. The roll joint 113 in one variation is coupled to a length of tubing serving as a static linkage arm (118) within the cable routing mechanism 100. Tubing or any suitable rigid structure may be used for rigid links 118 between the articulating mechanisms 110. The roll joint 113 allows a rigid link 118 or another connected articulating mechanism 110 to rotate about its center. The roll joint 113 is not limited to rotating about a defined center of some structure however, and alternative rotational joint and static links may be used. A roll joint 113 may be freely rotating so that they can rotate continuously in either direction. However, in some variations, a roll joint 113 may have a range of angular actuation limited to some defined range.

[0076] In a roll joint 113, the cables may extend freely through a defined opening of the roll joint 113. In one variation, a cable in contact with a pulley of a pulley joint 112 will extend through the roll joint 113 and a rigid link 118 to engage with another pulley joint 112 on the opposite end of the rigid link 118 as shown in FIG. 4. The roll joint 113 can rotate freely without substantially altering the length of the cable(s) 120.

[0077] In some instances, there may be some minor deformation and changes in length of the cable because the cables are aligned off center from the axis of rotation. Axial twisting of the cables may contribute to minimal translational deformation of the cables. The cables are preferably routed close to the center of the tubing to minimize or eliminate elongation due to twisting. Though in some variations, some amount of elongation may be within acceptable tolerances depending on the application and therefor the cables may be off center. Additionally, in some variations described herein, cable compensating mechanisms 150 (e.g., spring elements) may be added or connected to the cables to enable a specified amount of elongation which may be used to have the cables in tension but to permit some amount of elongation of the cable due to actuation of the routing mechanism 100.

[0078] In some variations, the series of articulating mechanisms 110 of the routing mechanism 100 may include a linear-sliding joint. This may be in addition to or as an alternative to a set of pulley hinge joints 112 and/or a set of roll joints 113. The linear-sliding joint variation 114 functions to enable a translational degree of freedom along a path. The path in one variation is a linear path that can be used to effectively make a connection between two points of the routing mechanism have variable length by extending and/or contracting. The linear-sliding joint 114 can be integrated along, within, or otherwise in connection with a rigid link 118. In some variations, rigid links 118 may extend from either side of the linear-sliding joint 114, which functions to make an effective link structure with variable length. In some variations, the linear-sliding joint 114 may structurally serve as the rigid link 118. In other words, in some variations, there may be no distinct separate part forming the rigid link 118. In such variations, a proximal end and a distal end of a linear-sliding joint 114 may serve as structural members for connecting to other articulating mechanisms 110. In other variations, a distal rigid link may connect to a distal end of a linear-sliding joint 114, and a proximal rigid link may connect to a proximal end of the linear-sliding joint 114.

[0079] The linear-sliding joint 114 may be used in place of one or more hinge joints 111 (e.g., pulley hinge joints 112). The linear-sliding joint 114 may be integrated in a series of articulating mechanisms 110 in a variety of positions. In one variation, as shown in FIG. 7 , a linear-sliding joint 114 may be integrated within a series of articulating mechanisms comprising a first roll joint coupled via a first rigid link to a first pulley hinge joint, a second roll joint coupled to the first pulley hinge joint, a linear-sliding joint wherein a second rigid link couples the second roll joint to a proximal end of the linear-sliding joint, and a second pulley hinge joint wherein a third rigid link couples the second pulley hinge joint to a distal end of the linear-sliding joint. The end effector can be coupled to the second pulley-hinge joint in such a variation.

[0080] In some variations, the linear-sliding joint 114 may be a prismatic joint 115 that includes an internal compensating pulley system for routing cable while maintaining pulley length during changes in linear articulation of the prismatic joint.

[0081] Within the prismatic joint 115, a set of opposing pulleys may be configured such that articulation of the prismatic joint at any point internally manages cable length to account for the change in linear articulation. The pulley system routes the cable such that a reserve of cable length can be extended to compensate for extending the prismatic joint 115 and retracted for contracting of the prismatic joint 115.

[0082] The prismatic joint 115 may include two rack and pinion mechanisms that are integrated through coupled pinions (e.g., implemented as a compound gear) so that the two racks move in opposing directions. The two rack and pinion mechanisms can include a distal rack and pinion mechanism and a proximal rack and pinion mechanism. The distal rack and pinion mechanism includes a distal rack (i.e., a distal joint rack) coupled to a distal pinion, and the proximal rack and pinion mechanism includes a proximal rack (i.e., proximal joint rack) coupled to a proximal pinion. The racks (the distal rack and the proximal rack) are preferably linear gears. The pinions can be round gears that are coaxially aligned and connected as a compound gear. Accordingly, in some variations, the prismatic joint 115 includes a first rack 810 and second rack 820 coupled for opposing actuation through a compound gear 830 with a first gear 832 and second gear 834 with a two to one gear ratio, where the first gear 832 engages the first rack 810 and the second gear 834 engages the second rack 820. Here the first gear 832 and the second gear 834 serve as the pinion gear of a rack and pinion mechanism. The pinions may alternatively be coupled in an alternative manner through intermediary gears, belts, and/or other mechanisms. In one variation, the pinion has a two to one gear ratio. In some variations, the first rack 810 is a distal rack and the second rack may be a proximal rack when integrated as an articulating mechanism 110. In this configuration, the extension of one rack by a length may be compensated by movement of the rack by half the length.

[0083] The prismatic joint 115 can include a pulley system routing a reserve of cable that compensates for actuation of the prismatic joint 115. The pulley system functions to manage the feeding or contracting of a reserve amount of cable. The pulley system may include a set of rolling pulleys and/or cable guides to change direction of the cable through the prismatic joint 115. In particular, the set of pulleys can include redirecting pulleys used to redirect the direction of the cable. In some variations, such as shown in FIG. 8A and FIG. 8B, the prismatic joint 115 includes two redirecting pulleys including a first pulley 842 at a distal end of a proximal rack that functions to redirect the cable back towards the proximal end and then a second pulley 844 that is located between the two racks and adjacent to the pinions that functions to redirect the cable towards the distal end of the prismatic joint (e.g., the distal end of the distal rack). The pulleys may be rotating pulleys but could alternatively be cable guides, preferably made of low friction material.

[0084] As shown in FIG. 9, an exemplary prismatic joint with a pulley system including two redirecting pulleys may function as follows: as a distal rack moves forward length L, a proximal rack moves backward a distance half the length (L/2). In moving backwards, the proximal rack feeds the cable length gained by the distal rack. The distal rack contributes to lengthening the cable in a first subsection, while the proximal rack impacts the lengths of two subsections of cable, which is why the prismatic joint includes pinions with gear ratios of two to one with the proximal rack and pinion having the smaller gear and the distal rack and pinions having the larger gear. In a similar manner, when the distal rack contracts some distance the proximal rack moves forward half the distance. As shown in exemplary implementation of FIG. 10, such a prismatic joint may actuate forward and backwards.

[0085] In this way, the proximal joint rack serves to manage a “reservoir” of cable to either feed or eat the cable length gained or reduced as the distal joint moves as shown in FIG 10. In this variation, pulley P1 and the pinion gear may be grounded to the proximal rack and not move when the distal joint moves. Similarly, point T1 of the cable may not move as the distal joint moves. The cable can be free to route from point T1 through some adjacent articulating mechanism 110 (e.g., a roll joint 113). The cable exiting the distal rack may similarly be connected to another adjacent articulating mechanism 110 and/or some terminated at the end effector 130.

[0086] The prismatic joint may use a pulley system with variety of cable routing configurations to manage cable routing so as to articulate freely while not altering effective cable length. These variations of pulley systems may use additional or alternative pulleys or cable guides. Some alternative pulley systems of a prismatic joint are shown in FIGs. 10A-10C.

[0087] As shown in FIG. 11A, in another variation, a pulley system may include three redirecting pulleys. In this variation, the pulley system may include: a first pulley at a distal end of a proximal rack that functions to redirect the cable back towards the proximal end, a second pulley that is located between the two racks and adjacent to the pinions that functions to redirect the cable towards the distal end of the prismatic joint, and a third pulley at a distal end of the distal rack that functions to redirect the cable back towards the distal end of the prismatic joint 115. In this variation, the pinions may be a compound gear that is grounded and fixed with the second pulley.

[0088] As shown in FIG. 11B in another variation, a pulley system may include four redirecting pulleys. In this variation, the pulley system may include a first pulley at a distal end of a proximal rack that functions to redirect the cable back towards the proximal end, a second pulley that is located between the two racks and adjacent to the pinions that functions to redirect the cable towards the distal end of the prismatic joint, a third pulley at a distal end of the distal rack that functions to redirect the cable back towards the distal end of the prismatic joint 115, and a fourth pulley grounded to the distal rack that functions to redirect the cable towards a distal end of the distal rack. In this variation, the pinions may be a compound gear that is grounded and fixed with the second pulley.

[0089] As shown in FIG. 11C in another variation, a pulley system may include four redirecting pulleys. In this variation, the pulley system may include a first pulley grounded at some position adjacent to the proximal rack that functions to redirect the cable back towards the proximal direction, a second pulley at a proximal end of the proximal rack that functions to redirect the cable back towards the distal direction, a third pulley that grounded and located between the two racks and adjacent to the pinions on a proximal side that functions to redirect the cable towards the proximal direction, and a fourth pulley grounded proximal to the distal rack that functions to redirect the cable towards a distal end of the distal rack.

[0090] In a system with a prismatic joint 115 or an alternative linear-sliding joint 115, the system may forgo one of the other articulating mechanisms (like a hinge joint 111 or a roll joint 113) in place of a prismatic joint 114. This variation may have the potential benefit of being a more compact option. Use of a prismatic joint 115 could also potentially reduce mass being actuated through space. In one variation a prismatic joint 115 could be configured as a linear-sliding joint 114 between as an articulating mechanism between two pulley hinge joints 112 as shown in FIG. 7. In this implementation, the linear-sliding joint 114 may be directly between an adjacent roll joint 113 (connected to a first pulley hinge joint 112) and a second pulley hinge joint 112.

[0091] The cable system 120 functions to supply actuation input and/or output between the end effector 130 and some coupled mechanism on a proximal end of the routing mechanism 100. The cable system 120 (or more concisely referred to as cable 120) is preferably used to mechanically transfer motion from some input to a distal end of the routing mechanism 100. In a preferred variation, the cable 120 is used to mechanically couple actuation on a proximal end of the routing mechanism 100 with the distal end of the routing mechanism 100 (e.g., at the end effector 130).

[0092] When used for actuation, one or more cables are routed through the routing mechanism with the cables held in tension. The cables may be made of any suitable material. In some variations, the cable may be made of metal like steel or stainless steel, and/or synthetic materials like nylon or Kevlar cable.

[0093] In some alternative variations, one or more cables may be a cable not used for actuation but for some other application. In some variations, the cable may be sensing cable and/or data communication cables. Such alternative types of cable may be optical cable, electrical cable, and/or tubing. In one variation, the cables include a fiber optic cable used for optical communication or sensing with a device on a distal end of the cable routing mechanism. Fiber optic cable may be used to sense force and/or shape deformations at a distal point. In another variation, the cable could be used for engaging with a piezo actuator a distal end. The cable may be made of brass or conductive ceramic (if being made of MRI or scanner compatible materials) and used to engage with piezo crystals. In another variation, the cables 120 includes a tube used for hydraulic or pneumatic actuation. Such cables may similarly benefit from being a fixed length. These variations may have the potential benefit of possibly being made of MRI compatible materials. Herein, the system is primarily described where the cables are held in tension and used for mechanical actuation of an end effector, but the system is not limited for cable routing for actuating such an end effector. The cable system 120 may include one or more such sensing cables.

[0094] The system may include a cable system 120 with a single cable or a plurality of cables. In general, a set of cables are centrally routed through the series of articulating mechanisms 110 of the routing mechanism 100. In a variation, when a set of cables comprises a single cable, the cable is routed through substantially through the axial centers of the articulating mechanisms 110 and/or the rigid links 118. In particular, for the roll joint(s) 113 and the rigid link(s) 118, the cable is routed or aligned at or substantially near an axial center of these components. For a pulley hinge joint 112, the cable can enter and/or exit the pulley hinge joint to align with a defined axial center of an adjacent component.

[0095] In some cable system 120 variations, the cable may be terminated and grounded at a distal end of the cable routing mechanism. For example, when attached to an end effector 130 for actuation, the cable may be terminated with some actuating degree of freedom. When a single cable is used, the end effector may be configured to have a restorative force that opposes a direction of applied force of the cable. For example, a spring or magnet could apply a force to a mechanism in a first direction. The cable when pulled may apply a force to the mechanism in an opposing direction. Alternatively, in some variations, a single cable may be sufficient for supplying forces in two directions.

[0096] In other variations, the cable system 120 includes multiple cables (or cable lengths) routed through the routing mechanism 100. Accordingly, a set of cables making up the cable system 120 may include at least a first cable and a second cable. When the cable system 120 includes multiple cables, the cables are similarly preferably routed through the series of articulating mechanisms 110 and the rigid links 118 at or near an axial center of the articulating mechanisms 110 and/or the rigid links 118. In many variations, cables may be used in pairs for actuating a distinct degree of freedom of the end effector 130. A pair of cables may supply antagonistic reciprocal forces for one degree of freedom. Variations with multiple cables may include one or more pairs of cables routed through the routing mechanism. Additionally or alternatively, one or more cable in a cable system 120 with multiple cables may be used individually for actuating one degree of freedom of the end effector 130.

[0097] In many variations, each cable is terminated at the end effector 130, preferably in connection with the component the cable is used to control. A pair of cables used for one degree of freedom may each be terminated and attached to opposing ends of a degree of freedom so that forces may be supplied in opposing directions. In some variations, a set of cables with multiple cables may technically be multiple cable "lengths" of a single cable where the cable is routed back through the routing mechanism one or more times. In other words, the cable may not be terminated at the distal end where it is fixed or rigidly grounded.

[0098] In some variations, the set of cables are symmetrically arranged around a defined axial center. For example, two cables may each aligned symmetrically offset from an axial center. The offset is preferably minimized so that each of the two cables are close or near the axial center. Accordingly, in a variation with at least two cables, a first cable and a second cable may be symmetrically arranged around a defined axial center of the articulating mechanisms and the set of rigid links. Here the axial center is the axial center of the connected adjacent articulating mechanism or rigid link depending on the configuration of the series of articulating mechanisms 110 and rigid links 118. A pulley hinge joint 112 variation used to route two cables may include two sets of pulleys where each set of pulleys is symmetrically arranged for routing of the cables with an offset from the axial center. The two sets of pulleys are preferably arranged to put the cables as close as pragmatically possible given constraints in cable sizes, pulley sizes and tolerances of the system.

[0099] In a variation with three cables, the set of cables are symmetrically arranged around a defined axial center with one cable substantially aligned with the defined axial center. For example, two cables may each aligned symmetrically offset from an axial center and the third cable being arranged in routed aligned with the axial center. The offset is preferably minimized so that each of the two cables are close or near the axial center. A pulley hinge joint 112 variation used to route three cables may include two sets of pulleys where each set of pulleys is symmetrically arranged for routing of the cables with an offset from the axial center and a another set of pulleys aligned with the axial center.

[0100] In a variation with four cables, a first pair of cables may be aligned symmetrically around a defined axial center with a first offset, and a second pair of cables aligned symmetrically around the defined axial center with a second offset. In this way, the four cables will be arranged with two cables on one side of the defined axial center and two cables on the opposite side. A pulley hinge joint 112 variation used to route four cables may include four sets of pulleys where four sets of pulleys are symmetrically arranged for routing of the cables with an offset from the axial center.

[0101] Some variations may use an asymmetric arrangement. For example, one cable may be centrally located at or substantially aligned with a defined axial center of an articulating mechanisms 110 and the rigid links 118, while a second cable may be offset from the defined axial center.

[0102] Aligning with or being near an axial center, functions to minimize changes to cable length resulting from actuation of the routing mechanism 100. When axially aligned, a cable in theory may experience no or minimal longitudinal displacement when the routing mechanism 100 is actuated. In this way, any longitudinal displacement results from actuation at an input mechanism 200 or an end effector 130. In practice, some longitudinal displacement may happen from twisting of cable and/or from a cable being offset from an axial center. For example, rotating of a roll joint 113 may twist the cable, which can contribute to some allowable displacement. The longitudinal displacement in such cases is preferably within a tolerated range of cable displacement.

[0103] In some variations, cable length within the routing mechanism 100 may experience some changes. However, such changes are preferably within a permitted tolerance range in terms of amount of tension force and/or total change in cable length / cable displacement. Axial twisting of cables and/or minor offsets from an axial center may contribute to some amount of cable length changes. In some variations, however, the length of cable defined along a path of the cable that is projected onto at least one plane may be maintained as a constant length based on the configuration of the routing mechanism 100 and the articulating mechanism 110. As shown in FIG. 4, when the cable length is projected onto a side profile of the routing mechanism, actuation of the articulating mechanisms will see no or negligible change in cable length. As the routing mechanism 100 will move and change positions, each subsection of a pulley hinge joint 112, roll joint 113, and a rigid link 118 may maintain constant cable length when viewed coplanar with the plane of rotation of the pulley hinge joint 112.

[0104] In some variations, the system may include a cable compensating mechanism 150 as shown in FIG. 18, which functions to adjust for deviations in cable lengths thereby permitting amounts of elongation or contraction within one or more cables of the cable system 120. A cable compensating mechanism 150 may be used for each degree of freedom controlled by a cable.

[0105] The cable compensating mechanism 150 may be a device or component through which one or more of the cables run or with which one or more of the cables connect. The cable compensating mechanism 150 may have an amount of cable length that is used as slack within the cable system. Alternatively, the cable compensating mechanism 150 can elongate and/or contract a component to which the cable is connected. The able compensating mechanism 150 can be used to dispense or retract cable to account for variations in the cable length.

[0106] The cable compensating mechanism 150 may be connected in-line with a cable. The cable compensating mechanism 150 in some variations are coupled to a proximal end of each cable of the set of cables 120 (or coupled to a subset of cables of the set of cables 120). In one variation, the cable compensating mechanism 150 may be integrated at one terminating end of the cable 120 such as at the end effector 130 or proximal to the routing mechanism 100. In another variation, the cable compensating mechanism 150 may be connected in-line where on one side the cable is routed through the routing mechanism and on the opposite side of the cable compensating mechanism 150, a cable is routed to some proximal device or end point.

[0107] In one variation, the cable compensating mechanism 150 may be used to calibrate the system. For example, the cable compensating mechanism 150 may be used to take up any slack in cables after an initial setup of the system.

[0108] In another variation, the cable compensating mechanism 150 may be used to remove some cable motion or translation. In some variations, as described, the cable routing mechanism 100 in some eliminates cable movement in and out of the system. However, in some other variations, some amount of cable movement may be present. For example, there may be extreme ends of actuation where cable motion may occur when manipulating the end effector 130 (and as a result the cable routing mechanism 100). The cable compensating mechanism 150 may be used to correct for this cable displacement.

[0109] The cable compensating mechanism 150 may provide some set amount of elongation of the cable. The cable compensating mechanism 150 may also provide a ceiling and floor to amount of elongation displacement of a cable. The cable compensating mechanism 150 may be used to accommodate elongation or displacement of a cable 120, which may happen during manipulation of the cable 120. In some variations, the elongation stiffness of the cable may serve to accommodate displacement of the cable during movement of the routing mechanism 100 through a workspace. However, in some variations, such as when using a cable with high stiffness, a cable compensating mechanism may serve to augment or control allowed amount of displacement.

[0110] The cable compensating mechanism 150 may be a passive mechanical mechanism. In one exemplary variation, the cable compensating mechanism 150 may be or include a spring. In some variations, the spring is a non-linear spring element that may bottom out to provide some fixed maximum or minimum amount of elongation.

[0111] In another variation, a subsection of cable made of a differing material may be used in line with the cable. This cable may be a compensating cable segment made of a material with flexibility in the longitudinal direction. In one implementation, the compensating cable segment may be integrated with rigid stops that prevent elongation beyond a certain amount as shown in FIG. 18. In one variation, a spring may be pre-compressed so that the cable compensating mechanism 150 compresses only for a set force. The amount of compression of the spring (and corresponding lengthening of the cable) may be fixed by a rigid stop. In one exemplary implementation, the compensating cable segment may include rigid stopping structure may be integrated at point such as at a meeting point between the cable and the compensating cable segment. A rigid frame may surround the compensating cable segment or otherwise connected such that the stopping structure engages with the rigid frame when a flexible cable is elongated a set distance.

[0112] The cable compensating mechanism 150 may alternatively be an active system. As an active cable compensating mechanism 150, may use a motorized or electromechanical way of controlling and/or augmenting cable positioning by effectively “elongating” the cable or “shortening” the cable. An active cable compensating mechanism 150 may include one or more sensor inputs to impact amount of cable length compensation supplied by the active cable compensating mechanism 150. In one variation, sensors may monitor actuation of each articulating mechanisms 110, interpret posture of the routing mechanism (e.g., the angles and position of each articulating mechanism), and then actively compensate cable longitudinal position based on the posture of the routing mechanism. Some postures may be predicted or modeled to cause more longitudinal elongation of the cable and therefore, the cable compensating mechanism 150 may extend or elongate to shift the cable to compensate. Some postures may be predicted or modeled to cause longitudinal contraction of the cable and therefore the cable compensating mechanism 150 may contract or shorten the cable to compensate. The sensors may additionally or alternatively include a camera or other type of imaging system to model posture of the routing mechanism 100. In another variation, the sensors could directly sense the tension of the cable. In this variation, the active cable compensating mechanism 150 may control cable longitudinal displacement through a control system to keep longitudinal tension to be maintained within a set threshold.

[0113] The end effector 130 functions as a system that is manipulated in space while remaining engaged with the cable(s) 120 routed through the cable routing mechanism 100. The end effector 130 will generally have one or more degrees of freedom or actuation effect. The end effector 130 may additionally include additional or alternative components such as sensors, applicators, scopes, and/or other components.

[0114] In one variation, the end effector has one degree of freedom that is driven by a cable that is routed through the cable routing mechanism. The degree of freedom may alternatively be driven by two cables such as two cables working antagonistically on the degree of freedom. The degree of freedom could, for example, be a form of linear actuation or rotational actuation. The end effector 130 can be mounted to a distal end of the routing mechanism 100. In some variations, this may include mounting the end effector 130 to a distal end of a final pulley hinge joint 112.

[0115] In one variation using two cables to actuate a needle end effector, the system can comprise a cable system 120 that is a set of cables with at least a first cable and a second cable; wherein the first cable and the second cable are symmetrically arranged around a defined axial center of the articulating mechanisms and the set of rigid links; and wherein the end effector is a needle insertion end effector with an actuating longitudinal insertion position; and wherein the first cable and the second cable may be mounted to opposing ends of the actuating longitudinal insertion position.

[0116] The end effector 130 is preferably coupled mechanically through the cable system 120 to some input mechanism 200. In some variations, the input mechanism 200 controlling the cable 120 may be fully or partially passive and controlled fully or partially by a human operator. An example of this could be a hydraulic manipulator system 210. Direct control by a human operator may have beneficial implications for medical device regulatory approval.

[0117] The end effector 130 can preferably be manipulated by an outside system or potentially by a human operator. In one variation, the end effector 130 may additionally connect to an actuation interface 310. The actuation interface 310 is a linkage or a suitable physical connection to a connected actuation system 300. The actuation interface 310 may have one or more degree of freedom with respect to the end effector. For example, in one variation, the actuation interface 310 may have a rotational degree of freedom. Additionally or alternatively, the end effector 130 may have an actuation interface 310 with a handle structure which functions as a human adapted physical interface for moving and positioning the end effector 130.

[0118] In some medical applications, a variation of the end effector 130 may include a needle insertion end effector 132 that functions to control insertion and/or retraction of a needle as shown in FIG. 6. A needle insertion end effector 132 may include a first linear degree of freedom for actuation of a needle component. Actuating the linear degree of freedom may facilitate needle insertion and removal. The needle insertion end effector 132 can include a needle or some other medical instrument subject to insertion manipulation. Insertion of a needle during a medical operation is one that can benefit from having high amounts of human control.

[0119] In one exemplary application, a cable 120 routed through the cable routing mechanism 100 couples to a needle end effector 132. This can enable insertion actuation of the needle to be driven through actuators (e.g., an input mechanism 200) at the base of the cable routing mechanism 100. When a single cable is used, a spring or some other mechanism with a restorative force may act on a degree of freedom of the device. When a pair of cables is used, a first cable may be mounted to pull in the direction of insertion and a second cable may be mounted to pull in a direction opposite of insertion (i.e., a direction of retraction).

[0120] Additionally or alternatively, the needle insertion end effector 132 may include a rotational degree of freedom. The angular orientation of the needle or some other device may be controlled using one or more cables. In one variation, a pair of cables is used to control angular orientation of a needle of the end effector 132. A first cable of the pair of cables may wrap around a hub coupled to the needle (or other end effector) in one direction and a second cable of the pair of cables may wrap around the hub in another direction. Pulling on one or the other cable can rotate the needle in one or the other direction.

[0121] In other variations, the degree of freedom may be actuating some opening or closing mechanism which may be used for cutting, grasping, deploying or retracting a device, and/or any suitable actuation.

[0122] Actuation of the needle insertion end effector may be controlled using an antagonistic pulley system, where the cable routing mechanism would include at least two cables routed through the cable routing mechanism 100. As shown in FIG. 6, a first end of a cable 601 is terminated at one end 602 of a pulley system of the needle insertion end effector 132 and a second cable 603 is terminated at another end 604 of a pulley system of the needle insertion end effector 132, which can result in antagonistic or opposing hydraulic actuation. For example, a fist cable (601) may be terminated at a distal end of the pulley system in a first termination structure (602) grounded to the needle insertion end effector 132, and a second cable (603) may be terminated at proximal end of the pulley system in a second termination structure (604) grounded to the needle insertion end effector 132. The two cables may be actuated in synchronized and opposing manners to control insertion and retraction of a needle along a linear path.

[0123] The end effector may alternatively be any suitable type of end effector including one or more aspects controlled through the cables.

[0124] In one variation, the needle insertion end effector 132 may include a needle guide 133 as shown in 1, which functions to physically guide a needle. The needle guide 133 may be attached to the needle end effector and rigidly block movement of the needle in some axial direction. In one variation, the needle guide 133 may surround the needle. A needle guide 133 may surround the needle with some distance between the needle and the guide. Alternatively, the needle guide 133 may surround the needle, where the guide contacts the needle. In such a variation, the needle guide 133 may be lubricated or be made of low friction material. The needle guide 133 and/or the needle used with the needle insertion end effector 132 may be removable and replaceable components. This may be done so that the needle and guide can be replaced between use.

[0125] In some variations, the system may alternatively include an interface with an outside end effector (e.g., an end effector interface). Accordingly, an end effector may not be part of the system, but an end effector interface may function to facilitate coupling to and integrating with an external end effector or any suitable component.

[0126] The routing mechanism 100 preferably includes a mounting base 140 used to ground or fix the routing mechanism 100 to some surface. The mounting base 140 is preferably on a proximal end of the routing mechanism. As shown in FIG. 1, the mounting base 140 may connect to a first articulating mechanism 110 like a pulley hinge joint 112. In another variation, the mounting base 140 may connect to a first rigid link 118.

[0127] In one variation, the mounting base 130 may connect to or be rigidly connected to a grounded structure as shown in FIG. 14. The grounded structure may be a substantially fixed structure that does not move during use of the system. As shown in the example of FIG. 16 and FIG. 17, a mounting base 130 may be connected to a grounded structure while a robotic actuation system is also grounded to the same ground structure moves.

[0128] In another variation, the mounting base 130 may be connected to a moving structure. In particular, the mounting base 130 may be connected to structure of an actuation system 300 or manipulator. In one example, the mounting base 130 may be connected to some movable segment of a robotic actuation system 300 while the end effector 130 can be manipulated by a distal end of the robotic actuation system 300 as shown in FIG. 15. In this way, the routing mechanism 100 may move with the motion of the actuation system 300, while the end effector can also be independently moved relative to the mounting base 140. When a hydraulic manipulator system 210 is used as an input mechanism, hydraulic lines may be routed to the movable segment. In one variation, hydraulic tubes may be flexible so that they can move and route as the movable segment moves. In another variation, hydraulic tubes or conduits may be built into robotic rotary joints of the robotic actuation system 300.

[0129] In some variations, the system may include or interface with an input mechanism 200, wherein the input mechanism functions to actuate the cables 120. Actuation of the cables 120 by extension may mechanically manipulate the coupled end effector 130. The input mechanism is preferably coupled to a proximal end of the cable system 120 (e.g., to each of the set of cables). The actuation input to the input mechanism could be hydraulically controlled, motor controlled, human operator controlled, or controlled in any suitable manner.

[0130] When multiple degrees of freedom are controlled, then the system may include multiple input mechanisms 200 for controlling different degrees of freedom. However, one input mechanism 200 may control multiple degrees of freedom. The input mechanism 200 may actuate a pair of cables in an antagonistic manner where the actuation of cables is inversely directly proportional: extending one cable results in contracting of the other cable of an equal distance. The cables are preferably held in tension with the input mechanism 200.

[0131] In some variations, the input mechanism 200 may be an active actuating system such as an input hydraulic manipulator system 210 or a motor-driven actuator. An actively actuated input mechanism 200 may be used to drive actuation of the cables through some connected system. In some variations, the connected system may be electrically or digitally controlled. In other variations, the connected system may be mechanically coupled (such as through pneumatic or hydraulic means) to some other actuation system driving actuation.

[0132] In one variation, an active input mechanism 200 is a hydraulic manipulator system 210. The cable 120 may be connected to the input hydraulic manipulator system 210 on the proximal end of the cable routing mechanism 100 and to some actuating component of an end effector 130. In some variations, the cable 120 is one suitable for a pulley-based mechanism and may be used to actuate components of the end effector based on supplied cable actuation input from some proximal point of the cable routing mechanism as shown in FIG 13.

[0133] A hydraulic system may be used to drive the hydraulic manipulator system 210. A hydraulic system could include hydraulic system sub-components like a reservoir, pressure pump, circulation pump, pressure sensor, exhaust valve, and/or other components. In some variations, the system may include the hydraulic system.

[0134] In other variations, the input mechanism 200 may be a manual input mechanism 200 that is a mechanical user interface input mechanism 200. A manual input mechanism functions to provide a physical device that when manipulated by an operator drives the actuation of the cables and by extension a connected end effector.

[0135] The input mechanism 200 could be human operated control or alternatively coupled to some other form of actuation. In one exemplary variation, a pair of cables routed through the routing mechanism 100 may be routed around a perimeter of a rotating cylinder as shown in FIG. 14. In one variation, the cables are routed around rotatable disc on opposing sides and then terminated. Rotating the disc may pull one cable while pushing (or extending) the other cable. The size of the disc may be adjusted based on the actuation range for the end effector. For example, the diameter of the disc may correspond to the distance of needle insertion. In another variation, the cables may be wrapped around a wheel so that the wheel can be turned multiple times where a supply of cable comes from a reserve of cable wrapped around the wheel.

[0136] The system may include or interface with an actuation system 300. In some variations, the system includes an actuation interface 310 to facilitate connecting to an actuation system 300.

[0137] The actuation interface 310 functions as a point of manipulation of the distal end of the routing mechanism (e.g., the end effector) for a connected actuation system or a manipulator. The actuation interface 310 may be a fixture or structure with which an actuation system or some manipulator may connect and manipulate the distal portion of the routing mechanism 100. The actuation interface 310 may be coupled to the end effector and/or distal to the last articulating mechanism 110. As shown in FIG. 1, the actuation interface 310 may be coupled distal to a third pulley hinge joint 112.

[0138] The actuation interface 310 may include a rotational degree of freedom (e.g., a roll joint). When used with a routing mechanism 100 with five articulating mechanisms contributing 5 degrees of freedom to the routing mechanism 100, a rotational degree of freedom in the actuation interface 310 may result in effectively enabling manipulation of the end effector with six degrees of freedom. For example, the actuation interface 310 may rotate in the example of FIG. 1, which would result in a total of six DOF.

[0139] The actuation interface may include an attachment shaft or some other structural element to which some source of physical actuation and manipulation attaches. This outside source of movement can reposition the end effector in different ways depending on the degrees of freedom.

[0140] In some variations the actuation interface may be configured for manipulation by a human. Accordingly, the actuation interface 310 may be a grip, handle or other suitable physical user interface for manual manipulation of the end effector 130.

[0141] The system may include or interface with an actuation system 300. The actuation system 300 functions to actively actuate and move the end effector and by extension move the routing mechanism 100. The actuation system can preferably actuate position and/or orientation of the end effector 130. The cable routing mechanism 100, being physically coupled to the end effector 130, will passively follow actuation of the actuation system 300. The system can preferably accommodate a wide variety of types of actuation systems such as articulated robotic arms, an RCM (Remote Center of Motion) actuation system (which itself may be hydraulically driven), and/or any suitable source of actuation.

[0142] In one variation, a robotic arm 320 or other sort of motor controlled robotic system could physically couple to the end effector and move the end effector. For example, a robotic arm 320 with six DOF could move a needle insertion end effector 132 into position, and then a doctor could use a hydraulic input to control insertion of the needle, which would provide haptic feedback and enhanced control of the insertion process.

[0143] As shown in FIG. 16, the routing mechanism 100 may be mounted to shared ground structure as an articulated robotic arm 320 used as the actuation system 300. In another variation shown in FIG. 15, the system (e.g., the routing mechanism) includes a mounting base 140 connected distally to the series of articulating mechanisms (e.g., directly or via a rigid link), where the mounting base 140 is connected with a segment of the articulated robotic arm 320. In a variation where a hydraulic manipulator system 210 is used or some other input mechanism 200 that requires a connection for controlling the end effector, cables or connections can be run to the input mechanism 200 that is also mounted on the segment of the articulated robotic arm 320. In one variation, hydraulic tubes may be flexible so that they can move and route as the movable segment moves. In another variation, hydraulic tubes or conduits may be built into robotic rotary joints of the robotic actuation system 300.

[0144] In another variation, the actuation system 300 may be an RCM actuation mechanism. The RCM actuation mechanism 330 could be hydraulically controlled as well. Accordingly, the system may include or interface with a hydraulic actuation system 332 connected to the RCM actuation mechanism 330 as shown in FIG. 12. As one advantage of the RCM actuation mechanism 330, the RCM actuation mechanism 330 may be an actuation system 300 that can be made with MRI compatible materials. In some variations, the RCM mechanism may be made of MRI-compatible materials along with all the components of the system. In such variations, the system could be used for MRI-guided use of the end effector. For example, a needle could be inserted into a patient while the patient is undergoing MRI scanning. In some variations, to facilitate use of MRI compatible materials or for other reasons, the input mechanism 200 used to actuate the cable system 120 may additionally be driven by a hydraulic manipulator system 210 connected to another hydraulic system as shown in FIG. 13.

[0145] The RCM actuation mechanism 330 may provide remote center of motion movements suitable for surgical procedures. While the system may be adapted to any suitable type of surgical tool, one variation of the end effector is a needle insertion mechanism. As shown in FIG. 19, the RCM actuation mechanism 330 may include a translational mechanism 3310; a remote center of motion (RCM) mechanism 3322 coupled to a distal end of the translational mechanism 3310; the needle insertion end effector 132 being coupled to the distal end of the RCM mechanism 3322; a driving actuation system 3350 which includes a set of actuation couplers 3352 that are coupled to the translational mechanism 3310 and the RCM mechanism 3322 for integration with at least four degrees of freedom. The actuation couplers 3352 may be hydraulic transmissions or some other mechanical transmission to interface with mechanical linkages of the translational mechanism 3310.

[0146] In some variations, the system includes an RCM connector to couple the RCM mechanism 3322 to the distal end of the translational mechanism 3310. Additionally, the translational mechanism 3310 may include two multi-bar linkages arranged in a stacked parallel configuration. In other words, the translational mechanism 3310 may be a mechanism with translational actuation aligned along a defined horizontal plane, and that includes a top multi-bar linkage and a bottom multi-bar linkage. For example, the system may include a 5-bar linkage 3311 and a 6-bar linkage 3312 arranged in a stacked arrangement, one on top of another as shown in FIG. 20A. In some variations, the system may include two 6-bar linkages 3312/3313 as shown in FIG. 20B. In such variations, the translational mechanism can actuate or otherwise provide in part four degrees of freedom with two translational actuation and two angular degrees of freedom. In some variations, the RCM actuation mechanism 330 may be substantially similar to the system described in published PCT application WO2024086671.

[0147] When the system is to be used alongside imaging technology like an MRI device, then part or all the components of the system may be made of MRI compatible materials such as using plastic or other non-metal components. For example, the components of the system may be made of materials compatible with an MRI machine or another type of scanner device. MRI compatible materials or more generally scanner compatible materials may include non-magnetic materials, non-conductive materials, radio frequency (RF) transparent materials, non-ferromagnetic materials, and/or other material types that would be suitable for use in environments or conditions with material restrictions. This may additionally mean that system components in the restricted environment may lack any electronics. Variations of the system may enable MRI or scanner compatible devices for the routing mechanism 100, the input mechanism 200 and/or the actuation system 300 and its components. For example, the routing mechanism 100 may be MRI compatible by making the articulating mechanisms 110, the rigid links 118, the set of cables 120, and the end effector 130 out of MRI compatible material. The RCM actuation mechanism 330 is on device that may be used to actuate and manipulate the end effector while being made out of MRI compatible material. Accordingly, the articulating mechanisms 110, the rigid links 118, the set of cables 120, the end effector 130, and the remote center of motion mechanism 330 may be made of MRI compatible material. Additionally, the input mechanism 200 such as a hydraulic manipulator system 210 may be made of MRI compatible material.

[0148] The structural form of the cable routing mechanism may support easy actuation of the end effector without the cable routing mechanism interfering with the actuation system 300. As shown in the examples of FIG. 12 and FIG. 13, using the cable routing mechanism 100, actuation of needle insertion axis leapfrogs the exemplary RCM actuation mechanism 330 and can be done with a grounded actuator at the base. The exemplary RCM actuation mechanism 330 is used to manipulate the cable routing mechanism 100 to any position within its workspace. In this case, the RCM actuation mechanism 330 may be a specialized 4-DoF device, but this could be replaced with a robot arm or other device.

[0149] As used herein, first, second, third, etc. are used to characterize and distinguish various elements, components, regions, layers and/or sections. These elements, components, regions, layers and/or sections should not be limited by these terms. Use of numerical terms may be used to distinguish one element, component, region, layer and/or section from another element, component, region, layer and/or section. Use of such numerical terms does not imply a sequence or order unless clearly indicated by the context. Such numerical references may be used interchangeable without departing from the teaching of the embodiments and variations herein.

[0150] As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the embodiments of the invention without departing from the scope of this invention as defined in the following claims.

CLAIMS

We Claim:

1. A system comprising:

    a series of articulating mechanisms interconnected through a set of rigid links, wherein the series of articulating mechanisms comprises:
    a set of pulley hinge joints and a set of roll joints;
    a set of cables routed through the series of articulating mechanisms, wherein each articulating mechanism is configured to actuate while preserving cable length of the set of cables; and
    an end effector with at least one degree of freedom coupled to the cable.

2. The system of claim 1, wherein the end effector is a needle end effector with a linearly actuating degree of freedom that actuates longitudinal insertion position of the needle end effector.
3. The system of claim 1, wherein each pulley hinge joint of the set of pulley hinge joints comprises: opposing pulleys that engage with the set of cables passing through the pulley hinge joint, the opposing pulleys configured for conservation of cable length across a defined range of rotational motion.
4. The system of claim 1, further comprising a cable compensating mechanism coupled to a proximal end of at least one cable of the set of cables.
5. The system of claim 1, wherein the series of articulating mechanisms comprises of at least a first pulley hinge joint directly coupled to a roll joint, wherein the roll joint is connected to another articulating mechanism through a rigid link.
6. The system of claim 1, wherein the series of articulating mechanisms comprised of the set of pulley hinge joints and the set of roll joints comprises a first pulley hinge joint coupled of to a first roll joint, the first roll joint coupled to a second pulley hinge joint through a first rigid link, the second pulley hinge joint coupled to a second roll joint, the second roll joint coupled to a third pulley hinge joint through a second rigid link, and the third pulley hinge joint coupled to the end effector.

7. The system of claim 6, further comprising an actuation interface with a rotational degree of freedom, the actuation interface coupled distal to the third pulley hinge joint.
8. The system of claim 1, wherein the series of articulating mechanisms further comprises a prismatic linear-sliding joint.
9. The system of claim 8, wherein the prismatic linear-sliding joint comprises a first rack and second rack coupled for opposing actuation through a compound gear with a first gear and second gear that has a two to one gear ratio, where a first gear engages the first rack and the second gear engages the second rack, and the prismatic linear-sliding joint further comprising a pulley system that routes a reserve of the set of cables that compensates for actuation of the prismatic linear-sliding joint.
10. The system of claim 8, wherein the series of articulating mechanisms comprised of the set of pulley hinge joints, the set of roll joints, and the prismatic linear-sliding joint comprises a first roll joint coupled to a first pulley hinge joint through a rigid link, the pulley hinge joint coupled to a second roll joint, the second roll joint coupled to a prismatic linear joint, the prismatic linear joint coupled to a second pulley hinge joint through a second rigid link, and the second pulley hinge joint coupled to the end effector.
11. The system of claim 10, further comprising an actuation interface with a rotational degree of freedom, the actuation interface coupled distal to the second pulley hinge joint.
12. The system of claim 1, wherein the set of cables comprises at least a first cable and a second cable.
13. The system of claim 12, wherein the at least first cable and second cable are symmetrically arranged around a defined axial center of the articulating mechanisms and the set of rigid links.
14. The system of claim 13, wherein the end effector is a needle insertion end effector with an actuating longitudinal insertion position; and wherein the first cable and the second cable are mounted to opposing ends of the actuating longitudinal insertion position.

15. The system of claim 1, wherein the articulating mechanisms, the rigid links, the set of cables and the end effector are made with MRI-compatible materials.
16. The system of claim 1, further comprising an input mechanism wherein the input mechanism is coupled to a proximal end of the set of cables.
17. The system of claim 16, wherein the input mechanism is coupled to a hydraulic manipulator system.
18. The system of claim 16, wherein the input mechanism is a manual input mechanism.
19. The system of claim 1, further comprising: an actuation interface coupled to the end effector; and an actuation system that is coupled to the actuation interface, wherein the actuation system actuates position and orientation of the end effector.
20. The system of claim 19, wherein the actuation system is an articulated robotic arm.
21. The system of claim 20, further comprising a mounting base connected distally to the series of articulating mechanisms, the mounting base being connected to a segment of the articulated robotic arm.
22. The system of claim 19, wherein the actuation system is a remote center of motion mechanism, wherein actuation of the remove center of motion mechanism is driven by a hydraulically controlled.
23. The system of claim 22, wherein the articulating mechanisms, the rigid links, the set of cables, the end effector, and the remote center of motion mechanism are made with MRI-compatible materials.
24. The system of claim 1, wherein the set of cables comprises at least one sensing cable.

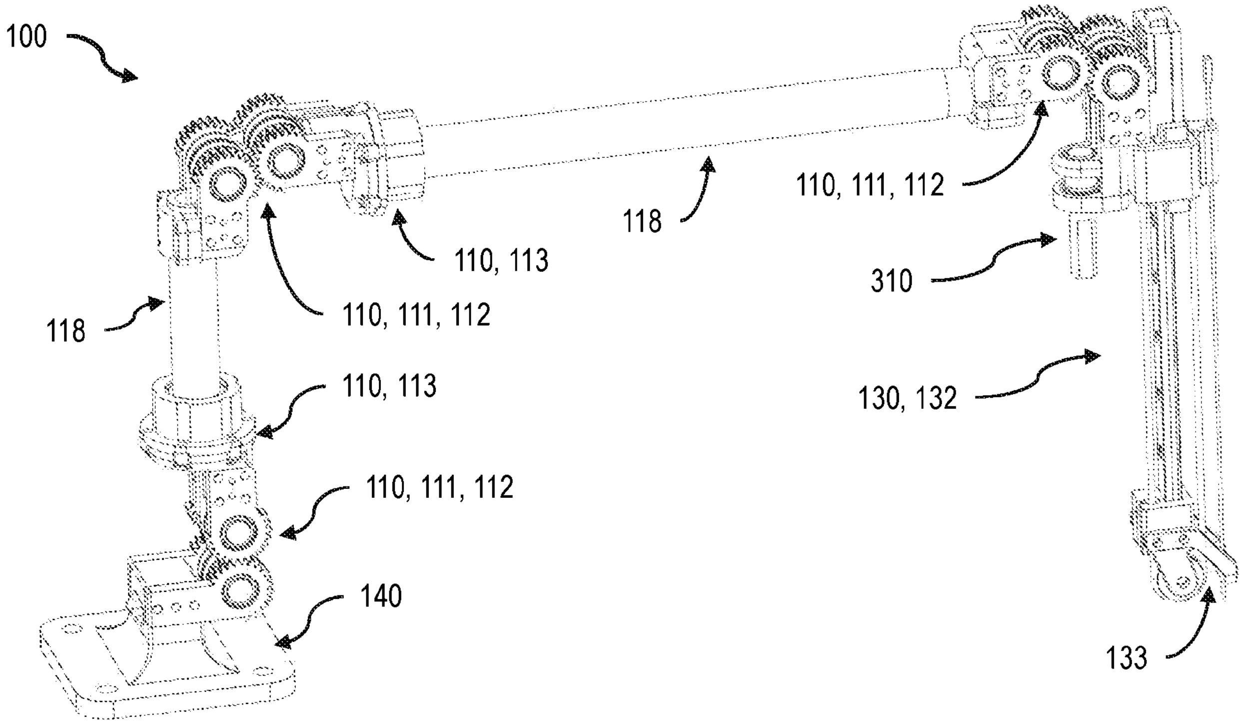
100
110, 111, 112
110, 113
118
110, 111, 112
310
118
110, 111, 112
110, 113
130, 132
110, 111, 112
140
133

FIG. 1

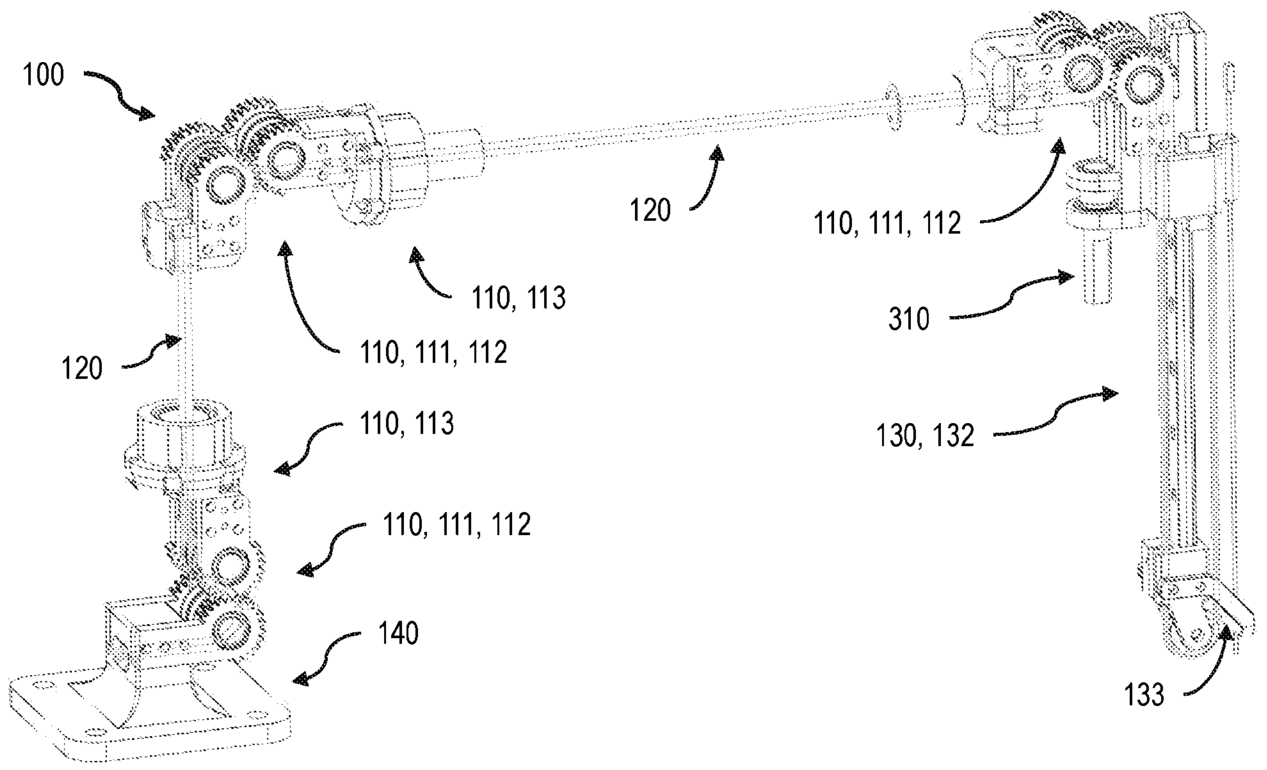
100
120
110, 111, 112
110, 113
110, 111, 112
120
110, 113
110, 111, 112
140
310
130, 132
133

FIG. 2

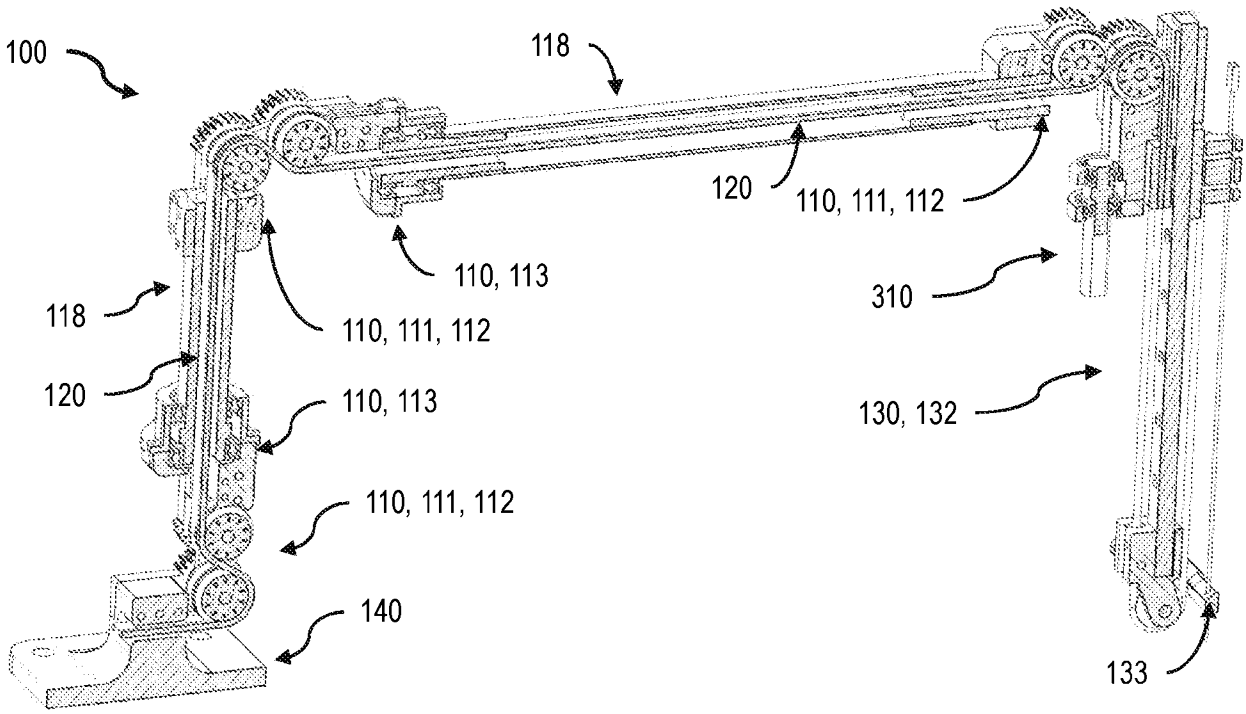
100
118
118
120
110, 113
110, 111, 112
120
110, 111, 112
110, 113
110, 111, 112
140
310
130, 132
133

FIG. 3

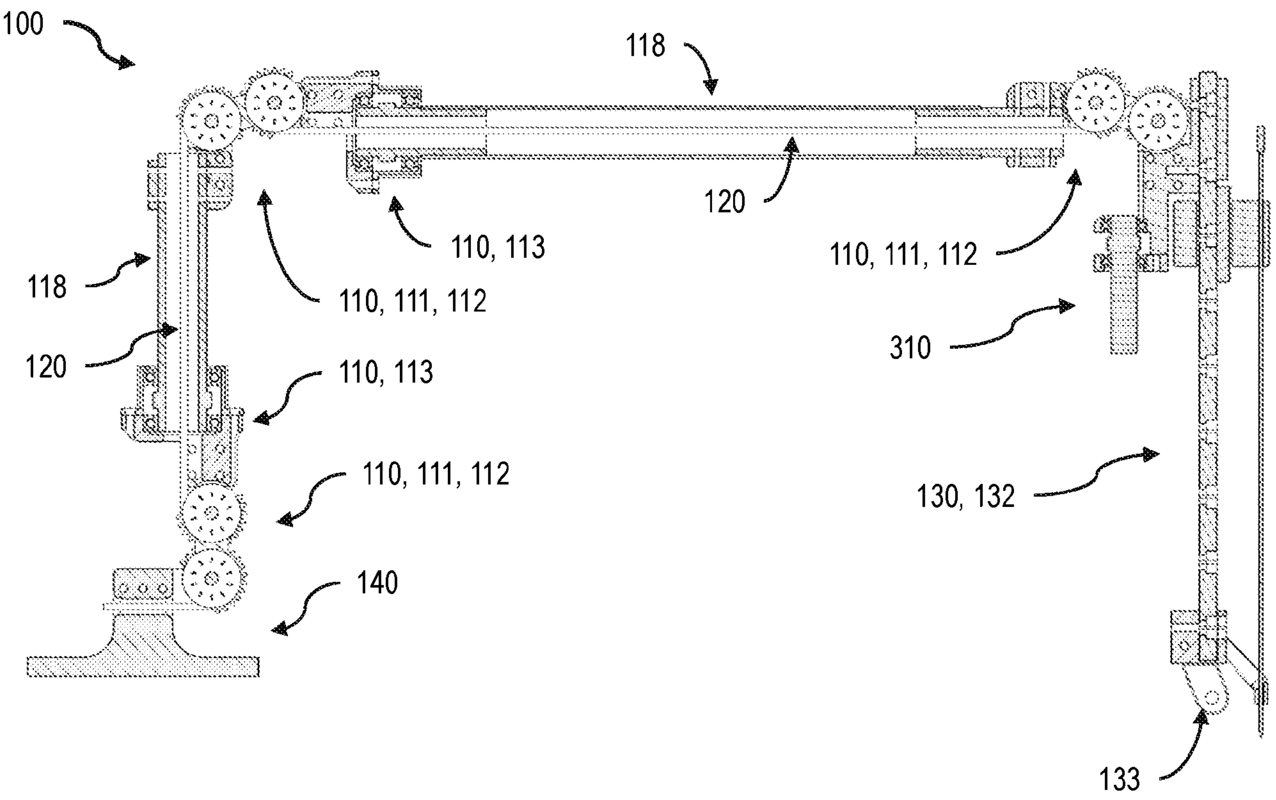
100
118
120
110, 113
110, 111, 112
310
118
120
110, 111, 112
110, 113
110, 111, 112
140
130, 132
133

FIG. 4

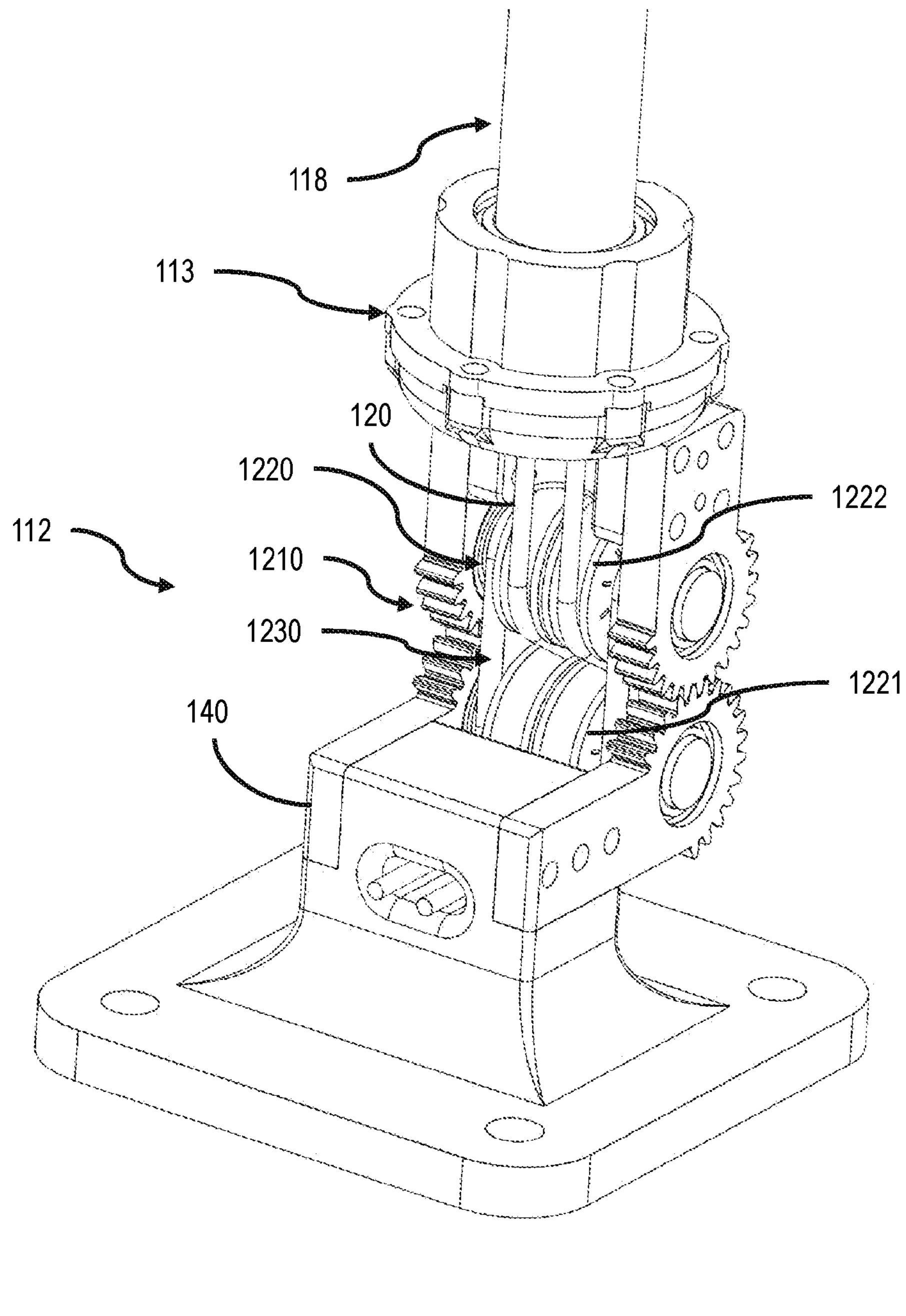

FIG. 5A

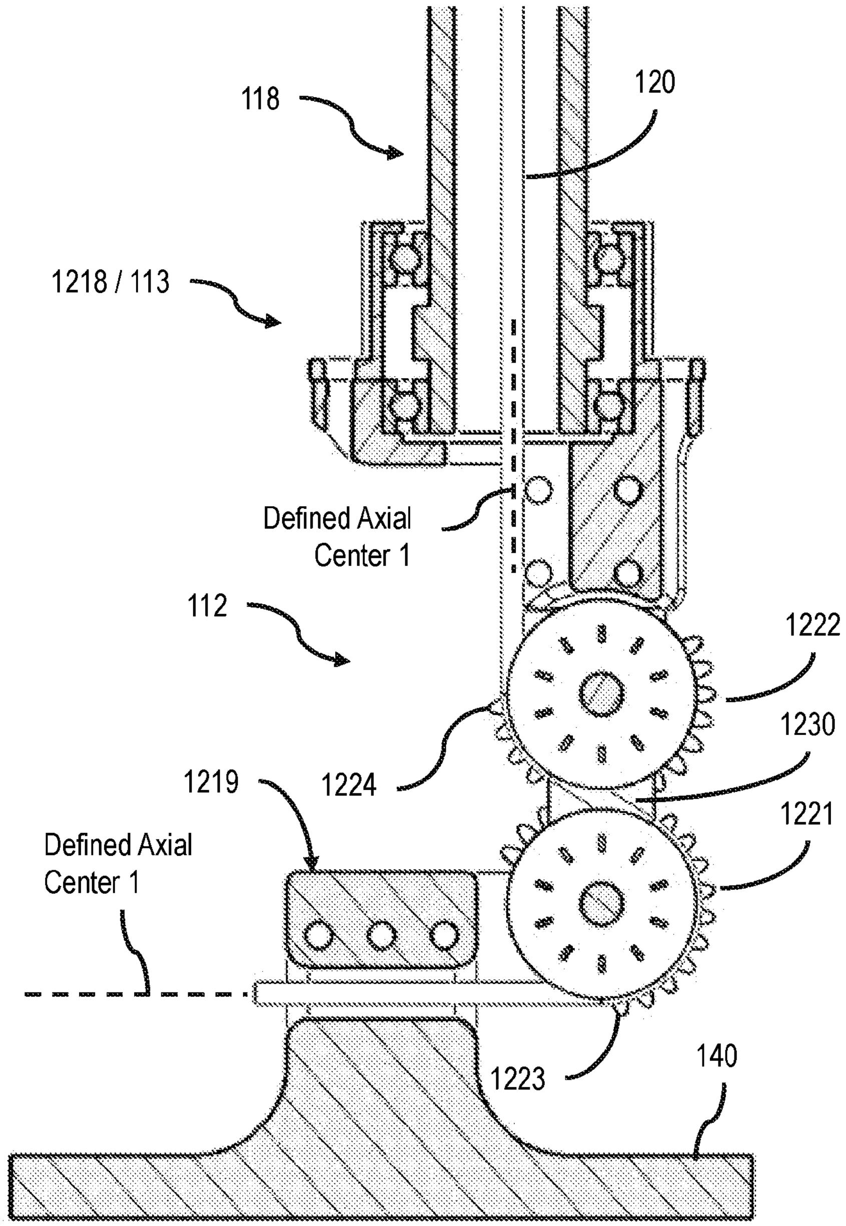
118
120
1218 / 113
Defined Axial
Center 1
112
1222
1230
1224
1219
1221
Defined Axial
Center 1
1223
140

FIG. 5B

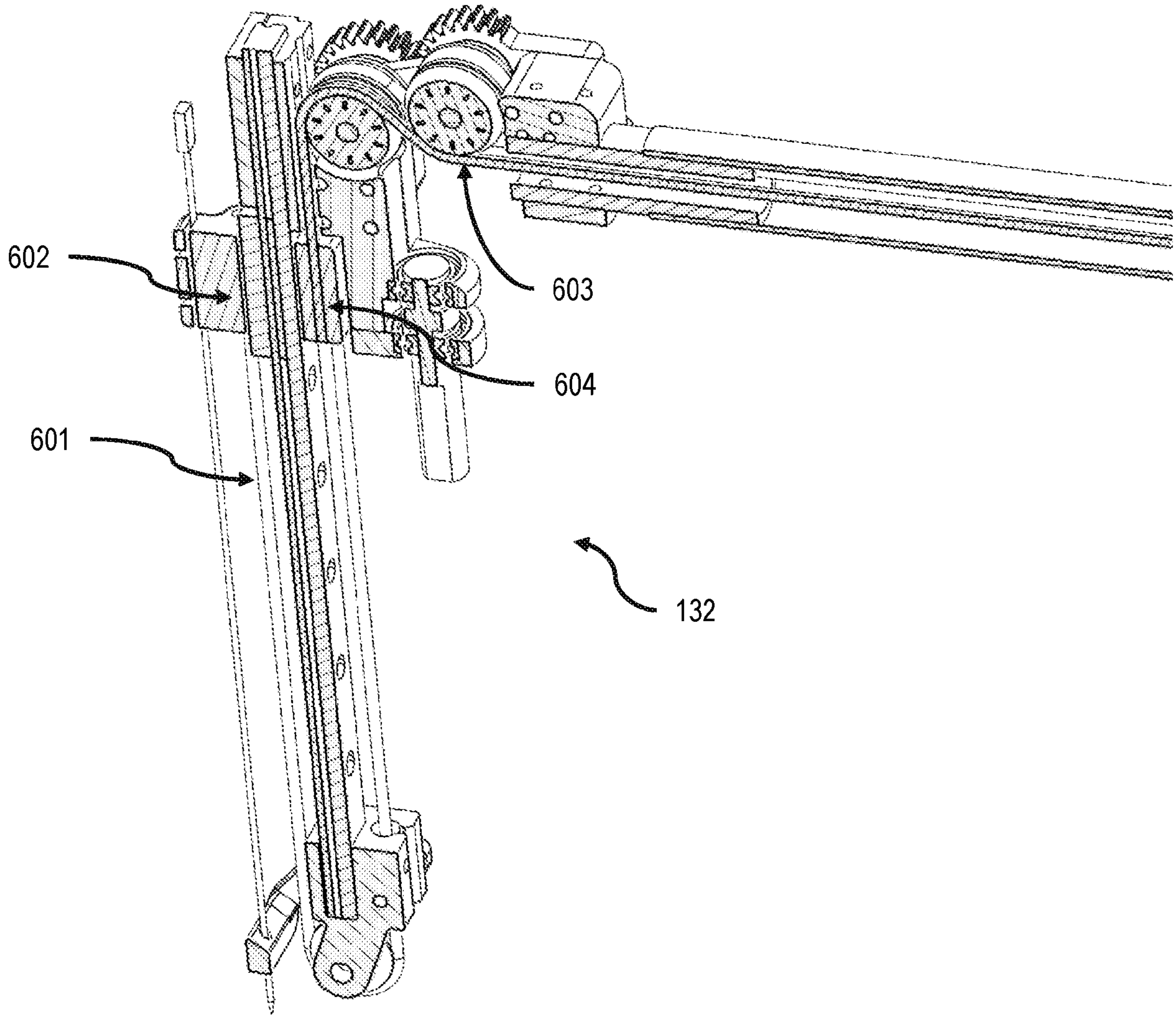

FIG. 6

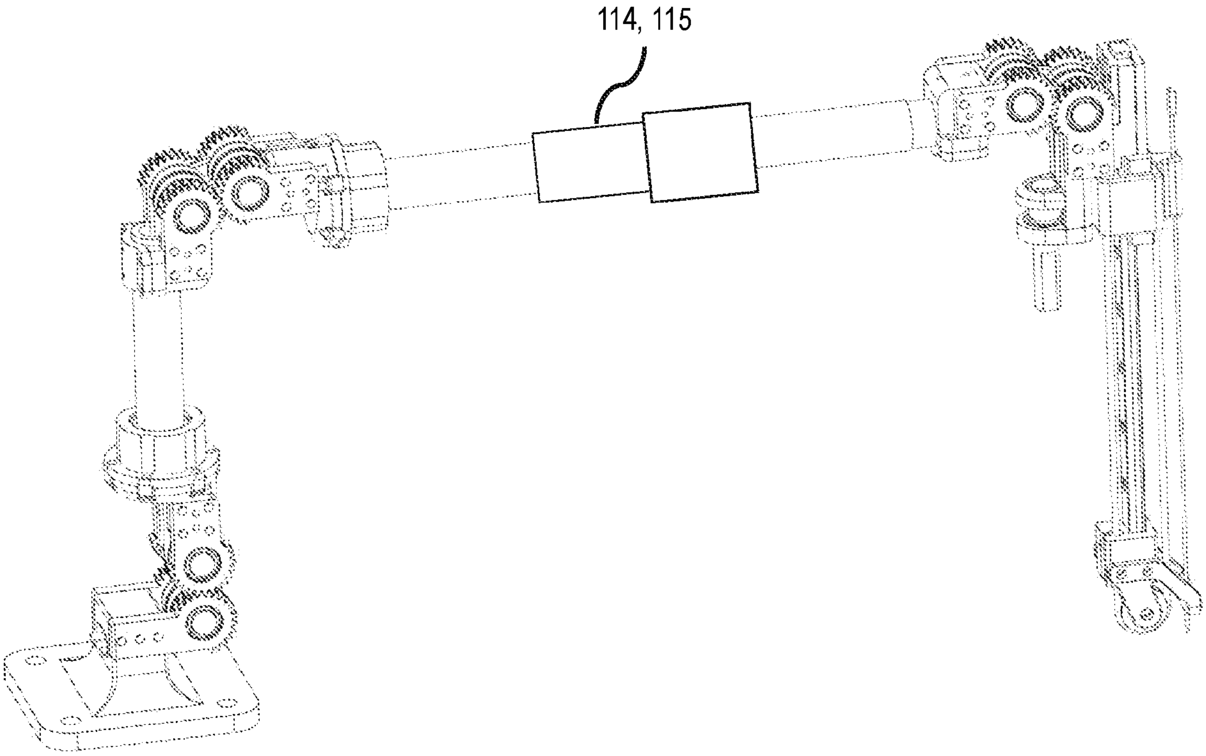

FIG. 7

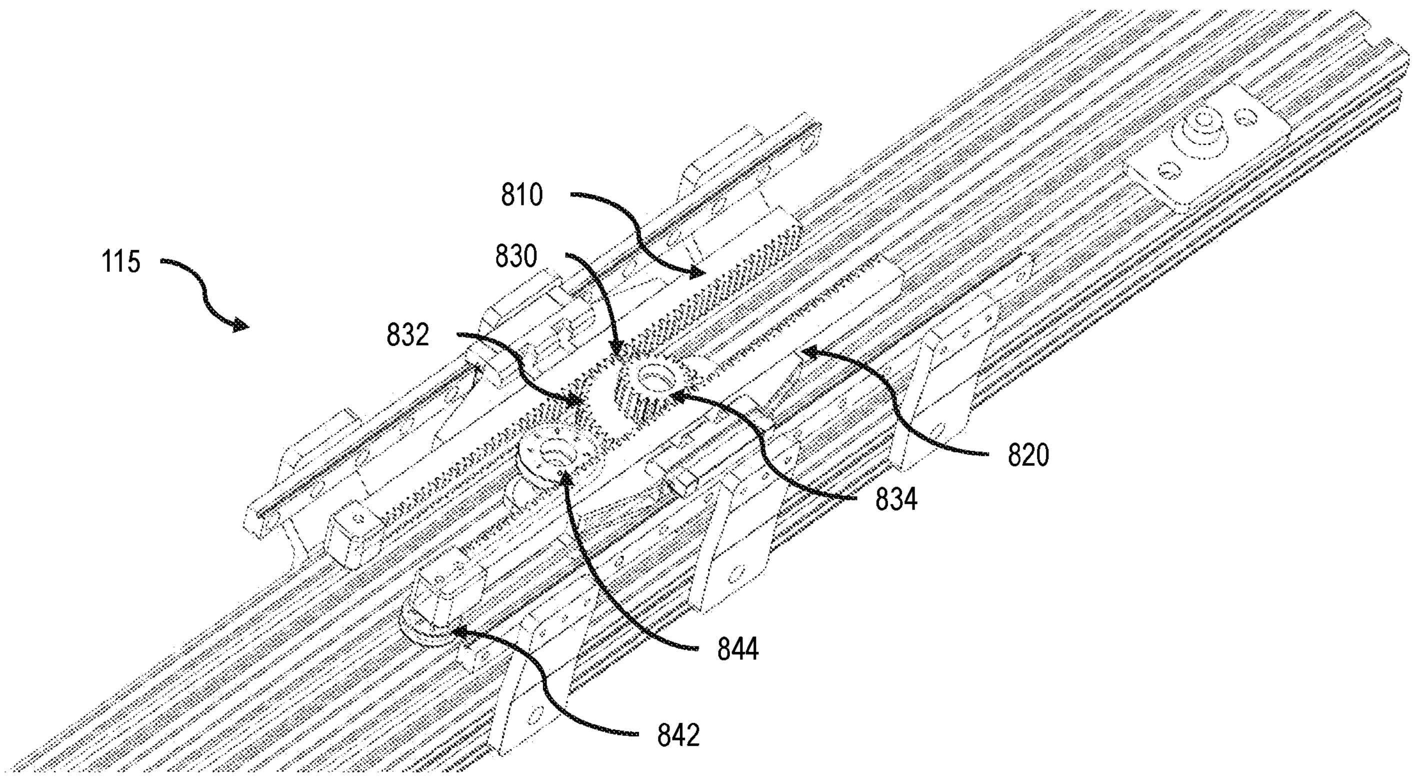

FIG. 8A

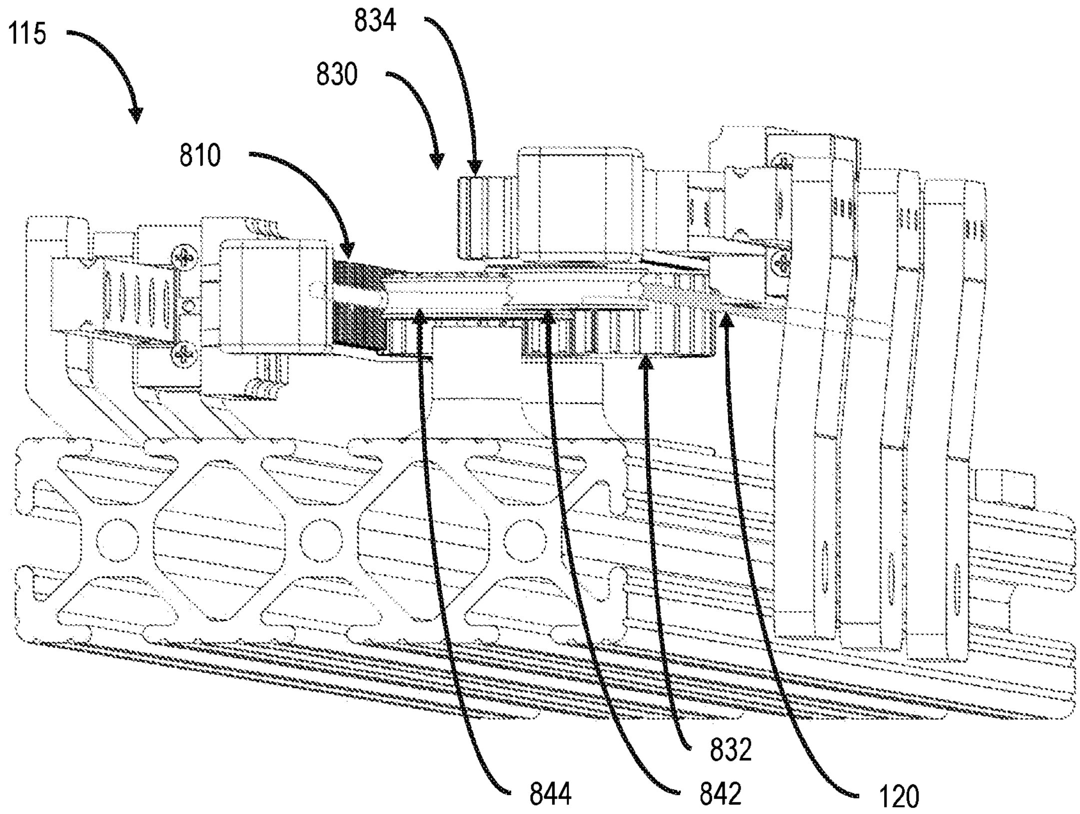

FIG. 8B

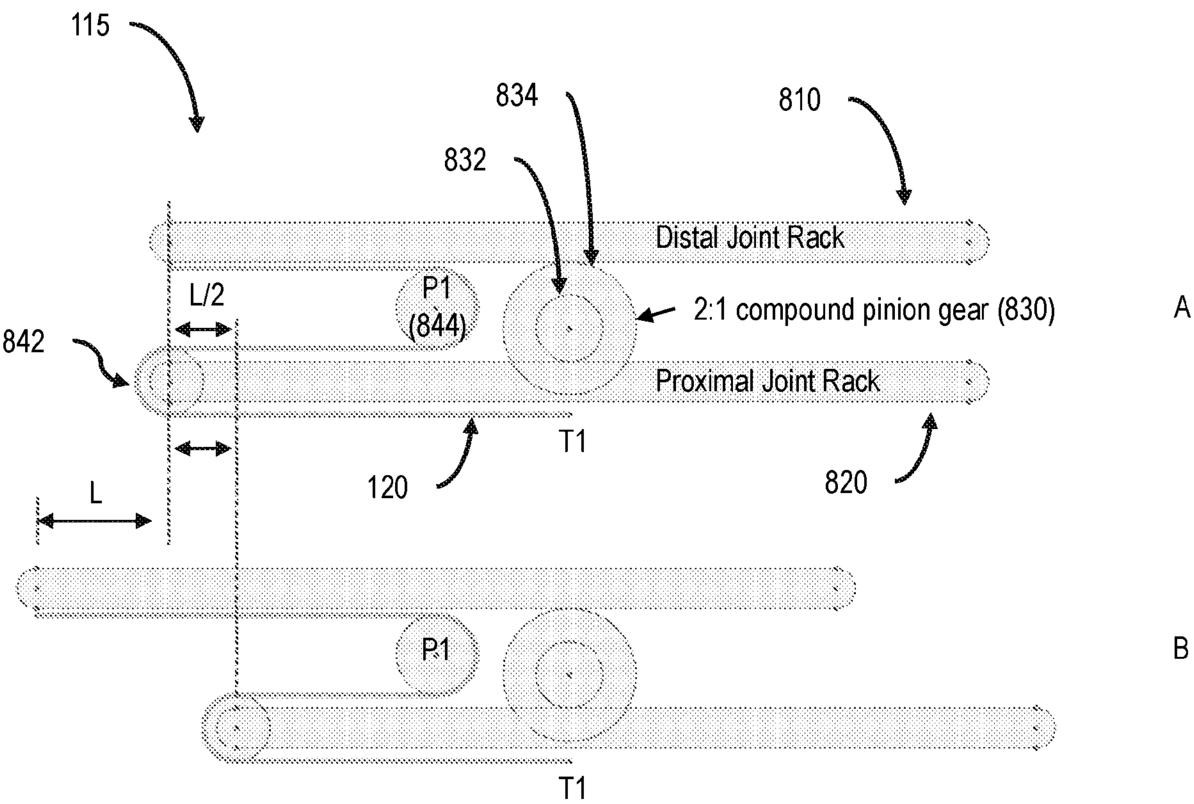
115
834
810
832
Distal Joint Rack
L/2
P1
(844)
2:1 compound pinion gear (830)
A
842
Proximal Joint Rack
T1
120
820
L
P1
B
T1

FIG. 9

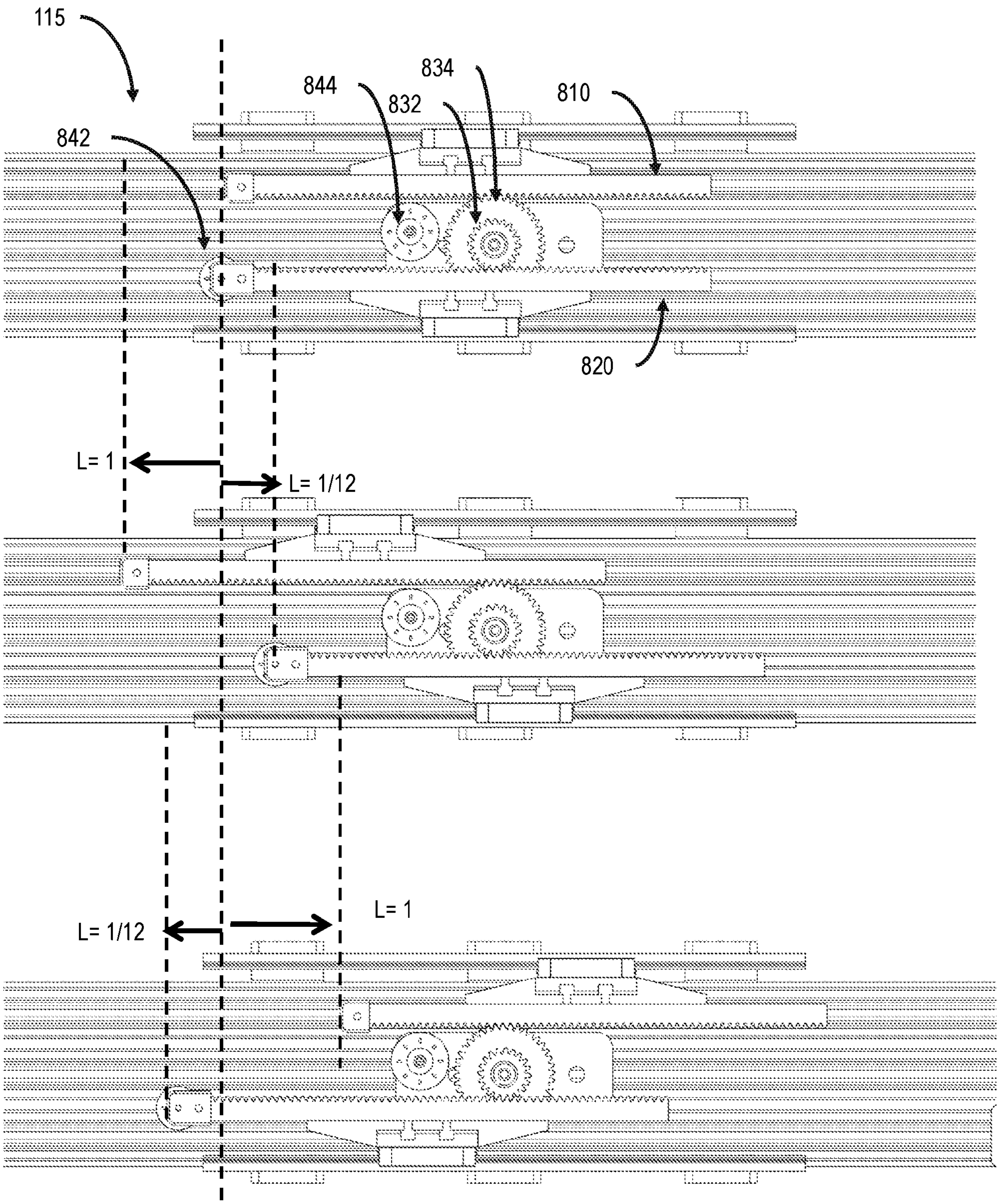

FIG. 10

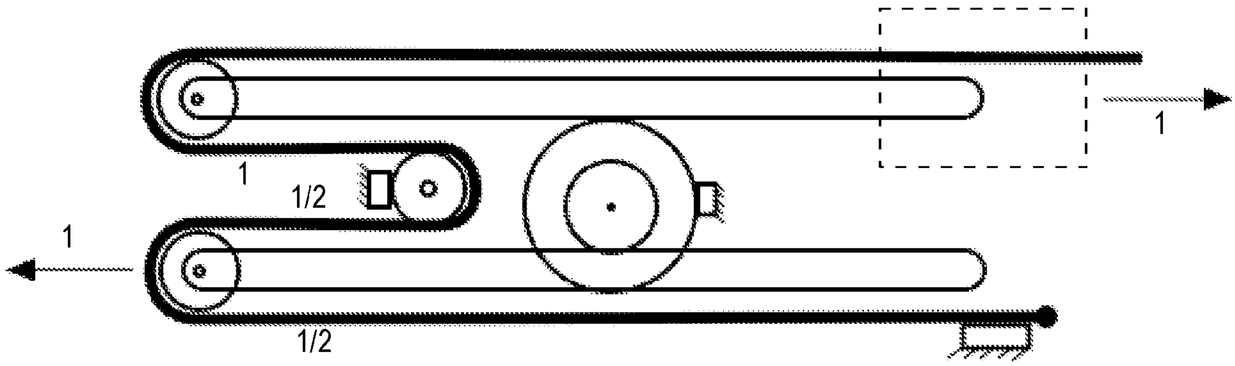

FIG. 11A

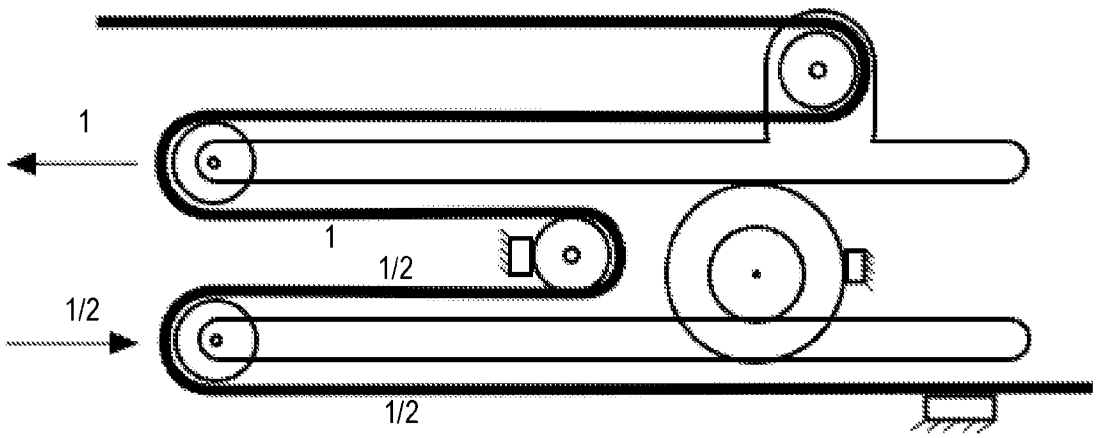

FIG. 11B

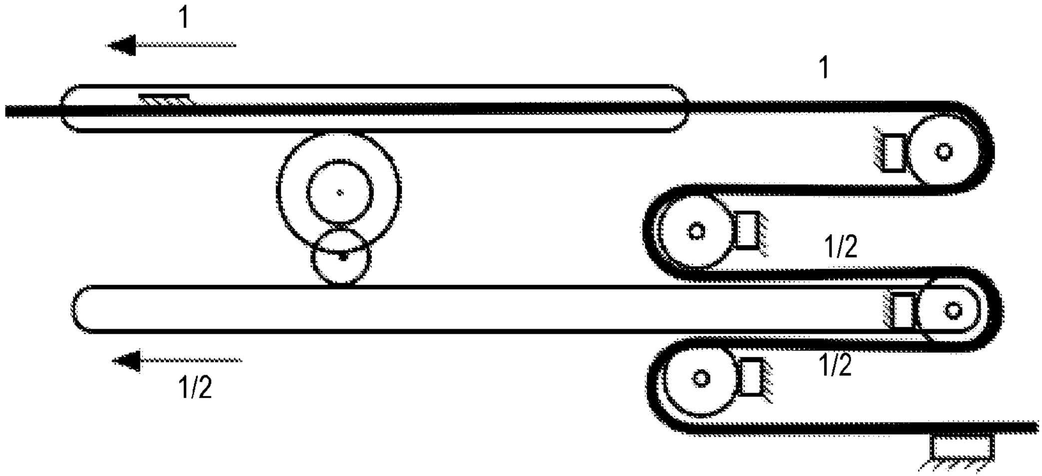

FIG. 11C

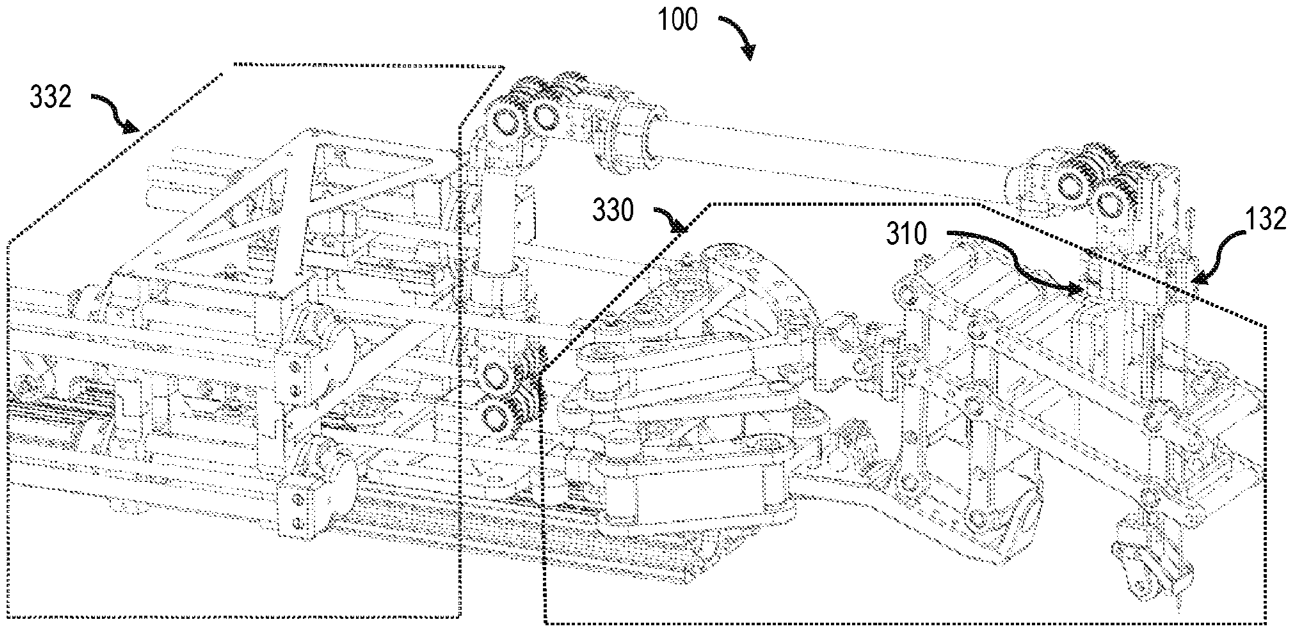

FIG. 12

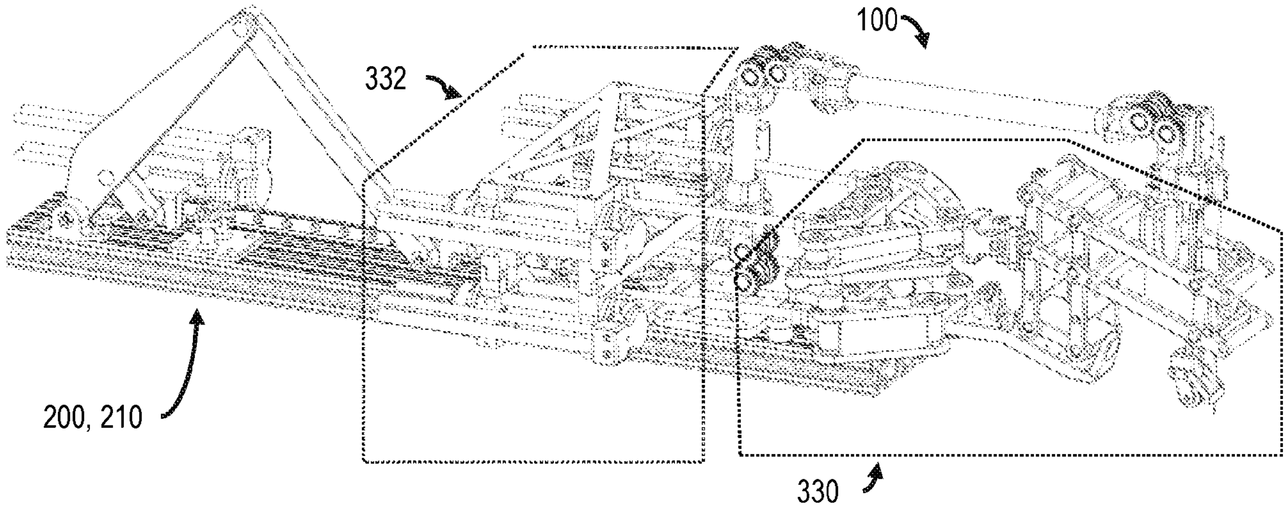

FIG. 13

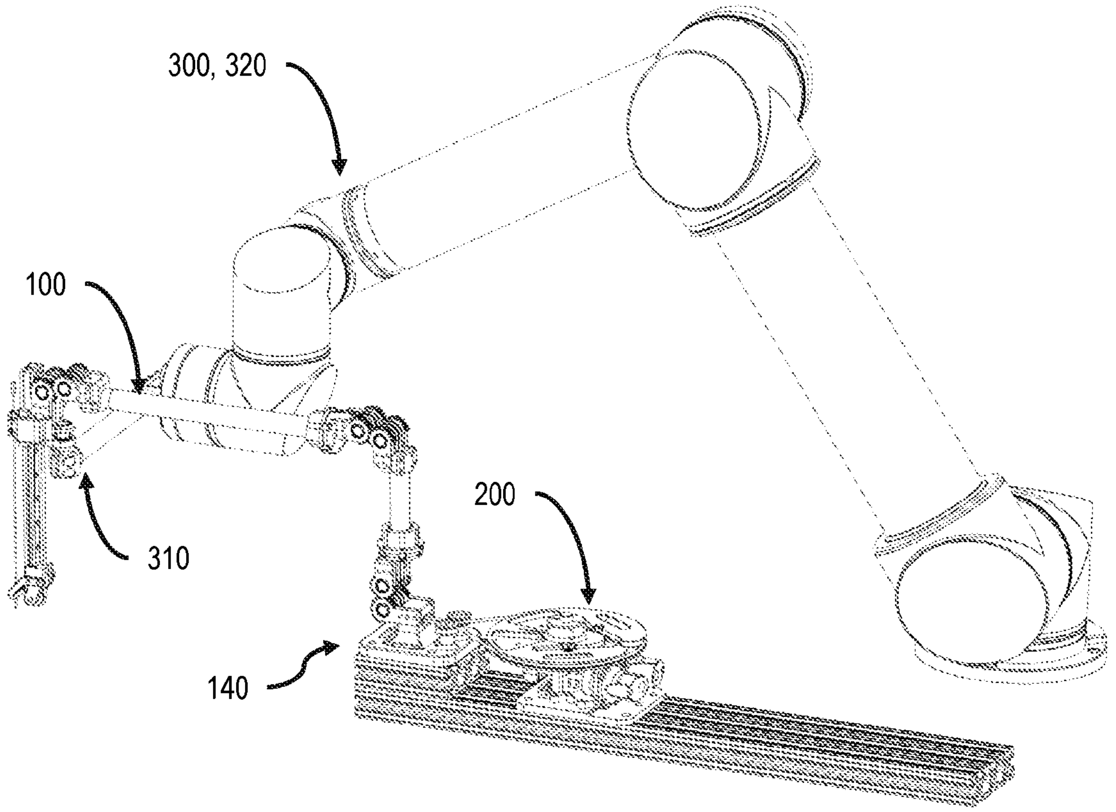

FIG. 14

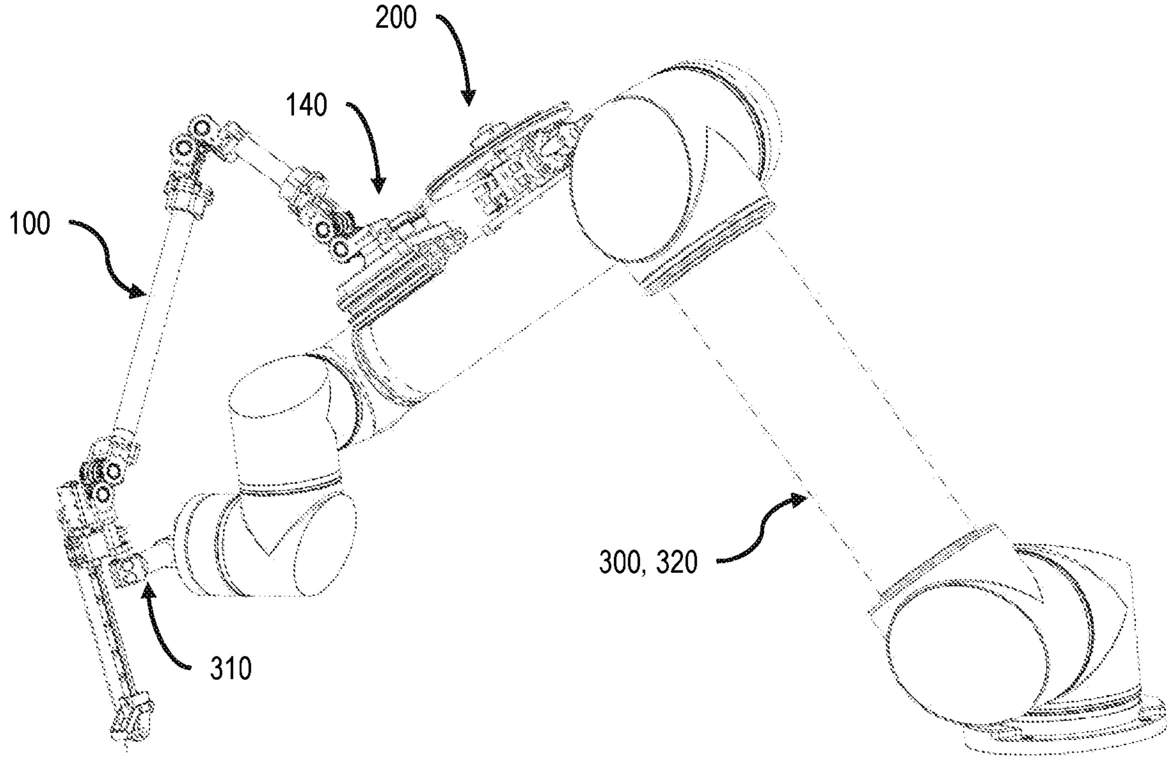

FIG. 15

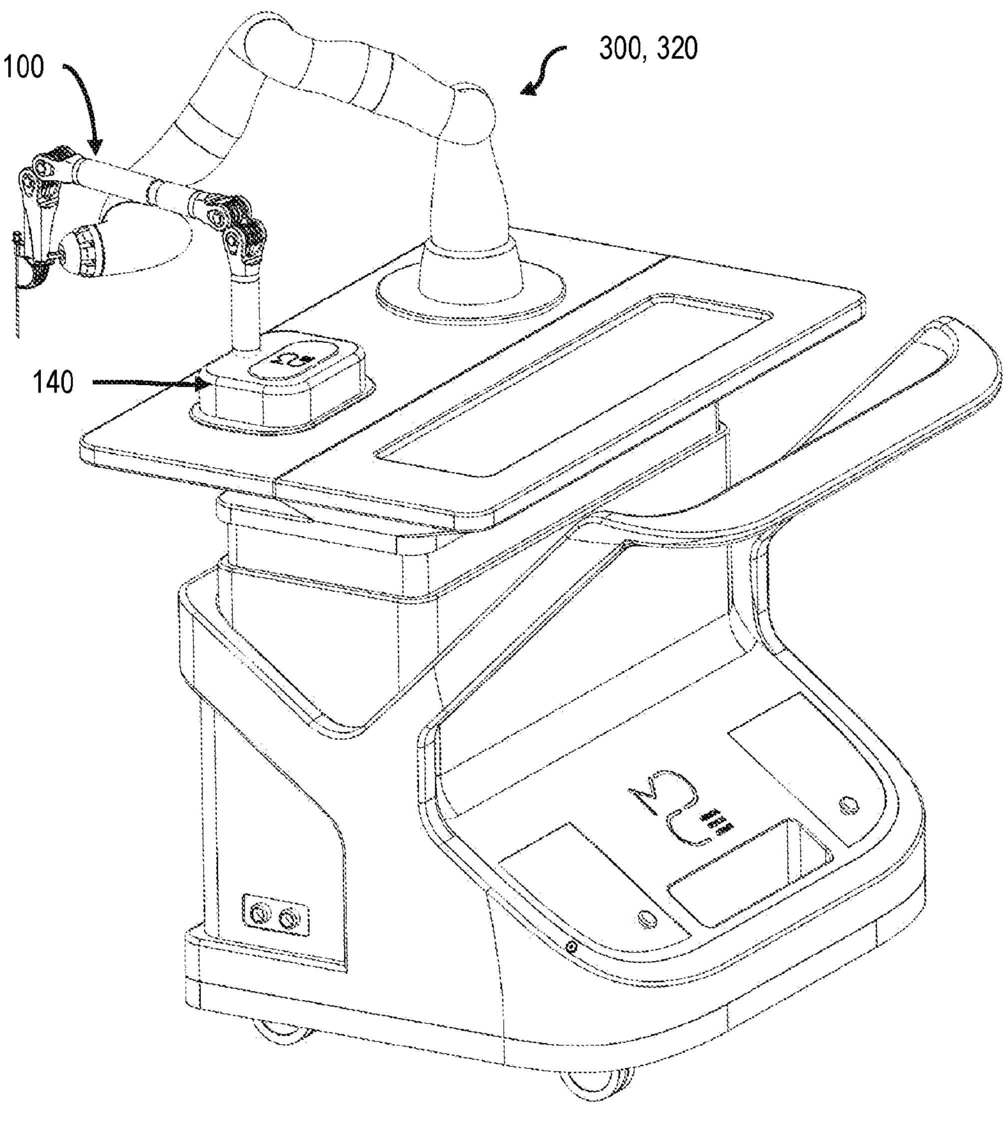

FIG. 16

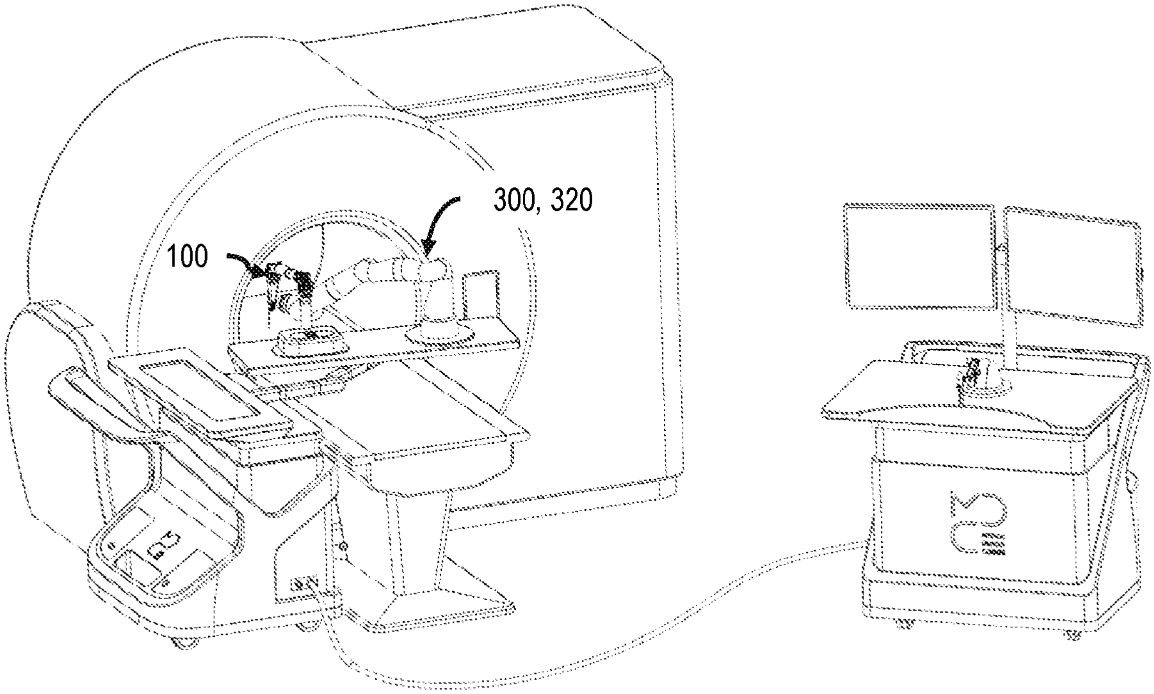

FIG. 17

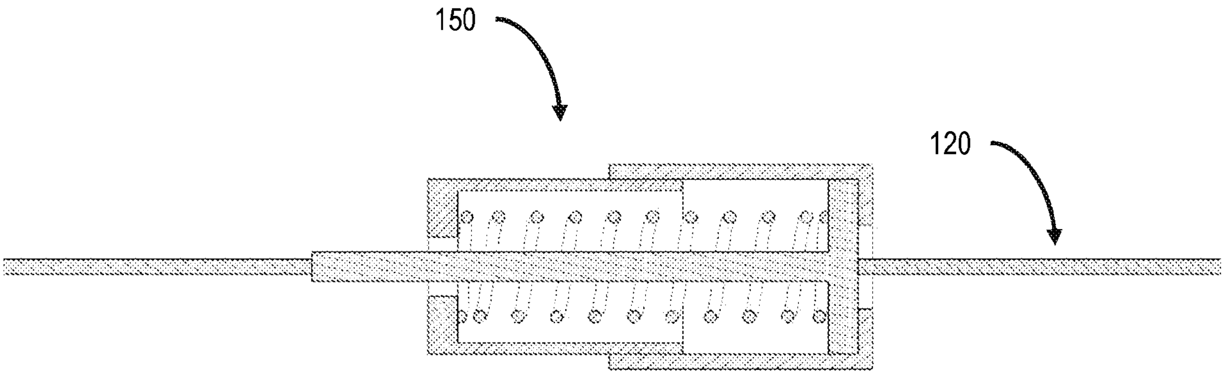

FIG. 18

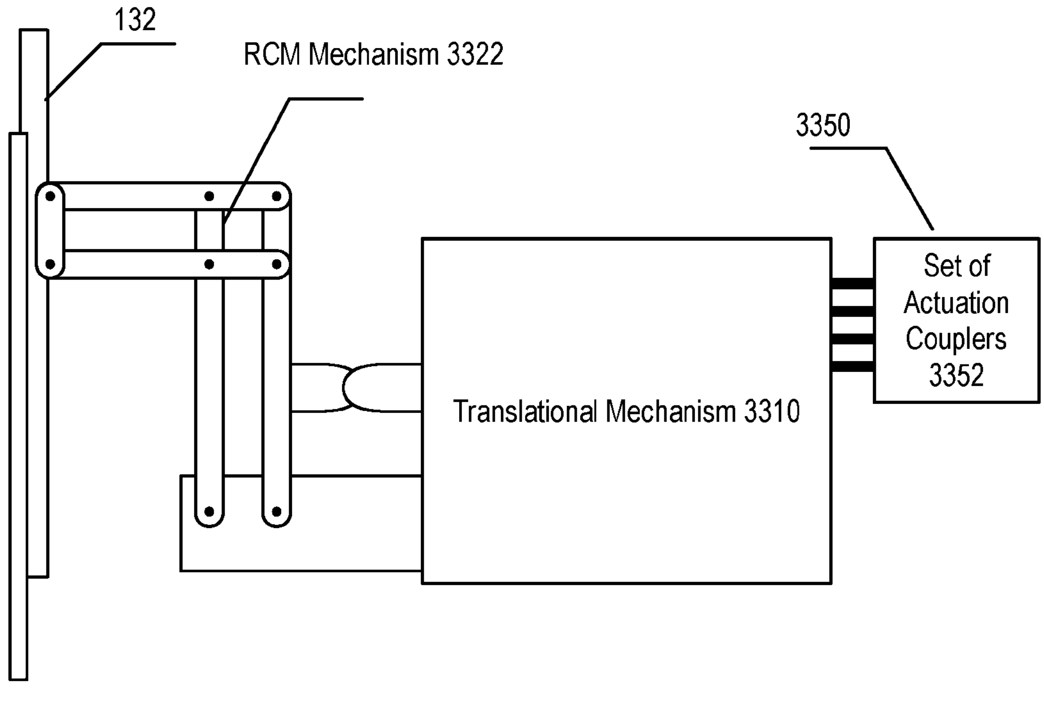
132
RCM Mechanism 3322
3350
Set of
Actuation
Couplers
3352
Translational Mechanism 3310

FIG. 19

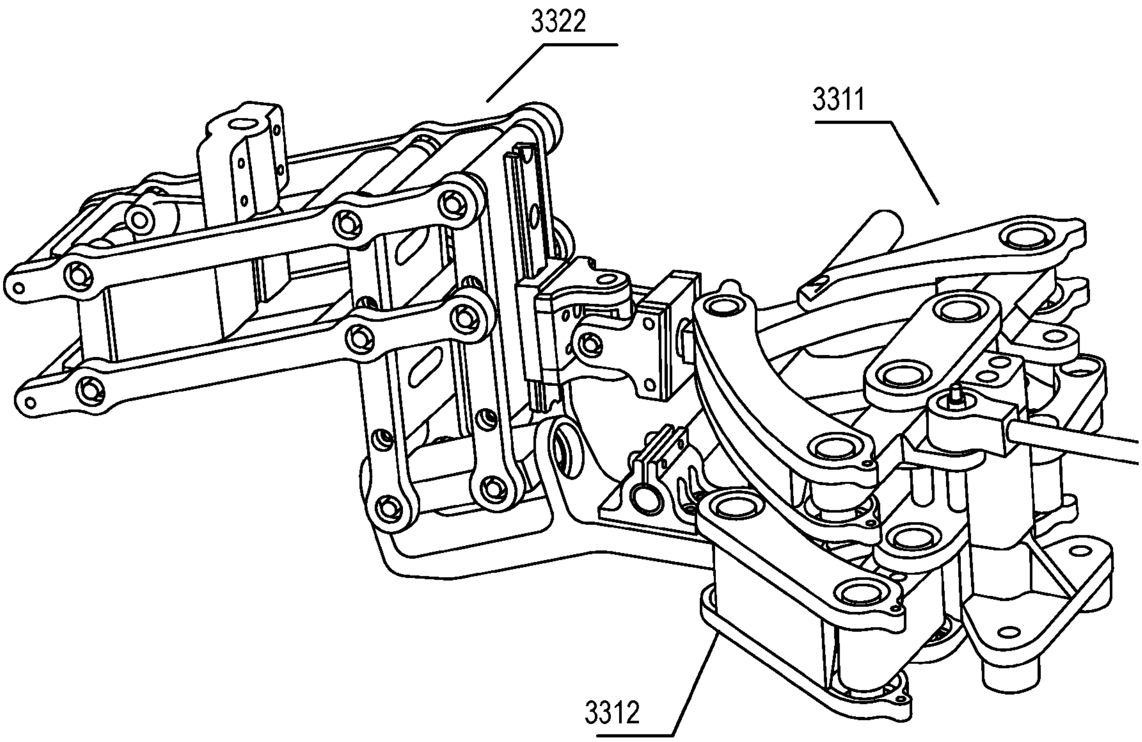

FIG. 20A

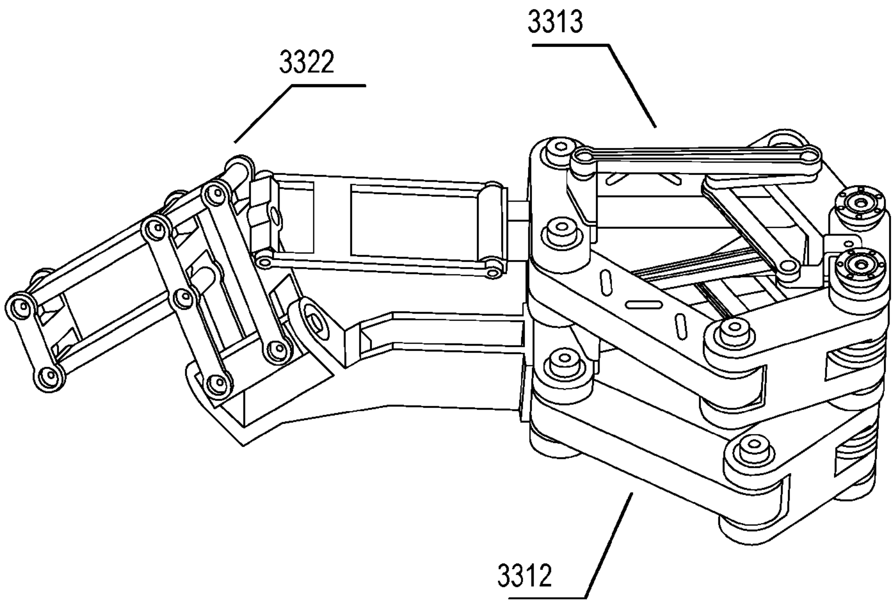

FIG. 20B