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Steger et al.

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(45) **Date of Patent: *May 7, 2024**

(54) **COMPUTER-ASSISTED TELEOPERATED SURGERY SYSTEMS AND METHODS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

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(65) **Prior Publication Data**

US 2023/0112200 A1 Apr. 13, 2023

Related U.S. Application Data

(63) Continuation of application No. 16/340,966, filed as application No. PCT/US2017/056990 on Oct. 17, 2017, now Pat. No. 11,564,760.

(Continued)

(51) **Int. Cl.**

A61B 90/50	(2016.01)
A61B 34/30	(2016.01)

(Continued)

(52) **U.S. Cl.**
CPC ***A61B 34/35*** (2016.02); ***A61B 34/30*** (2016.02); ***A61B 50/20*** (2016.02); ***A61B 90/50*** (2016.02);

(Continued)

(58) **Field of Classification Search**
CPC ... A61B 17/00; A61B 17/062; A61B 17/3423; A61B 2017/00464; A61B 2017/00477;

(Continued)

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(74) *Attorney, Agent, or Firm* — MARSHALL, GERSTEIN & BORUN LLP

(57) **ABSTRACT**

A computer-assisted teleoperated surgical system includes one or more manipulator devices and other components. A manipulator device includes a first link, a second link coupled to a distal end of the first link, a third link coupled to the second link, and an instrument actuator coupled to the third link. A joint that couples the second link to the first link defines a yaw axis. A joint that couples the third link to the second link defines a pitch axis. The instrument actuator defines an insertion axis. The yaw, pitch, and insertion axes are fixed in relation to each other and intersect at a remote center of motion. The instrument actuator may insert a surgical instrument along the insertion axis roll and may roll

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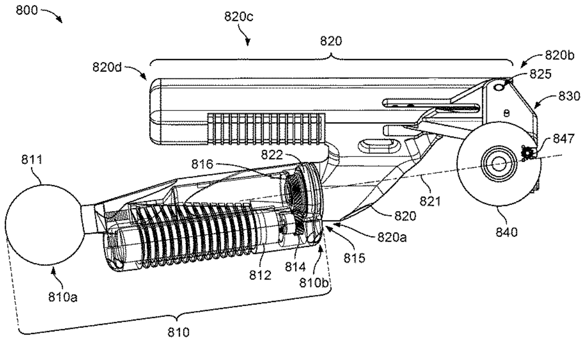

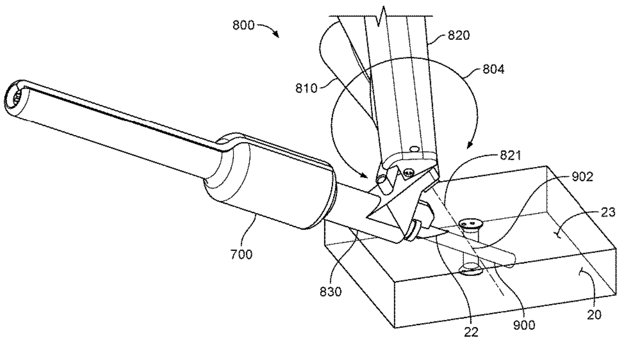

the surgical instrument around the insertion axis. The proximal end of the first link may be coupled to a repositionable setup structure, which may optionally be mechanically grounded to an operating room table. A user control unit includes a processor that acts as a controller, and user inputs at the user control unit teleoperated the manipulator device via the controller.

20 Claims, 16 Drawing Sheets

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(60) Provisional application No. 62/409,625, filed on Oct. 18, 2016.

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A61B 34/35	(2016.01)
A61B 50/20	(2016.01)
B25J 9/10	(2006.01)
B25J 9/16	(2006.01)
A61B 17/00	(2006.01)
A61B 17/34	(2006.01)

(52) **U.S. Cl.**
CPC ***B25J 9/106*** (2013.01); ***B25J 9/1689*** (2013.01); *A61B 2017/00464* (2013.01); *A61B 2017/00477* (2013.01); *A61B 17/3423* (2013.01); *A61B 2034/301* (2016.02); *A61B 2034/305* (2016.02)

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CPC A61B 2034/301; A61B 2034/305; A61B 34/00; A61B 34/30; A61B 34/35; A61B 50/20; A61B 90/50; B25J 9/106; B25J 9/1689; F16H 25/20; Y10T 403/32; Y10T 403/32008; Y10T 403/32049; Y10T 403/37041
USPC 606/130; 403/52, 53, 57, 58
See application file for complete search history.

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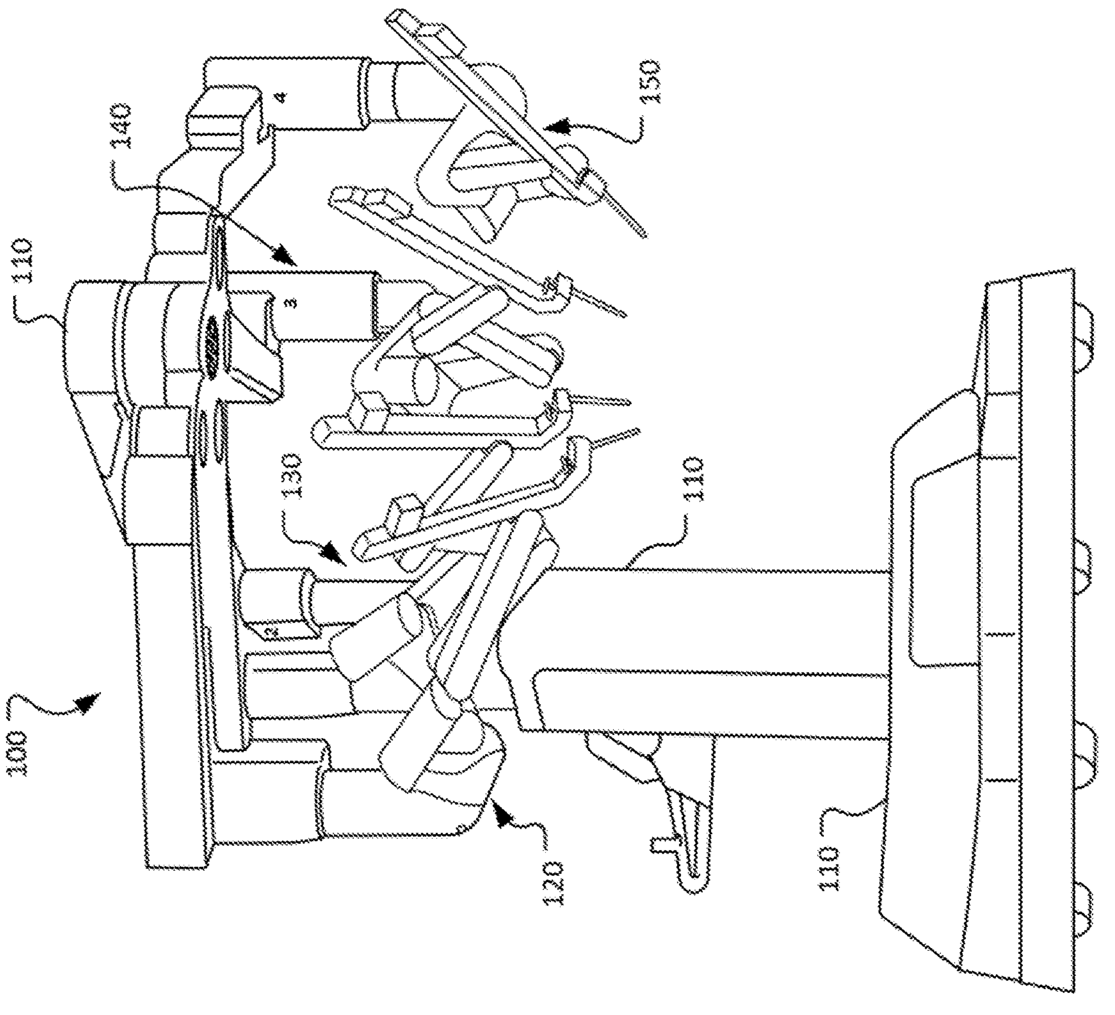
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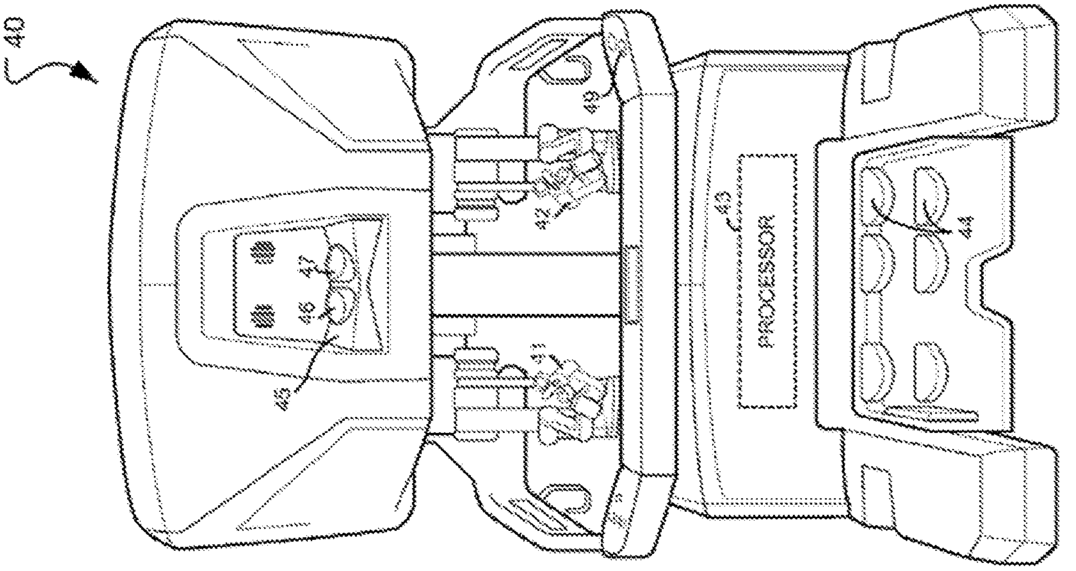
FIG. 1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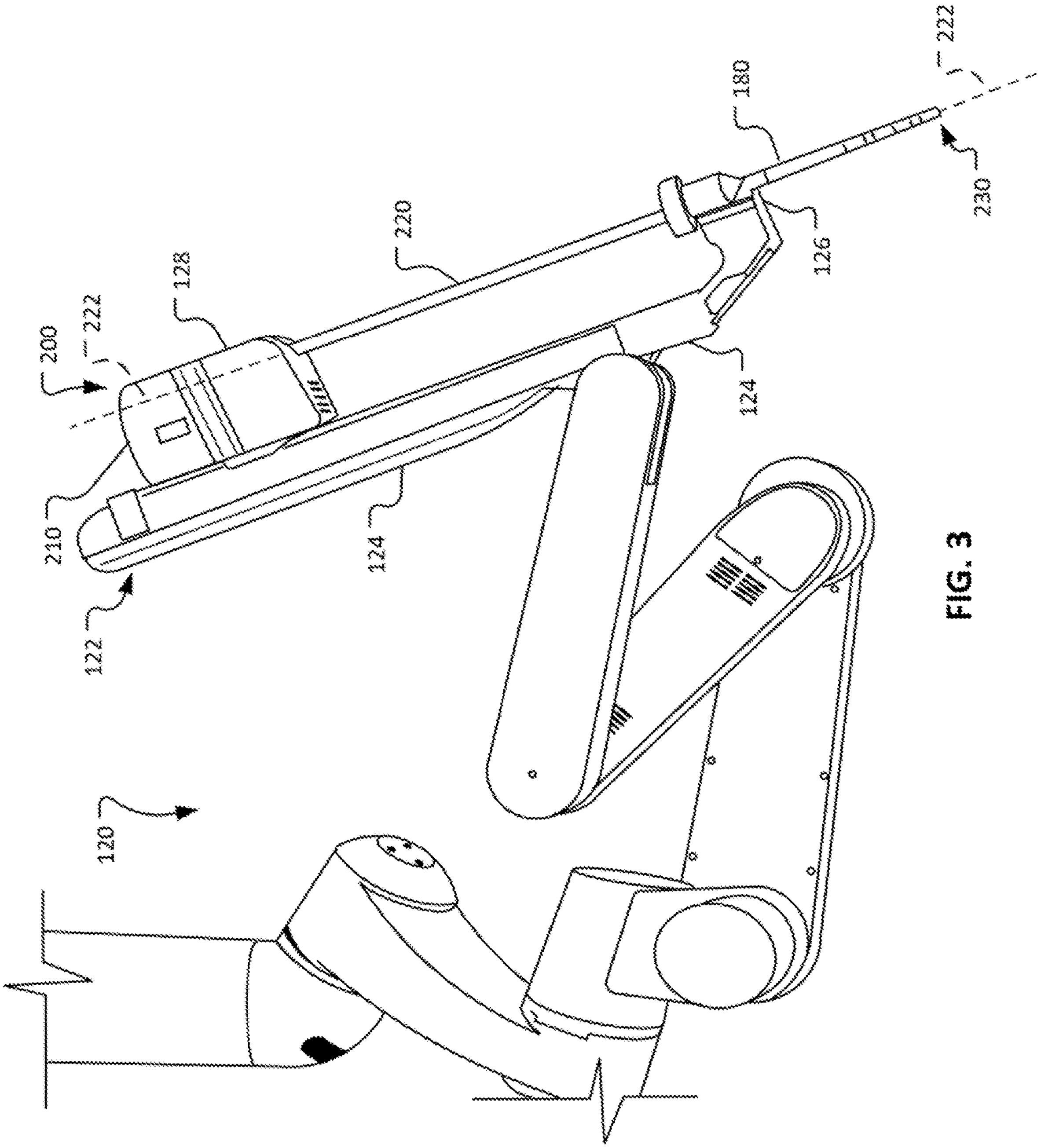
PROCESSOR

FIG. 2



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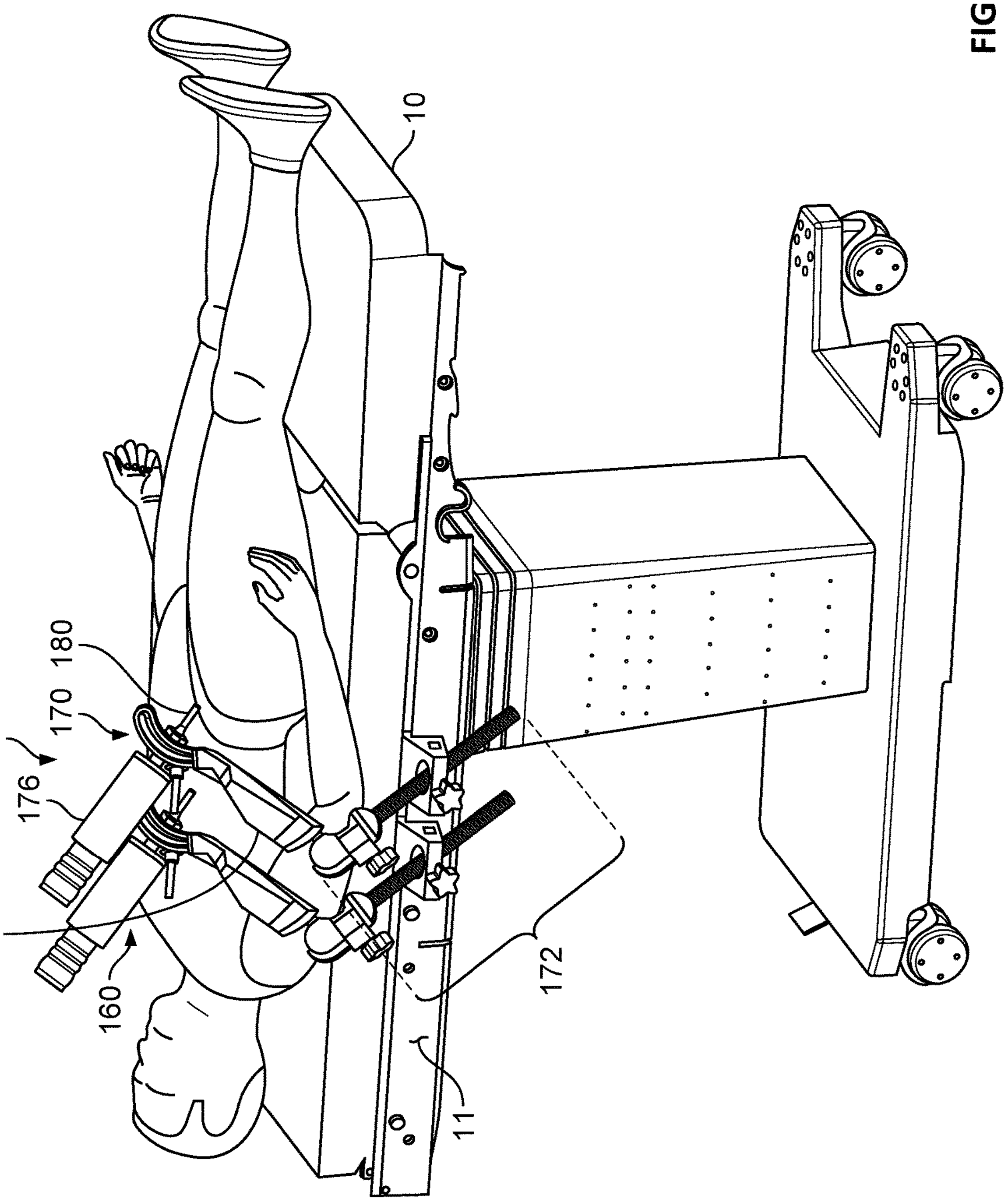

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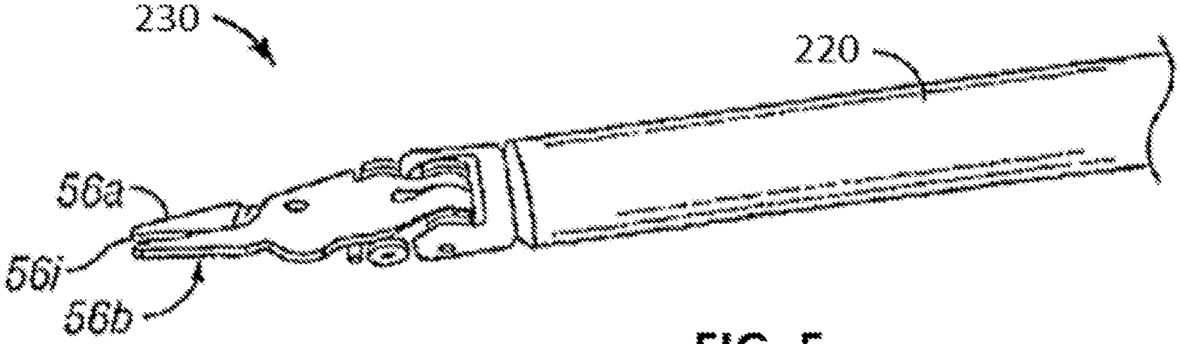

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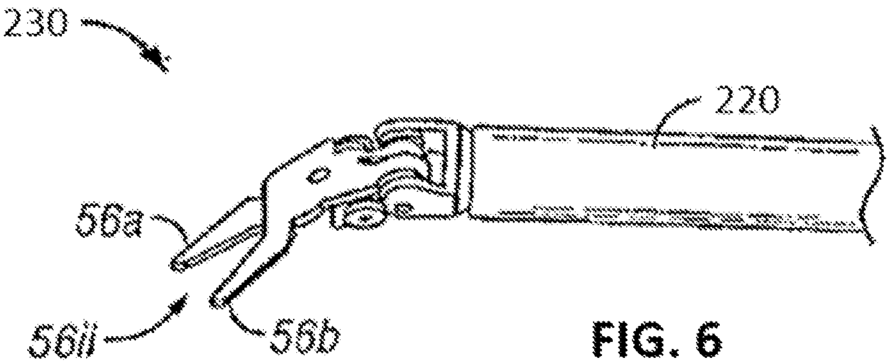

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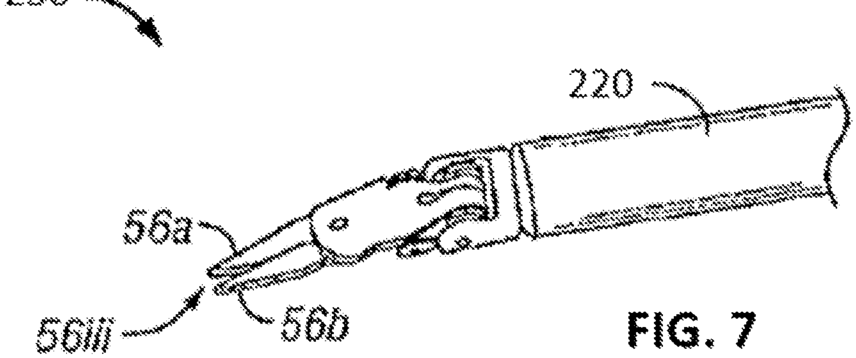

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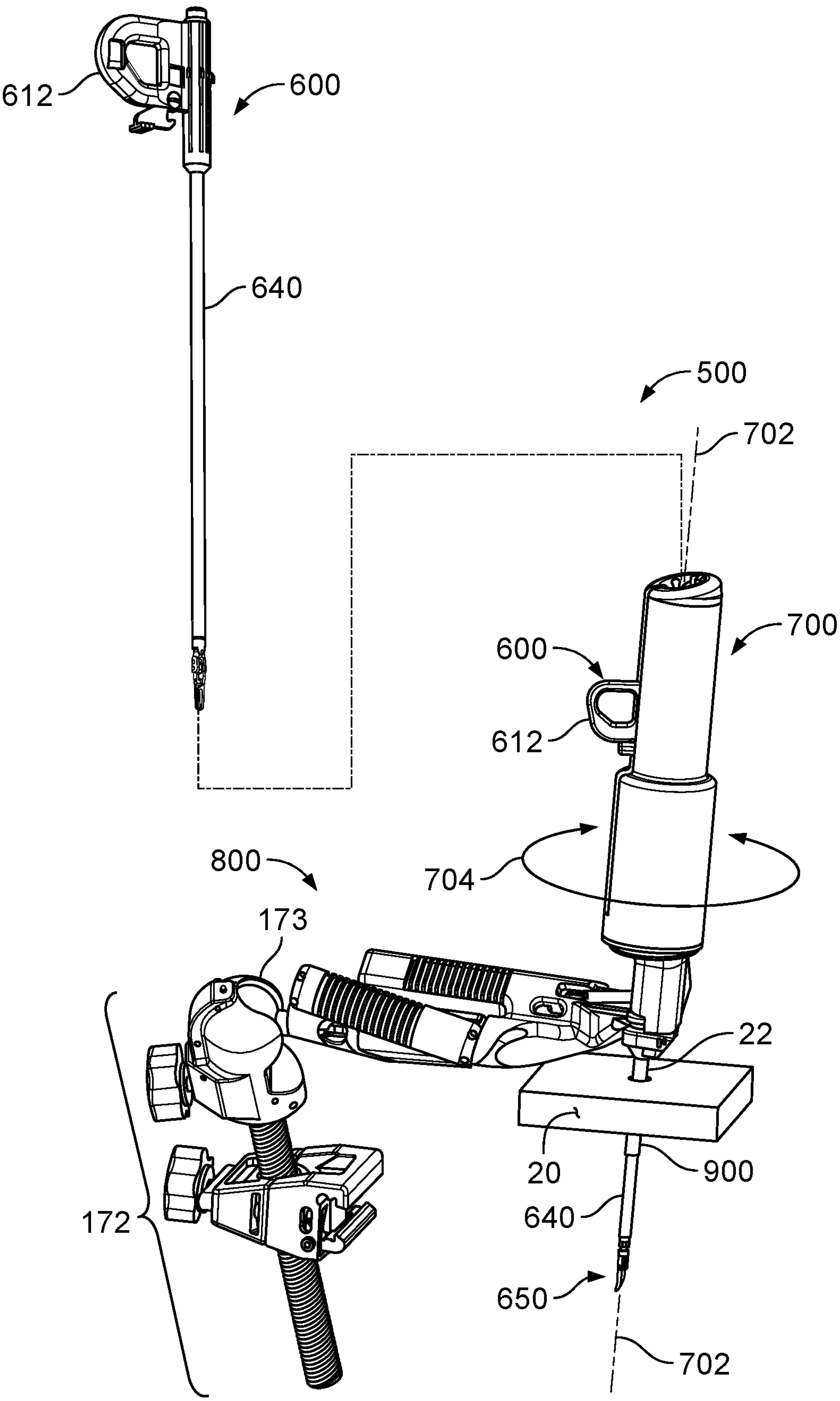
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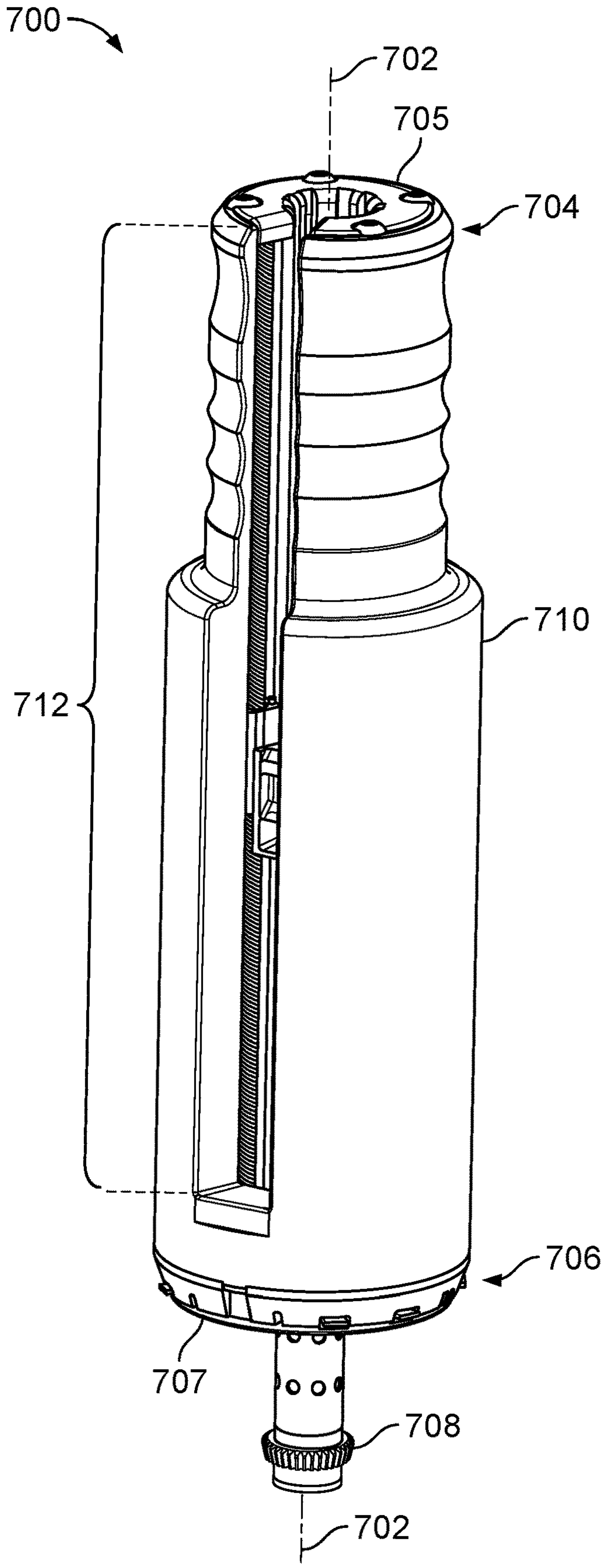
FIG. 8



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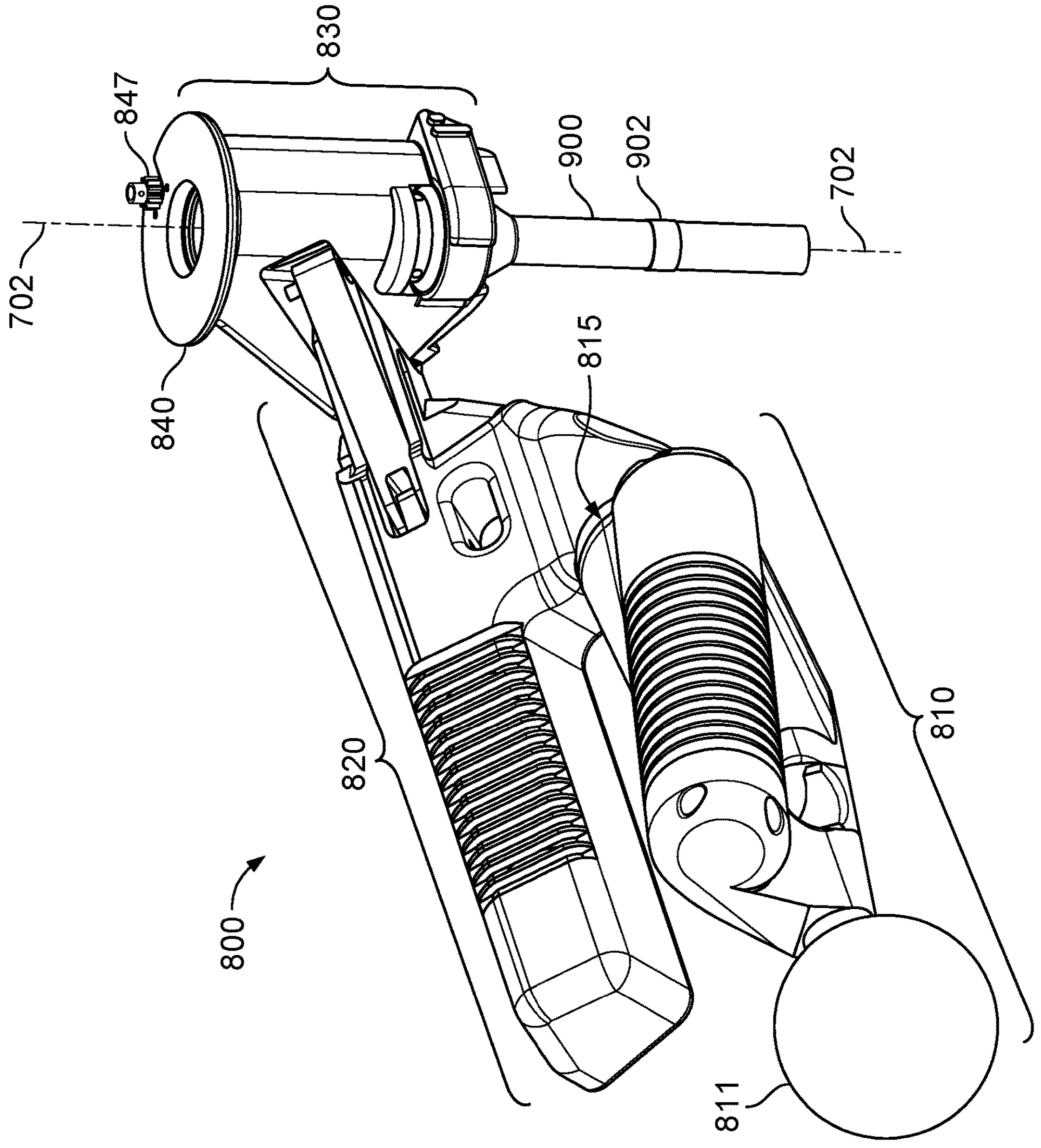

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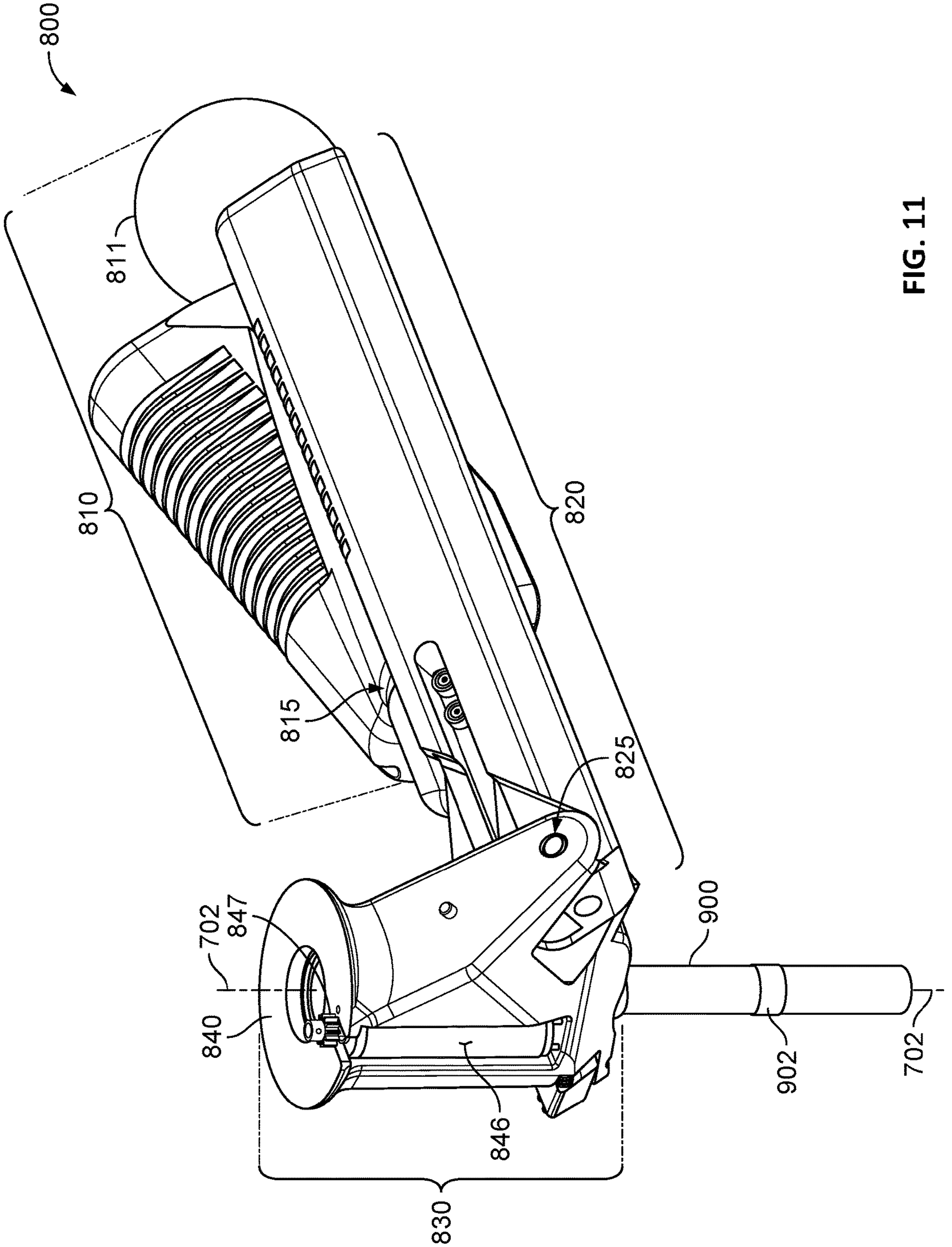

FIG. 11

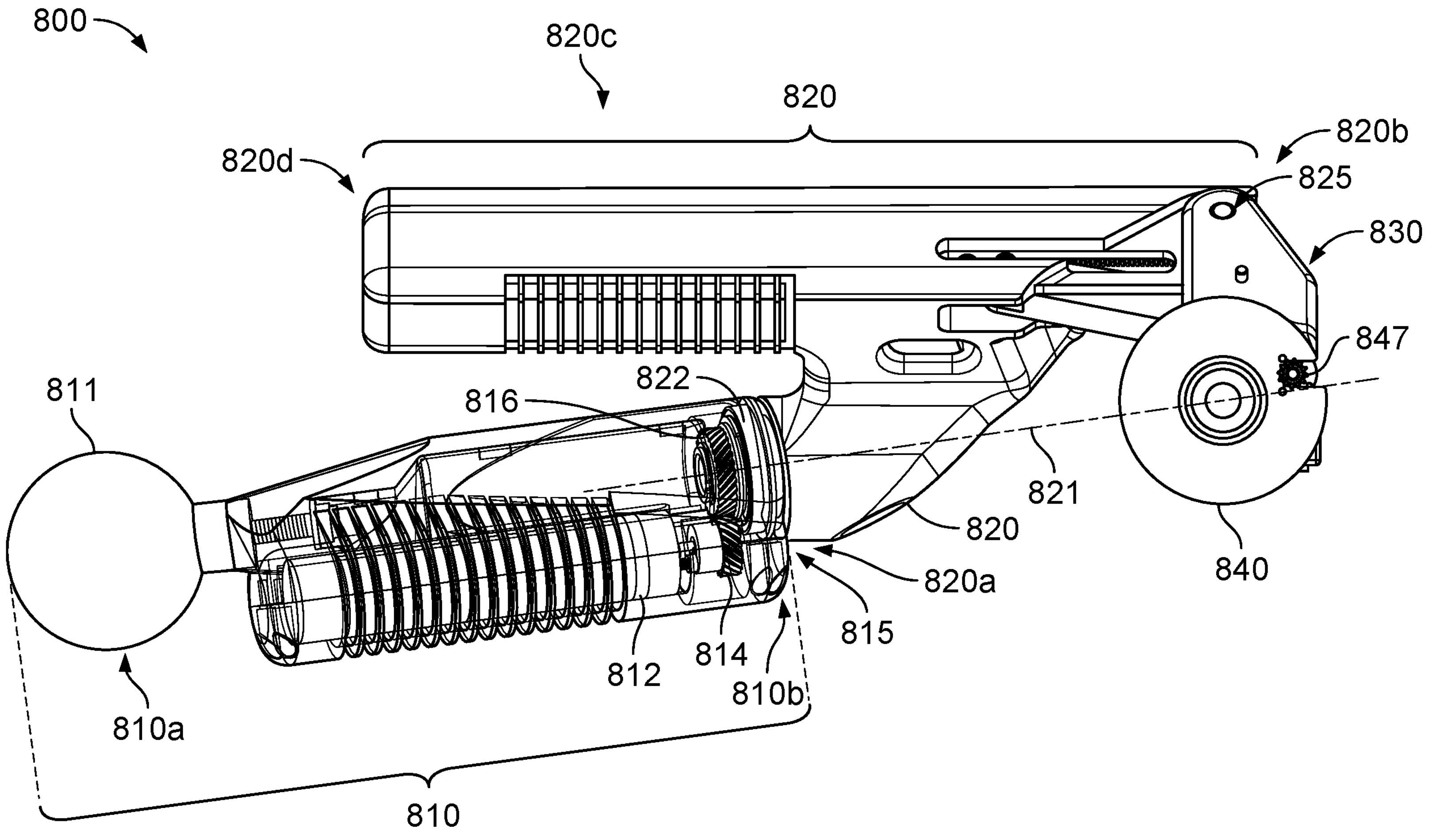
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FIG. 12

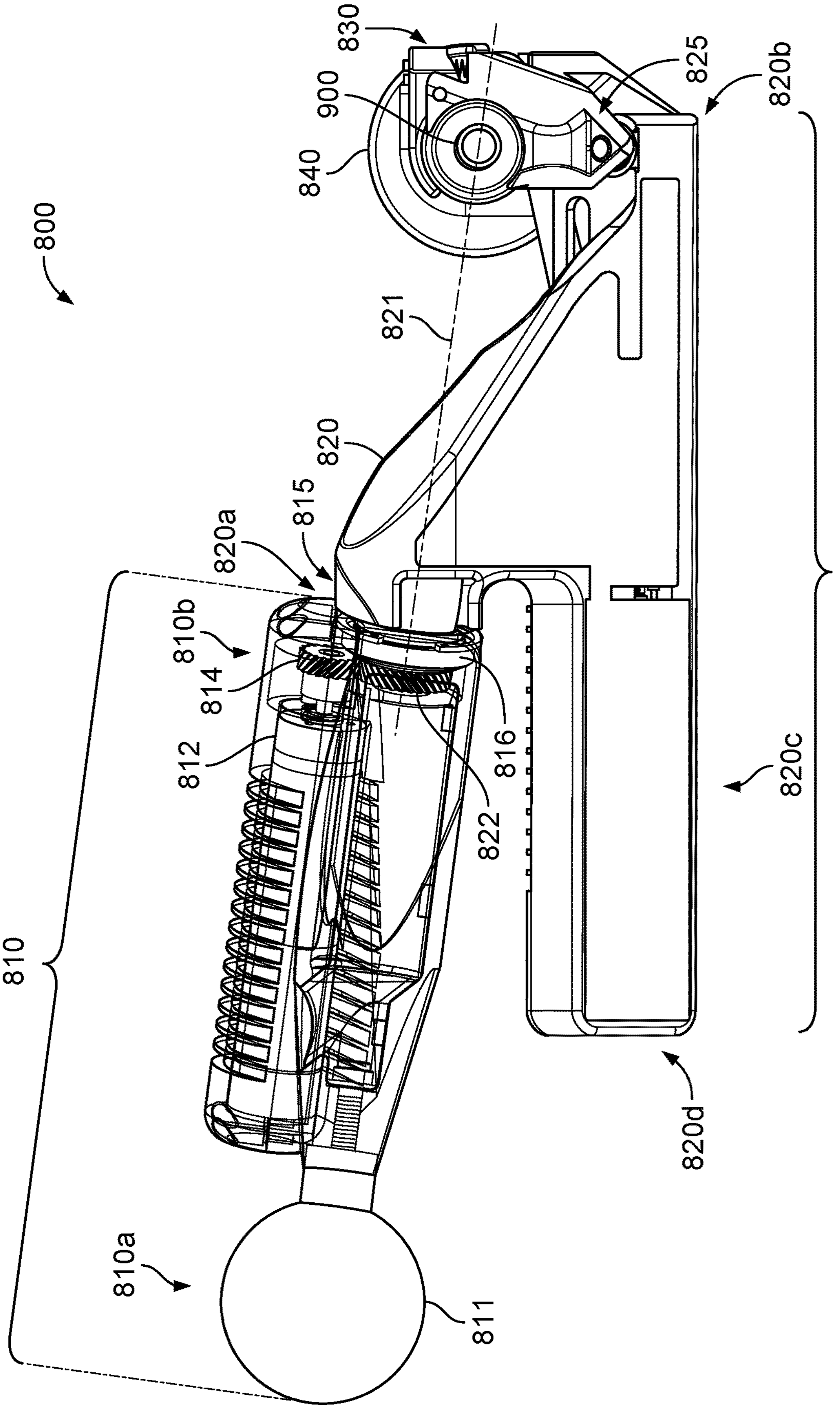
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FIG. 13

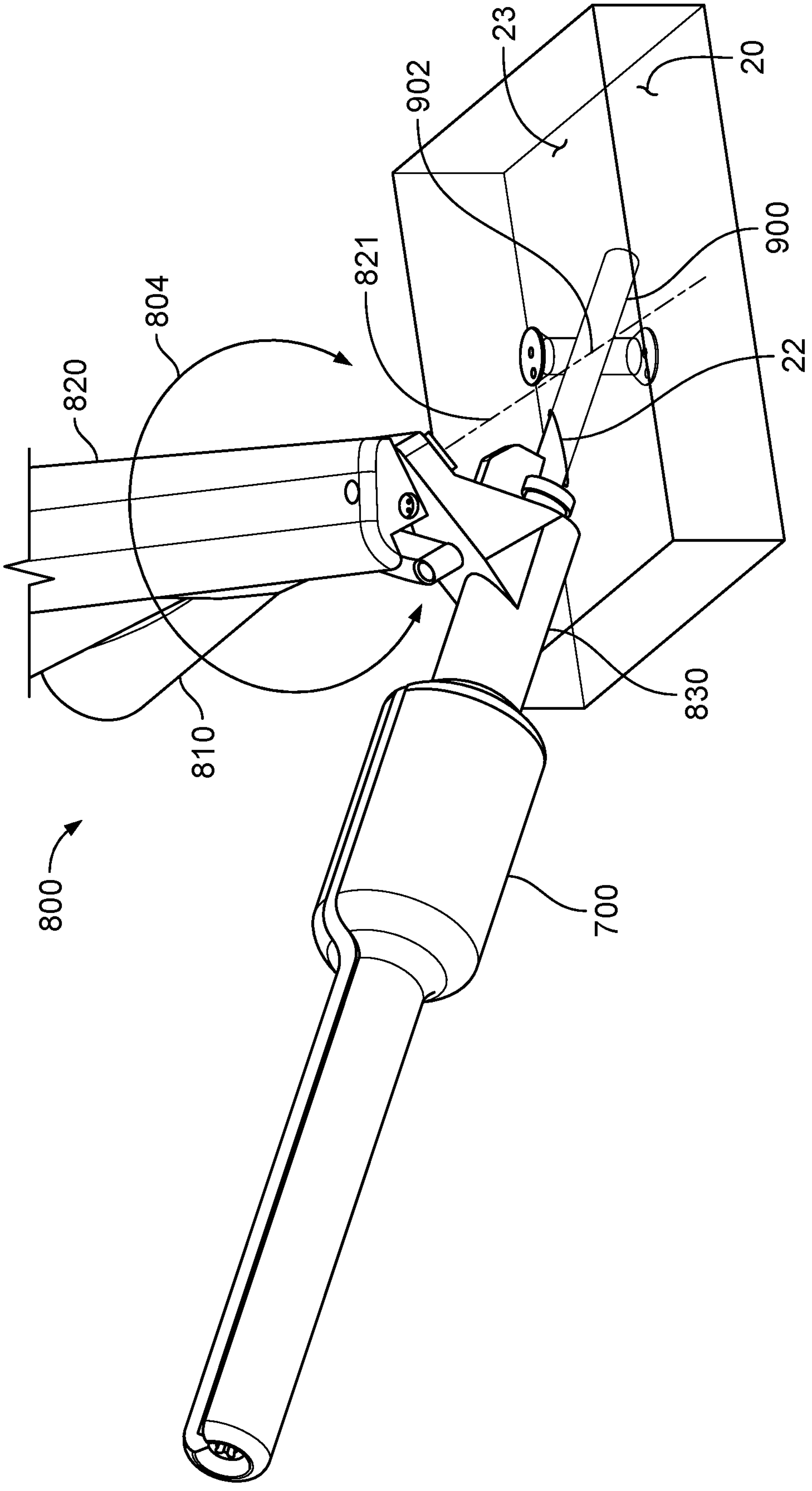

FIG. 14

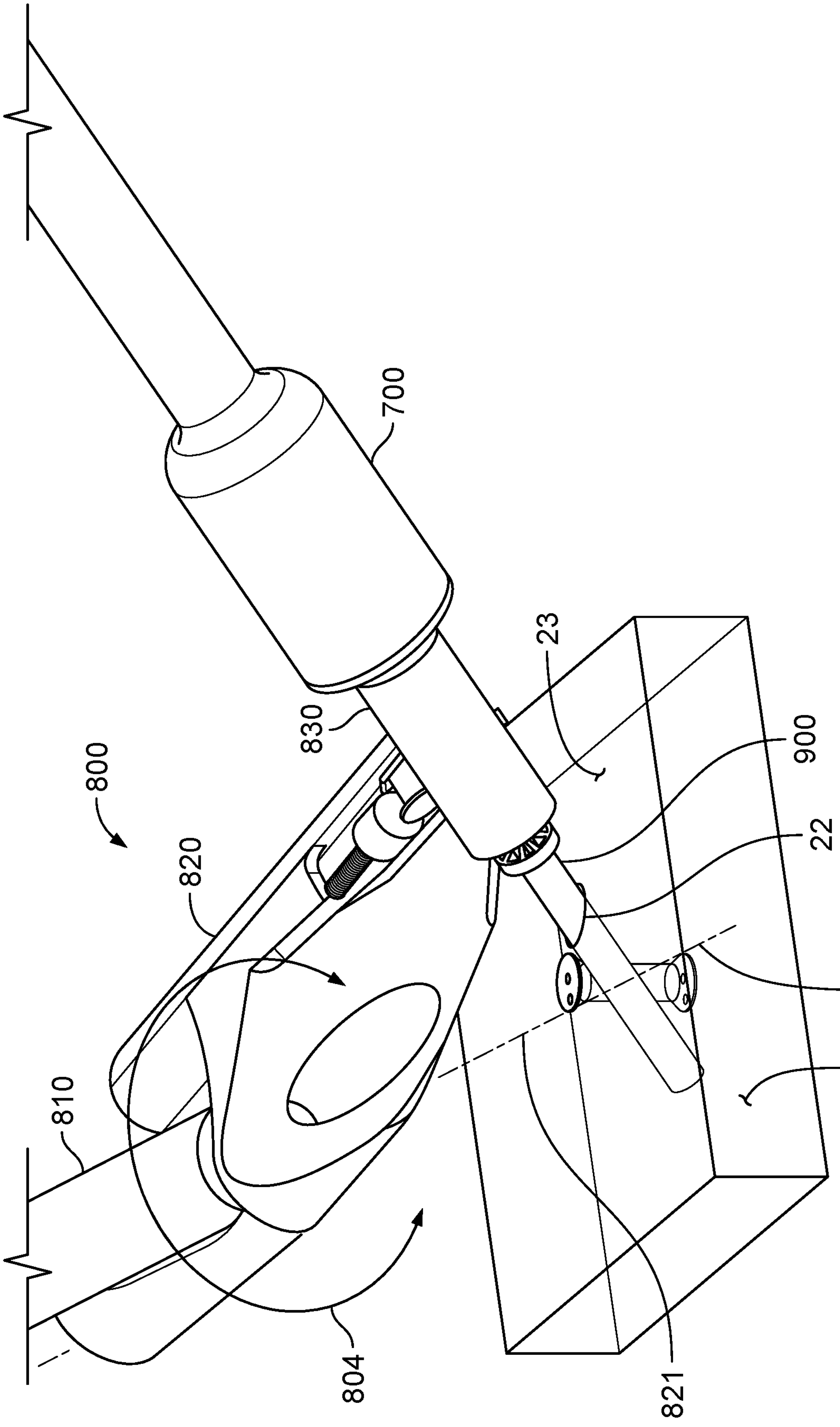

FIG. 15

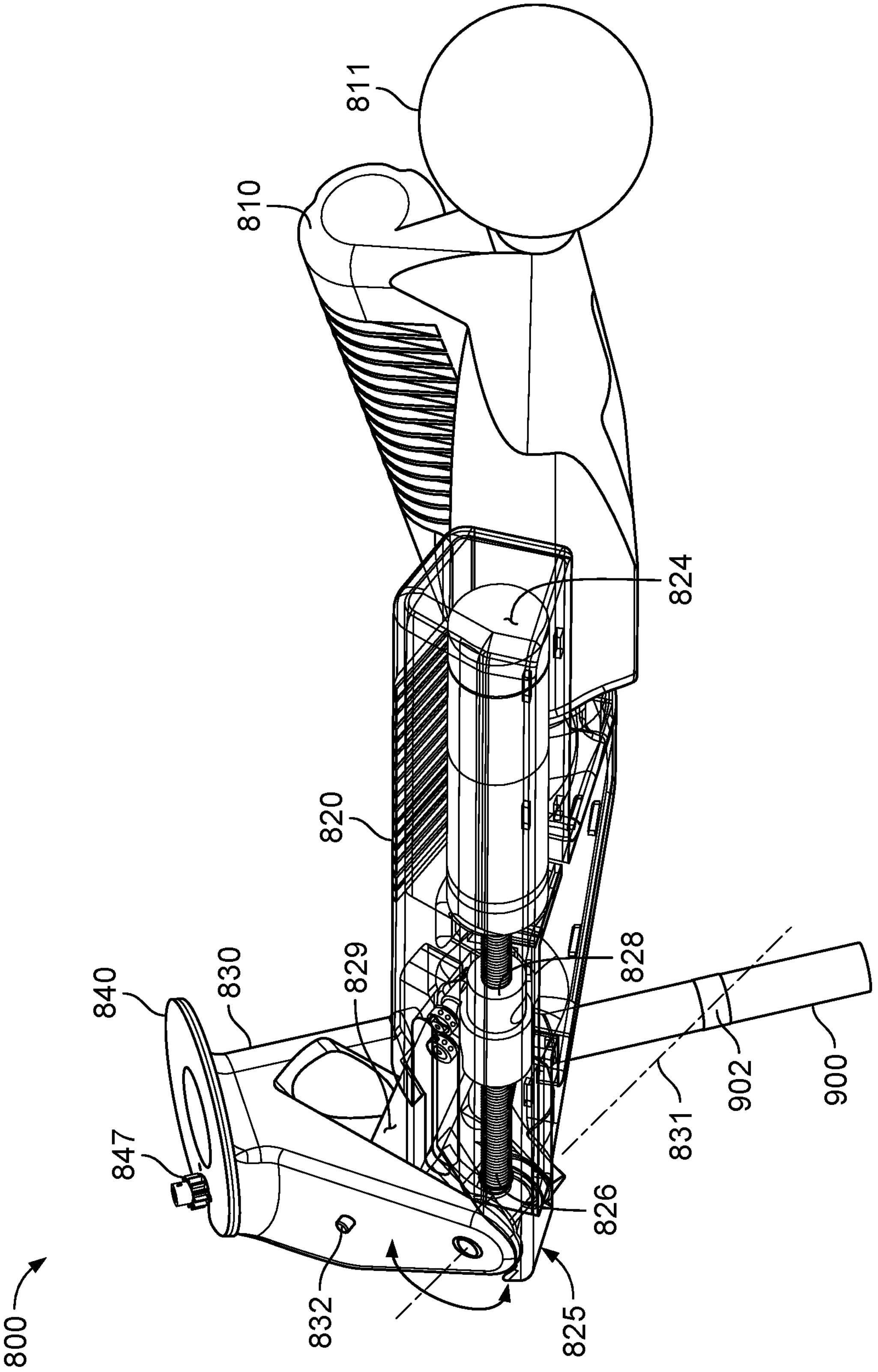

FIG. 16

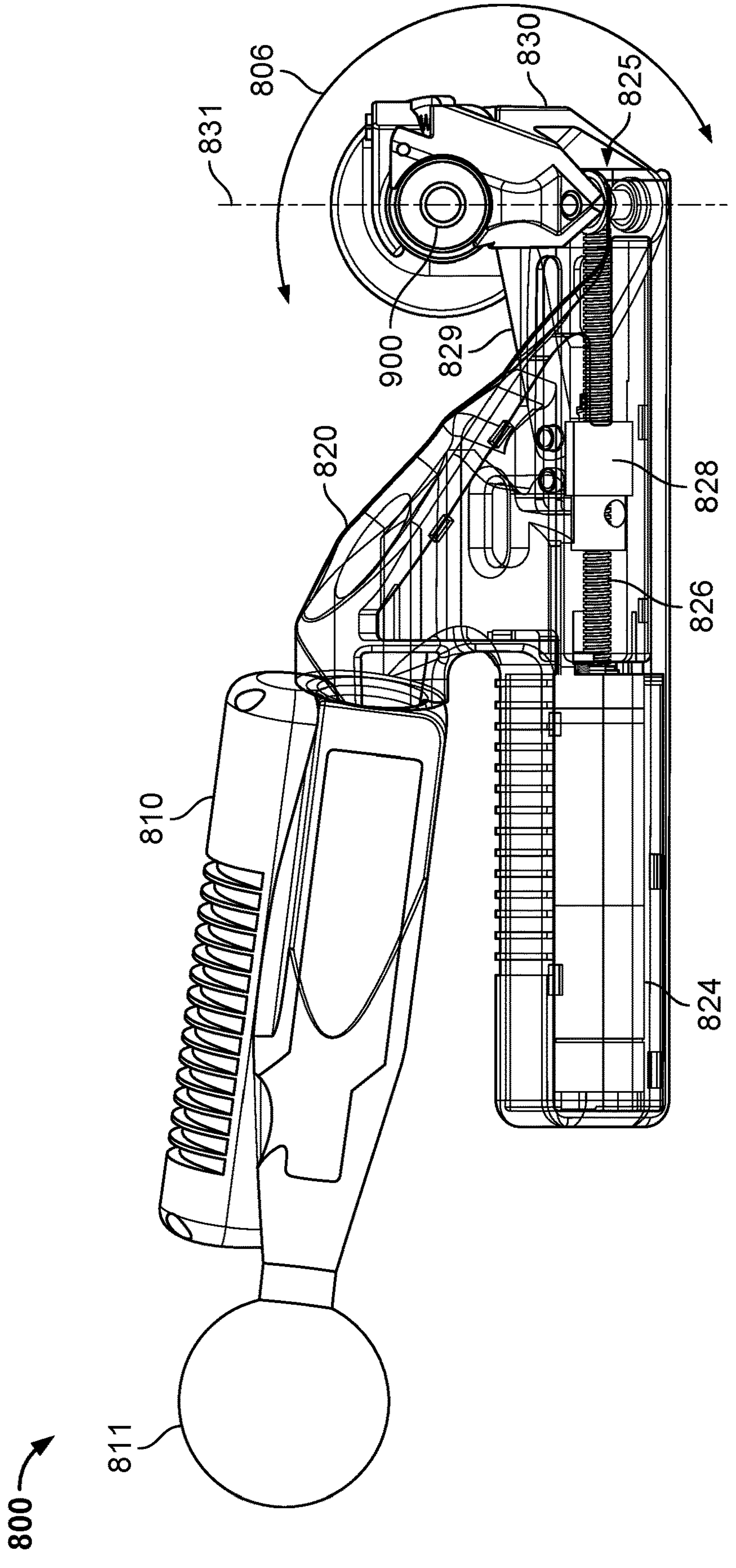

FIG. 17

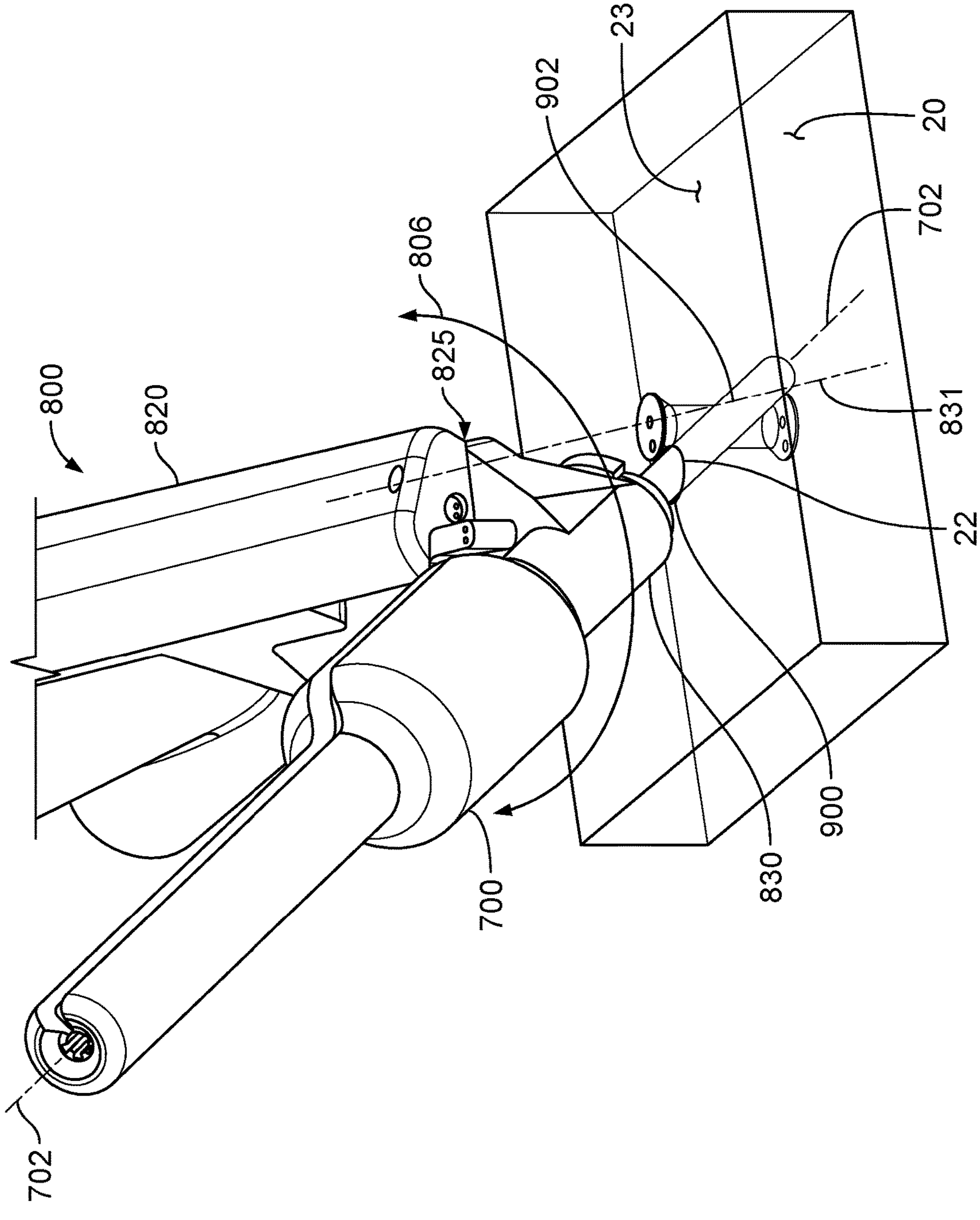

FIG. 18

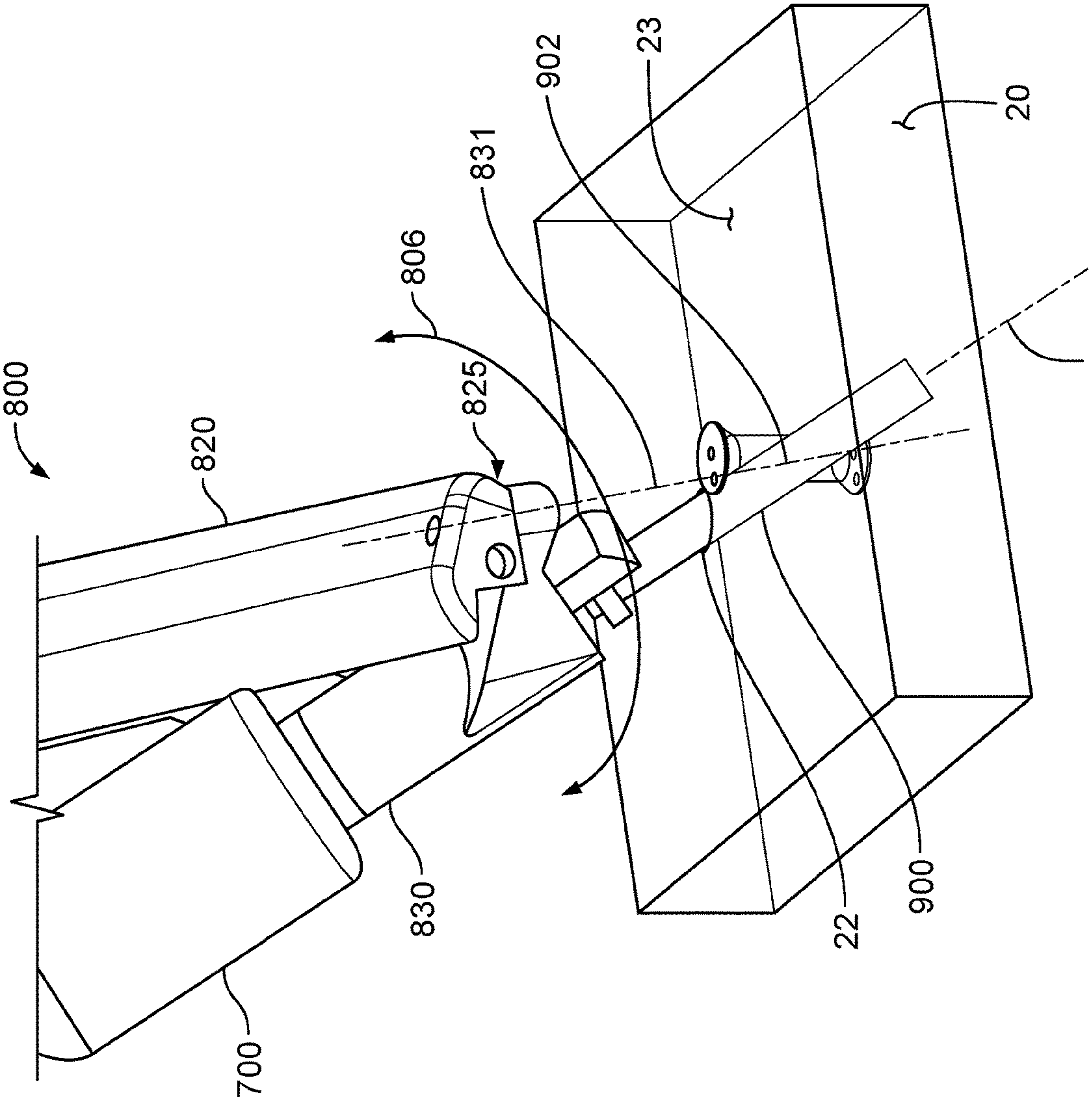

FIG. 19

COMPUTER-ASSISTED TELEOPERATED SURGERY SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation application of U.S. patent application Ser. No. 16/340,966 filed on Apr. 10, 2019, which is a National Stage Application under 35 U.S.C. § 371 and claims the benefit of International Application No. PCT/US2017/056990, filed Oct. 17, 2017, which claims the benefit of priority to U.S. Provisional Patent Application Ser. No. 62/409,625 filed Oct. 18, 2016, the disclosures of which are incorporated herein by reference.

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Not Applicable.

BACKGROUND

1. Field of Invention

This disclosure relates to devices and methods for minimally invasive computer-assisted teleoperated surgery. For example, this disclosure provides manipulator devices for a computer-assisted teleoperated surgery system.

2. Art

Teleoperated surgical systems (often called "robotic" surgical systems because of the use of robot technology) and other computer-assisted devices often include one or more instrument manipulators to manipulate instruments for performing a task at a surgical work site and at least one manipulator for supporting an image capturing device which captures images of the surgical work site. A manipulator arm comprises a plurality of links coupled together by one or more actively controlled joints. In many embodiments, a plurality of actively controlled joints may be provided. The robot arm may also include one or more passive joints, which are not actively controlled, but which comply with movement of an actively controlled joint. Such active and passive joints may be various types, including revolute or prismatic joints. The kinematic pose of the manipulator arm and its associated instrument or image capture device may be determined by the positions of the joints and knowledge of the structure and coupling of the links and the application of known kinematic calculations.

Minimally invasive telesurgical systems for use in surgery are being developed to increase a surgeon's dexterity as well as to allow a surgeon to operate on a patient from a remote location. Telesurgery is a general term for surgical systems in which the surgeon uses some form of remote control, e.g., a servomechanism, or the like, to manipulate surgical instrument movements rather than directly holding and moving the instruments by hand. In such a telesurgery system, the surgeon is provided with an image of the surgical site at the remote location. While viewing typically a stereoscopic image of the surgical site that provides the illusion of depth on a suitable viewer or display, the surgeon performs the surgical procedures on the patient by manipulating master control input devices, which in turn control the motion of corresponding teleoperated instruments. The teleoperated surgical instruments can be inserted through small, minimally invasive surgical apertures or natural orifices to treat tissues at surgical sites within the patient, often avoiding the trauma generally associated with accessing a surgical worksite by open surgery techniques. These computer-assisted tele-operated systems can move the working ends (end effectors) of the surgical instruments with sufficient dexterity to perform quite intricate surgical tasks, often by pivoting shafts of the instruments at the minimally invasive aperture, sliding of the shaft axially through the aperture, rotating of the shaft within the aperture, and the like.

SUMMARY

This disclosure provides devices and methods for minimally invasive robotic surgery using a computer-assisted tele-operated surgery device. For example, this disclosure provides manipulator devices for a computer-assisted tele-operated surgery system. In some embodiments, the manipulator device includes a first link that couples with a set-up structure, a second link that is rotatably coupled to the first link, and a third link that is pivotably coupled to the second link. The third link is configured to receive a surgical instrument actuator that can, in turn, receive a surgical instrument. The surgical instrument defines an insertion axis. In some such embodiments, pivoting the third link in relation to the second link causes a sweeping motion of the insertion axis that traces a portion of a conical surface. In some such embodiments, the manipulator device has a hardware-constrained remote center of motion (RCM). The RCM is a point in space around which the roll, pitch, and yaw motions of the manipulator device are made. When the manipulator devices are used for minimally invasive computer-assisted teleoperated surgery, movement of the manipulator assembly is constrained to a safe motion through a minimally invasive surgical access site or other aperture that is substantially coincident with the RCM. The motion of the manipulator device will thereby preclude excessive lateral motion of the body wall access cannula which might otherwise tear the tissues adjacent the aperture or enlarge the access site inadvertently.

In one aspect, this disclosure is directed to a computer-assisted tele-operated surgery manipulator device that includes a first link configured to releasably couple with a set-up structure of a computer-assisted tele-operated surgery system; a second link rotatably coupled to the first link such that the second link is rotatable in relation to the first link about a first axis; and a third link pivotably coupled to the second link such that the third link is pivotable in relation to the second link about a second axis. The third link is configured to releasably couple with a patient body wall access cannula defining an insertion axis for a surgical instrument. The first axis, the second axis, and the insertion axis consistently intersect at a particular fixed point in space throughout rotation of the second link in relation to the first link and pivoting of the third link in relation to the second link. Pivoting the third link in relation to the second link sweeps the insertion axis to trace a portion of a conical surface.

Such a computer-assisted tele-operated surgery manipulator device may optionally include one or more of the following features. The second link may include a leadscrew, a motor for rotating the leadscrew, and a nut threadably coupled to the leadscrew. The nut may be coupled to a linkage pivotably coupled to the third link at a location spaced apart from the second axis. Rotation of the leadscrew may cause the third link to pivot in relation to the second link. The third link may be releasably coupleable with a computer-assisted teleoperated surgical instrument actuator. The third link may include a motor for driving rotations of the computer-assisted tele-operated surgical instrument actuator about the insertion axis. The first link may include a motor that drives rotations of the second link in relation to the first link. In some embodiments, throughout rotation of the second link in relation to the first link and pivoting of the third link in relation to the second link, the second axis may remain non-orthogonal to the insertion axis. In some embodiments, during surgery using the computer-assisted teleoperated surgery manipulator device and at all positions of the third link in relation to the second link, the second link may be rotated in relation to the first link through an arc of at least 120 degrees without contact between the manipulator device and a plane that includes the particular fixed point in space. In particular embodiments, during surgery using the computer-assisted tele-operated surgery manipulator device the first axis may be at an angle of less than 30 degrees in relation to the plane that includes the particular fixed point in space.

In another aspect, this disclosure is directed to a computer-assisted teleoperated surgery manipulator device including: a first link configured to releasably couple with a set-up structure of a computer-assisted tele-operated surgery system; a second link rotatably coupled to the first link such that the second link is rotatable in relation to the first link about a first axis, the second link comprising a leadscrew and a nut threadably coupled to the leadscrew; and a third link pivotably coupled to the second link such that the third link is pivotable in relation to the second link about a second axis. The third link is configured to releasably couple with a patient body wall access cannula defining an insertion axis for a surgical instrument. The first axis, the second axis, and the insertion axis consistently intersect at a particular fixed point in space throughout rotation of the second link in relation to the first link and pivoting of the third link in relation to the second link. The nut is coupled to a linkage that is pivotably coupled to the third link at a location spaced apart from the second axis, and wherein rotation of the leadscrew causes the third link to pivot in relation to the second link.

Such a computer-assisted teleoperated surgery manipulator device may optionally include one or more of the following features. The insertion axis may trace a portion of a conical surface as the third link is pivoted in relation to the second link. The third link may be releasably coupleable with a computer-assisted tele-operated surgical instrument actuator. The third link may include a motor for driving rotations of the computer-assisted teleoperated surgical instrument actuator about the insertion axis. The first link may include a motor that drives rotations of the second link in relation to the first link. Throughout rotation of the second link in relation to the first link and pivoting of the third link in relation to the second link, the second axis may remain non-orthogonal to the insertion axis. During surgery using the computer-assisted tele-operated surgery manipulator device and at all positions of the third link in relation to the second link, the second link may be rotatable in relation to the first link through an arc of at least 120 degrees without contact between the manipulator device and a plane that includes the particular fixed point in space. In some embodiments, during surgery using the computer-assisted teleoperated surgery manipulator device the first axis is at an angle of less than 30 degrees in relation to the plane that includes the particular fixed point in space.

In another aspect, this disclosure is directed to a computer-assisted teleoperated surgery system including: a set-up structure releasably coupleable with a frame; a manipulator device; and a computer-assisted tele-operated surgical instrument actuator releasably coupleable with the third link. The manipulator device includes: a first link configured to releasably couple with a set-up structure of a computer-assisted tele-operated surgery system; a second link rotatably coupled to the first link such that the second link is rotatable in relation to the first link about a first axis; and a third link pivotably coupled to the second link such that the third link is pivotable in relation to the second link about a second axis. The third link is configured to releasably couple with a patient body wall access cannula defining an insertion axis for a surgical instrument. The first axis, the second axis, and the insertion axis consistently intersect at a particular fixed point in space throughout rotation of the second link in relation to the first link and pivoting of the third link in relation to the second link. Pivoting the third link in relation to the second link sweeps the insertion axis to trace a portion of a conical surface. The third link includes a roll-adjustment motor that drives rotation of the surgical instrument actuator about the insertion axis.

Such a computer-assisted tele-operated surgery system may optionally include one or more of the following features. An entirety of the instrument actuator can be rotatably drivable by the roll-adjustment motor. The system may also include the computer-assisted teleoperated surgical instrument receivable by the surgical instrument actuator. The second link may include a leadscrew, a motor for rotating the leadscrew, and a nut threadably coupled to the leadscrew. The nut may be coupled to a linkage that is pivotably coupled to the third link at a location spaced apart from the second axis. Rotation of the leadscrew causes the third link to pivot in relation to the second link. In some embodiments, during surgery using the computer-assisted teleoperated surgery manipulator device and at all positions of the third link in relation to the second link, the second link may be rotated in relation to the first link through an arc of at least 120 degrees without contact between the manipulator device and a plane that includes the particular fixed point in space.

Some or all of the embodiments described herein may provide one or more of the following advantages. In some cases, the teleoperated surgical manipulator devices provided herein are advantageously structured to have a low-profile, i.e., to be spatially-compact and/or able to be oriented at a low angle (e.g., in a range of about 15° to about 30°) to the patient. Such a compact configuration is advantageous in that the working space occupied by the teleoperated surgical manipulators above the patient is minimized, allowing for enhanced patient access by the surgical team. Additionally, greater visualization of the patient and communications between the surgical team members is facilitated by the compact manipulator working space.

Further, lessening the size of the manipulator working space can reduce the potential for collisions between manipulators. In result, the need for redundant degrees of freedom of the manipulators is mitigated. Hence, the complexity of the manipulators can be lessened in some cases.

The compact size of the tele-operated surgical manipulator devices provided herein can also advantageously facilitate mounting the manipulators to a rail of an operating table in some cases. In such a case, as the operating table is manipulated to enhance surgical access, the table-mounted manipulator devices inherently follow. Therefore, the need to reposition the manipulators in response to movements of the operating table is advantageously reduced or eliminated.

In addition, the teleoperated surgical manipulator devices provided herein are advantageously structured to have a relatively low mass and inertia. In addition, the mass distribution is substantially constant such that the inertia is substantially constant, and therefore predictable.

The details of one or more embodiments are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an example patient-side cart of a computer-assisted tele-operated surgery system.

FIG. **2** is a front view of an example surgeon console of a computer-assisted tele-operated surgery system.

FIG. **3** is a side view of an example robotic manipulator arm assembly of a computer-assisted tele-operated surgery system.

FIG. **4** is a perspective view of another type of patient-side computer-assisted tele-operated surgery system.

FIG. **5** is a perspective view of a distal end portion of an example surgical instrument in a first configuration.

FIG. **6** is a perspective view of the distal end portion of the surgical instrument of FIG. **5** in a second configuration.

FIG. **7** is a perspective view of the distal end portion of the surgical instrument of FIG. **5** in a third configuration.

FIG. **8** is a perspective view depicting a surgical instrument coupled with a surgical instrument actuation pod that is mounted to an example computer-assisted tele-operated surgery manipulator device in accordance with some embodiments.

FIG. **9** is a perspective view of an example surgical instrument actuation pod in accordance with some embodiments.

FIG. **10** is a perspective view of an example computer-assisted tele-operated surgery manipulator device in accordance with some embodiments.

FIG. **11** is another perspective view of the manipulator device of FIG. **10**.

FIG. **12** is a top view of the computer-assisted tele-operated surgery manipulator device of FIG. **10**. The first link of the manipulator device is shown transparently.

FIG. **13** is a bottom view of the computer-assisted tele-operated surgery manipulator device of FIG. **10** with the first link shown transparently.

FIG. **14** is a perspective view of the computer-assisted tele-operated surgery manipulator device of FIG. **10** in a first orientation in relation to a body wall.

FIG. **15** is a perspective view of the computer-assisted tele-operated surgery manipulator device of FIG. **10** in a second orientation in relation to the body wall.

FIG. **16** is another perspective view of the computer-assisted tele-operated surgery manipulator device of FIG. **10**. The second link of the manipulator device is shown transparently.

FIG. **17** is another perspective view of the computer-assisted tele-operated surgery manipulator device of FIG. **10** with the second link shown transparently.

FIG. **18** is a perspective view of the computer-assisted tele-operated surgery manipulator device of FIG. **10** in a third orientation in relation to the body wall.

FIG. **19** is a perspective view of the computer-assisted tele-operated surgery manipulator device of FIG. **10** in a fourth orientation in relation to the body wall.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

This description and the accompanying drawings that illustrate inventive aspects, embodiments, implementations, or applications should not be taken as limiting—the claims define the protected invention. Various mechanical, compositional, structural, electrical, and operational changes may be made without departing from the spirit and scope of this description and the claims. In some instances, well-known circuits, structures, or techniques have not been shown or described in detail in order not to obscure the invention. Like numbers in two or more figures represent the same or similar elements.

Further, specific words chosen to describe one or more embodiments and optional elements or features are not intended to limit the invention. For example, spatially relative terms—such as "beneath", "below", "lower", "above", "upper", "proximal", "distal", and the like—may be used to describe one element's or feature's relationship to another element or feature as illustrated in the figures. These spatially relative terms are intended to encompass different locations (i.e., translational placements) and orientations (i.e., rotational placements) of a device in use or operation in addition to the location and orientation shown in the figures. For example, if a device in the figures is turned over, elements described as "below" or "beneath" other elements or features would then be "above" or "over" the other elements or features. Thus, the exemplary term "below" can encompass both locations and orientations of above and below. A device may be otherwise oriented (e.g., rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly. Likewise, descriptions of movement along (translation) and around (rotation) various axes includes various special device locations and orientations. The combination of a body's location and orientation define the body's pose.

Similarly, geometric terms, such as "parallel", "perpendicular", "round", or "square", are not intended to require absolute mathematical precision, unless the context indicates otherwise. Instead, such geometric terms allow for variations due to manufacturing or equivalent functions. For example, if an element is described as "round" or "generally round", a component that is not precisely circular (e.g., one that is slightly oblong or is a many-sided polygon) is still encompassed by this description. The words "including" or "having" mean including but not limited to.

It should be understood that although this description is made to be sufficiently clear, concise, and exact, scrupulous and exhaustive linguistic precision is not always possible or desirable, since the description should be kept to a reasonable length and skilled readers will understand background and associated technology. For example, considering a video signal, a skilled reader will understand that an oscilloscope described as displaying the signal does not display the signal itself but a representation of the signal, and that a video monitor described as displaying the signal does not display the signal itself but video information the signal carries.

In addition, the singular forms “a”, “an”, and “the” are intended to include the plural forms as well, unless the context indicates otherwise. And, the terms “comprises”, “includes”, “has”, and the like specify the presence of stated features, steps, operations, elements, and/or components but do not preclude the presence or addition of one or more other features, steps, operations, elements, components, and/or groups. And, each of the one or more individual listed items should be considered optional unless otherwise stated, so that various combinations of items are described without an exhaustive list of each possible combination. The auxiliary verb may likewise implies that a feature, step, operation, element, or component is optional.

Elements described in detail with reference to one embodiment, implementation, or application optionally may be included, whenever practical, in other embodiments, implementations, or applications in which they are not specifically shown or described. For example, if an element is described in detail with reference to one embodiment and is not described with reference to a second embodiment, the element may nevertheless be claimed as included in the second embodiment. Thus, to avoid unnecessary repetition in the following description, one or more elements shown and described in association with one embodiment, implementation, or application may be incorporated into other embodiments, implementations, or aspects unless specifically described otherwise, unless the one or more elements would make an embodiment or implementation non-functional, or unless two or more of the elements provide conflicting functions.

Elements described as coupled may be electrically or mechanically directly coupled, or they may be indirectly coupled via one or more intermediate components.

The term “flexible” in association with a part, such as a mechanical structure, component, or component assembly, should be broadly construed. In essence, the term means the part can be repeatedly bent and restored to an original shape without harm to the part. Many “rigid” objects have a slight inherent resilient “bendiness” due to material properties, although such objects are not considered “flexible” as the term is used herein. A flexible part may have infinite degrees of freedom (DOF’s). Examples of such parts include closed, bendable tubes (made from, e.g., NITINOL, polymer, soft rubber, and the like), helical coil springs, etc. that can be bent into various simple or compound curves, often without significant cross-sectional deformation. Other flexible parts may approximate such an infinite-DOF part by using a series of closely spaced components that are similar to a snake-like arrangement of serial “vertebrae.” In such a vertebral arrangement, each component is a short link in a kinematic chain, and movable mechanical constraints (e.g., pin hinge, cup and ball, live hinge, and the like) between each link may allow one (e.g., pitch) or two (e.g., pitch and yaw) DOF’s of relative movement between the links. A short, flexible part may serve as, and be modeled as, a single mechanical constraint (joint) that provides one or more DOF’s between two links in a kinematic chain, even though the flexible part itself may be a kinematic chain made of several coupled links. Knowledgeable persons will understand that a part’s flexibility may be expressed in terms of its stiffness.

Unless otherwise stated in this description, a flexible part, such as a mechanical structure, component, or component assembly, may be either actively or passively flexible. An actively flexible part may be bent by using forces inherently associated with the part itself. For example, one or more tendons may be routed lengthwise along the part and offset from the part’s longitudinal axis, so that tension on the one or more tendons causes the part or a portion of the part to bend. Other ways of actively bending an actively flexible part include, without limitation, the use of pneumatic or hydraulic power, gears, electroactive polymer (more generally, “artificial muscle”), and the like. A passively flexible part is bent by using a force external to the part (e.g., an applied mechanical or electromagnetic force). A passively flexible part may remain in its bent shape until bent again, or it may have an inherent characteristic that tends to restore the part to an original shape. An example of a passively flexible part with inherent stiffness is a plastic rod or a resilient rubber tube. An actively flexible part, when not actuated by its inherently associated forces, may be passively flexible. A single part may be made of one or more actively and passively flexible parts in series.

An example of a teleoperated surgical system is the da Vinci® Surgical System, commercialized by Intuitive Surgical, Inc. of Sunnyvale, California. Inventive aspects are associated with computer-assisted teleoperated surgical systems. Knowledgeable persons will understand that inventive aspects disclosed herein may be embodied and implemented in various ways, including computer-assisted and hybrid combinations of manual and computer-assisted embodiments and implementations. As applicable, inventive aspects may be embodied and implemented in both relatively smaller, hand-held, hand-operated devices and relatively larger systems that have additional mechanical support, as well as in other embodiments of computer-assisted teleoperated medical devices. In addition, inventive aspects are associated with advances in computer-assisted surgical systems that include autonomous rather than teleoperated actions, and so both teleoperated and autonomous surgical systems are included, even though the description concentrates on teleoperated systems.

A computer is a machine that follows programmed instructions to perform mathematical or logical functions on input information to produce processed output information. A computer includes a logic unit that performs the mathematical or logical functions, and memory that stores the programmed instructions, the input information, and the output information. The term “computer” and similar terms, such as “processor” or “controller”, encompasses both centralized single-location and distributed implementations.

This disclosure provides improved surgical and telesurgical devices, systems, and methods. The inventive concepts are particularly advantageous for use with telesurgical systems in which a plurality of surgical tools or instruments are mounted on and moved by an associated plurality of teleoperated manipulators during a surgical procedure. The teleoperated surgical systems will often comprise tele-robotic, telesurgical, and/or telepresence systems that include processors configured as master-slave controllers. By providing teleoperated surgical systems employing processors appropriately configured to move manipulator assemblies with articulated linkages having relatively large numbers of degrees of freedom, the motion of the linkages can be tailored for work through a minimally invasive access site. The large number of degrees of freedom may also allow a processor to position the manipulators to inhibit interference or collisions between these moving structures, and the like.

The manipulator assemblies described herein will often include a teleoperated manipulator and a tool mounted thereon (the tool often comprising a surgical instrument in surgical versions), although the term “manipulator assembly” will also encompass the manipulator without the tool mounted thereon. The term “tool” encompasses both general or industrial robotic tools and specialized robotic surgical instruments, with these later structures often including an end effector that is suitable for manipulation of tissue, treatment of tissue, imaging of tissue, or the like. The tool/manipulator interface will often be a quick disconnect tool holder or coupling, allowing rapid removal and replacement of the tool with an alternate tool. The manipulator assembly will often have a base that is fixed in space during at least a portion of a telesurgical procedure, and the manipulator assembly may include a number of degrees of freedom between the base and an end effector of the tool. Actuation of the end effector (such as opening or closing of the jaws of a gripping device, energizing an electrosurgical paddle, or the like) will often be separate from, and in addition to, these manipulator assembly degrees of freedom.

The end effector will typically move in the workspace with between two and six degrees of freedom. As used herein, the term "position" encompasses both location and orientation. Hence, a change in a position of an end effector (for example) may involve a translation of the end effector from a first location to a second location, a rotation of the end effector from a first orientation to a second orientation, or a combination of both. As used herein, the term "end effector" therefore includes but is not limited to the function of changing the orientation or position (e.g., a "wrist" function, a parallel motion function) of its distal-most part or parts (e.g., jaw(s) and the like).

When used for minimally invasive teleoperated surgery, movement of the manipulator assembly may be controlled by a processor of the system so that a shaft or intermediate portion of the tool or instrument is constrained to a safe motion through a minimally invasive surgical access site or other aperture. Such motion may include, for example, axial insertion of the shaft through the aperture site, rotation of the shaft about its axis, and pivotal motion of the shaft about a pivot point adjacent the access site, but will often preclude excessive lateral motion of the shaft which might otherwise tear the tissues adjacent the aperture or enlarge the access site inadvertently. Some or all of such constraint on the manipulator motion at the access site may be imposed using mechanical manipulator joint linkages that inhibit improper motions, or may in part or in full be imposed using robotic data processing and control techniques. Hence, such minimally invasive aperture-constrained motion of the manipulator assembly may employ between zero and three degrees of freedom of the manipulator assembly.

Many of the exemplary manipulator assemblies described herein will have more degrees of freedom than are needed to position and move an end effector within a surgical site. For example, a surgical end effector that can be positioned with six degrees of freedom at an internal surgical site through a minimally invasive aperture may in some embodiments have nine degrees of freedom (six end effector degrees of freedom—three for location, and three for orientation—plus three degrees of freedom to comply with the access site constraints), but will often have ten or more degrees of freedom. Highly configurable manipulator assemblies having more degrees of freedom than are needed for a given end effector position can be described as having or providing sufficient degrees of freedom to allow a range of joint states for an end effector position in a workspace. For example, for a given end effector position, the manipulator assembly may occupy (and be driven between) any of a range of alternative manipulator linkage positions. Similarly, for a given end effector velocity vector, the manipulator assembly may have a range of differing joint movement speeds for the various joints of the manipulator assembly.

Referring to FIGS. **1** and **2**, systems for minimally invasive computer-assisted telesurgery (as referred to herein as "minimally invasive robotic surgery") can include a patient-side unit **100** and a surgeon control unit **40**. Telesurgery is a general term for surgical systems where the surgeon uses some form of remote control, e.g., a servomechanism, or the like, to manipulate surgical instrument movements by using robot technology rather than directly holding and moving the instruments by hand. The robotically manipulatable surgical instruments can be inserted through small, minimally invasive surgical apertures to treat tissues at surgical sites within the patient, avoiding the trauma associated with accessing for open surgery. These robotic systems can move the working ends of the surgical instruments with sufficient dexterity to perform quite intricate surgical tasks, often by pivoting shafts of the instruments at the minimally invasive aperture, sliding of the shaft axially through the aperture, rotating of the shaft within the aperture, and/or the like.

In the depicted embodiment, the patient-side unit **100** includes a base **110**, a first robotic manipulator arm assembly **120**, a second robotic manipulator arm assembly **130**, a third robotic manipulator arm assembly **140**, and a fourth robotic manipulator arm assembly **150**. As shown, the base **110** includes a portion that rests on the floor, a vertical column, and a horizontal boom, and other base configurations to mechanically ground the patient-side unit may optionally be used. Each robotic manipulator arm assembly **120**, **130**, **140**, and **150** is pivotably coupled to the base **110**. In some embodiments, fewer than four or more than four robotic manipulator arm assemblies may be included as part of the patient-side unit **100**. While in the depicted embodiment the base **110** includes casters to allow ease of mobility, in some embodiments the patient-side unit **100** is fixedly mounted to a floor, ceiling, operating table, structural framework, or the like.

In a typical application, two of the robotic manipulator arm assemblies **120**, **130**, **140**, or **150** hold surgical instruments and a third holds a stereo endoscope. The remaining robotic manipulator arm assembly is available so that another instrument may be introduced at the work site. Alternatively, the remaining robotic manipulator arm assembly may be used for introducing a second endoscope or another image capturing device, such as an ultrasound transducer, to the work site.

Each of the robotic manipulator arm assemblies **120**, **130**, **140**, and **150** is conventionally formed of links that are coupled together and manipulated through actuatable joints. Each of the robotic manipulator arm assemblies **120**, **130**, **140**, and **150** includes a setup arm and a device manipulator. The setup arm positions its held device so that a pivot point occurs at its entry aperture into the patient. The device manipulator may then manipulate its held device (tool; surgical instrument) so that it may be pivoted about the pivot point, inserted into and retracted out of the entry aperture, and rotated about its shaft axis.

In the depicted embodiment, the surgeon console **40** includes a stereo vision display **45** so that the user may view the surgical work site in stereo vision from images captured by the stereoscopic camera of the patient-side cart **100**. Left and right eyepieces **46** and **47** are provided in the stereo vision display **45** so that the user may view left and right display screens inside the display **45** respectively with the user's left and right eyes. While viewing typically an image of the surgical site on a suitable viewer or display, the surgeon performs the surgical procedures on the patient by manipulating master control input devices, which in turn control the motion of robotic instruments.

The surgeon console **40** also includes left and right input devices **41**, **42** that the user may grasp respectively with his/her left and right hands to manipulate devices (e.g., surgical instruments) being held by the robotic manipulator arm assemblies **120**, **130**, **140**, and **150** of the patient-side cart **100** in preferably six degrees-of-freedom ("DOF"). Foot pedals **44** with toe and heel controls are provided on the surgeon console **40** so the user may control movement and/or actuation of devices associated with the foot pedals. Additional input to the system may be made via one or more other inputs, such as buttons, touch pads, voice, and the like, as illustrated by input **49**.

A processor **43** is provided in the surgeon console **40** for control and other purposes. The processor **43** performs various functions in the medical robotic system. One function performed by processor **43** is to translate and transfer the mechanical motion of input devices **41**, **42** to actuate their respective joints in their associated robotic manipulator arm assemblies **120**, **130**, **140**, and **150** so that the surgeon can effectively manipulate devices, such as the surgical instruments. Another function of the processor **43** is to implement the methods, cross-coupling control logic, and controllers described herein.

Although described as a processor, it is to be appreciated that the processor **43** may be implemented by any combination of hardware, software, and firmware. Also, its functions as described herein may be performed by one unit or divided up among a number of subunits, each of which may be implemented in turn by any combination of hardware, software, and firmware. Further, although being shown as part of or being physically adjacent to the surgeon control unit **40**, the processor **43** may also be distributed as subunits throughout the telesurgery system. Accordingly, control aspects referred to herein are implemented via processor **43** in either a centralized or distributed form.

Referring also to FIG. **3**, the robotic manipulator arm assemblies **120**, **130**, **140**, and **150** can manipulate devices such as surgical instruments to perform minimally invasive surgery. For example, in the depicted arrangement the robotic manipulator arm assembly **120** is pivotably coupled to an instrument holder **122**. A cannula **180** and a surgical instrument **200** and are, in turn, releasably coupled to the instrument holder **122**. The cannula **180** is a tubular member that is located at the patient interface site during a surgery. The cannula **180** defines a lumen in which an elongate shaft **220** of the surgical instrument **200** is slidably disposed. As described further below, in some embodiments the cannula **180** includes a distal end portion with a body wall retractor member.

The instrument holder **122** is pivotably coupled to a distal end of the robotic manipulator arm assembly **120**. In some embodiments, the pivotable coupling between the instrument holder **122** and the distal end of robotic manipulator arm assembly **120** is a motorized joint that is actuatable from the surgeon console **40** and processor **43**.

The instrument holder **122** includes an instrument holder frame **124**, a cannula clamp **126**, and an instrument holder carriage **128**. In the depicted embodiment, the cannula clamp **126** is fixed to a distal end of the instrument holder frame **124**. The cannula clamp **126** can be actuated to couple with, or to uncouple from, the cannula **180**. The instrument holder carriage **128** is movably coupled to the instrument holder frame **124**. More particularly, the instrument holder carriage **128** is linearly translatable along the instrument holder frame **124**. In some embodiments, the movement of the instrument holder carriage **128** along the instrument holder frame **124** is a motorized, translational movement that is actuatable/controllable by the processor **43**.

The surgical instrument **200** includes a transmission assembly **210**, the elongate shaft **220**, and an end effector **230**. The transmission assembly **210** is releasably coupleable with the instrument holder carriage **128**. The shaft **220** extends distally from the transmission assembly **210**. The end effector **230** is disposed at a distal end of the shaft **220**.

The shaft **220** defines a longitudinal axis **222** that is coincident with a longitudinal axis of the cannula **180**. As the instrument holder carriage **128** translates along the instrument holder frame **124**, the elongate shaft **220** of the surgical instrument **200** is moved along the longitudinal axis **222**. In such a manner, the end effector **230** can be inserted and/or retracted from a surgical workspace within the body of a patient.

Also referring to FIG. **4**, another example patient-side system **160** for minimally invasive computer-assisted tele-operated surgery includes a first robotic manipulator arm assembly **162** and a second robotic manipulator arm assembly **164** that are each mounted to an operating table **10**. In some cases, this configuration of patient-side system **160** can be used as an alternative to the patient-side unit **100** of FIG. **1**. While only two robotic manipulator arm assemblies **162** and **164** are depicted, it should be understood that more than two (e.g., three, four, five, six, and more than six) can be included in some configurations.

In some cases, the operating table **10** may be moved or reconfigured during the surgery. For example, in some cases, the operating table **10** may be tilted about various axes, raised, lowered, pivoted, rotated, and the like. In some cases, by manipulating the orientation of the operating table **10**, the clinicians can utilize the effects of gravity to position internal organs of the patient in positions that facilitate enhanced surgical access. In some cases, such movements of the operating table **10** may be integrated as a part of the computer-assisted tele-operated surgery system, and controlled by the system.

Also referring to FIGS. **5**-**7**, a variety of alternative computer-assisted tele-operated surgical instruments of different types and differing end effectors **230** may be used, with the instruments of at least some of the manipulators being removed and replaced during a surgical procedure. Several of these end effectors, including, for example, DeBakey Forceps **56*i***, microforceps **56*ii***, and Potts scissors **56*iii*** include first and second end effector elements **56*a***, **56*b*** which pivot relative to each other so as to define a pair of end effector jaws. Other end effectors, including scalpels and electrocautery probes, have a single end effector element. For instruments having end effector jaws, the jaws will often be actuated by squeezing the grip members of input devices **41**, **42**.

In some cases, the computer-assisted tele-operated surgical instruments include multiple degrees of freedom such as, but not limited to, roll, pitch, yaw, insertion depth, opening/closing of jaws, actuation of staple delivery, activation of electro-cautery, and the like. At least some of such degrees of freedom can be actuated by an instrument drive system to which the surgical instrument can be selectively coupled.

In some embodiments, the computer-assisted tele-operated surgical instruments include end effectors with two individually movable components such as, but not limited to, opposing jaws designed for grasping or shearing. When a first one of the individually movable components is moved as a second one of the individually movable components remains generally stationary or is moved in an opposing manner, the end effector can perform useful motions such as opening and closing for grasping, shearing, releasing, and the like. When the two components are moved synchronously in the same direction, speed and distance, the resulting motion is a type of pitch or yaw movement of the end effector. Hence, in some surgical instrument embodiments that have end effectors with two individually movable components, such as jaws, the arrangement can provide two degrees of freedom (e.g., pitch/yaw movements and opening/closing movements).

The elongate shaft **220** allow the end effector **230** and the distal end of the shaft **220** to be inserted distally into a surgical worksite through a minimally invasive aperture (via cannula **180**), often through a body wall (e.g., abdominal wall) or the like. In some cases, a body wall retractor member on a distal end of the cannula **180** can be used to tent the body wall, thereby increasing the surgical workspace size. In some cases the surgical worksite may be insufflated, and movement of the end effectors **230** within the patient will often be effected, at least in part, by pivoting of the instruments **200** about the location at which the shaft **220** passes through the minimally invasive aperture. In other words, the robotic manipulator arm assemblies **120**, **130**, **140**, and **150** will move the transmission assembly **210** outside the patient so that the shaft **220** extends through a minimally invasive aperture location so as to help provide a desired movement of end effector **50**. Hence, the robotic manipulator arm assemblies **120**, **130**, **140**, and **150** will often undergo significant movement outside patient during a surgical procedure.

Referring to FIG. **8**, an example computer-assisted teleoperated surgery system **500** (a "telesurgical system") is shown in relation to a portion of a simulated patient body wall **20**. The system **500** includes the set-up structure **172**, a manipulator device **800**, which is an assembly that includes a surgical instrument actuator **700**, a surgical instrument **600**, and a cannula **900**.

The set-up structure **172** can be adjustably mounted to a base or frame (i.e., a mechanical ground) such as, but not limited to, a bed rail of an operating room table. The manipulator device assembly **800** is releasably and adjustably coupleable with the set-up structure **172**. In some embodiments, the set-up structure **172** and the manipulator device assembly **800** can be manually adjusted and then locked into a desired pose of a multitude of possible poses in relation to the patient's body wall **20**. For example, the set-up structure **172** and the manipulator device assembly **800** can be manually adjusted so that the cannula **900** is aligned with a surgical access location **22**. Such adjustments can be made prior to initiation of a surgery or during a surgery.

The manipulator device assembly **800** includes releasably coupleable compatible surgical instrument actuator **700** (also referred to herein as a "surgical instrument actuation pod," or a simply a "pod"). In some embodiments, the pod **700** is readily detachable from the manipulator assembly **800** such that the pod **700** can be conveniently interchanged with another pod. The pod **700** defines an insertion axis **702** along which a surgical instrument is inserted and withdrawn. In some embodiments, the manipulator device assembly **800** can rotatably drive an entirety of the pod **700** (and the surgical instrument **600** coupled with the pod **700**) to rotate at a revolute roll joint about the insertion axis **702** as depicted by arrow **704**. Such motion may be referred to as roll motion or simply "roll."

When the surgical instrument **600** is coupled with the pod **700**, a shaft **640** of the surgical instrument **600** slidably extends through the cannula **900**, which is releasably coupled with the manipulator assembly **800**. In use, the cannula **900** can extend through the body wall **20** of the patient at the surgical access location **22** (which can be defined by a trocar, a port, an incision, a natural body orifice, and the like). The surgical instrument **600** includes an end effector **650** that is controlled by the surgeon performing the computer-assisted teleoperated surgery.

The pod **700** defines a space configured to receive the surgical instrument **600**. When the surgical instrument **600** is coupled with the pod **700**, the pod **700** can actuate movements of the end effector **650** and of the surgical instrument **600** as a whole. For example, the pod **700** can actuate translational movements of the surgical instrument **600** along the longitudinal insertion axis **702** of the pod **700**. That is, the pod **700** can insert and retract the surgical instrument **600** deeper (distally) and shallower (proximally) in relation to the patient. Hence, the longitudinal axis **702** is sometimes also referred to as the insertion axis **702**.

Referring also to FIG. **9**, the example surgical instrument actuator pod **700** is shown in isolation from the surgical instrument **600** and the manipulator device assembly **800**. The pod **700** includes a proximal end **704** and a distal end **706**. The proximal and distal ends of the pod **700** define the longitudinal axis **702** along which a surgical instrument (or other device such as an endoscopic camera) can be installed.

In the depicted embodiment, the pod **700** includes a proximal end plate **705**, a distal end plate **707**, and a housing **710**. The housing **710** extends between the proximal end **704** and the distal end **706**.

In the depicted embodiment, the proximal end plate **705** is a C-shaped plate, while the distal end plate **707** is a fully circumferential plate that defines an open center. The opening in the proximal end plate **705** aligns with a slot opening **712** defined by the housing **710**. The slot opening **712** and the opening in the C-shaped proximal end plate **705** provide clearance for a handle **612** of the surgical instrument **600** to project radially from the housing **710** while the surgical instrument **600** is coupled with the instrument drive system **700**.

In the depicted embodiment, the pod **700** also includes a roll driven gear **708**. The pod's roll driven gear **708** is positioned to mesh with and to be driven by a roll drive gear **847** (refer to FIGS. **10-12** and **16**) coupled to a roll drive (roll-adjustment) motor **846** (FIG. **11**) of a third link **830** of the manipulator device assembly **800** when the pod **700** is coupled with the instrument actuator coupling **840** of the manipulator device assembly **800**. Roll drive gear **847** driven by motor **846** engages roll driven gear **708**, and motor **846** and roll drive gear **847** are illustrative of various roll drive assemblies that may be used. When the roll driven gear **708** is so driven, the entire pod **700** rotates or rolls (as depicted by arrow **704**, FIG. **8**) about the insertion axis **702**. When the surgical instrument **600** is engaged with the pod **700**, the surgical instrument **600** also rotates or rolls about the insertion axis **702** correspondingly as the roll driven gear **708** is driven by the roll drive gear **847** of the instrument actuator coupling **840**. Accordingly, insertion axis **702** also functions as an instrument roll axis around with elongate shaft **640** (FIG. **8**) rolls.

Referring also to FIGS. **10** and **11**, here a portion of the manipulator device assembly **800** is shown in isolation from the other devices of the computer-assisted teleoperated surgery system **500**. The manipulator device assembly **800** includes a first link **810**, a second link **820**, and a third link **830**. The first link **810** and the second link **820** are rotatably coupled. That is, as described further below, the second link **820** can be rotated in relation to the first link **810**. The second link **820** and the third link **830** are rotatably coupled at a pivot. That is, as described further below, the third link **830** can be pivoted in relation to the second link **820**.

The first link **810** is configured to releasably couple with the set-up structure **172**. Accordingly, in the depicted embodiment the first link includes a ball **811** extending from a proximal end of the first link **810**. The ball **811** is configured to be received in a socket **173** of the set-up structure **172**. The ball-in-socket connection between the ball **811** and the socket **173** (a spherical joint) allows for orientation adjustability between the manipulator device assembly **800** and the set-up structure **172**. When a desired orientation between the manipulator device **800** and the set-up structure **172** has been attained, the ball-in-socket connection between the ball **811** and the socket **173** can be releasably clamped in a fixed orientation. Thereafter, the first link **810** remains stationary in relation to the set-up structure **172** until the two are unclamped and readjusted.

The ball-in-socket connection is merely one non-limiting example of the types of mechanical connections that can be used between the manipulator device assembly **800** and the set-up structure **172**. For example, articulating joints, x-y-z adjustment mechanisms, and the like, and combinations thereof, can be used. The connection between the manipulator device assembly **800** and the set-up structure **172** can be passive (manually adjustable) or active (power adjustable or power-assist adjustable).

The third link **830** is configured to releasably couple with the patient body wall access cannula **900** that is coaxial with the insertion axis **702**. The cannula **900** defines a lumen that slidably receives the shaft **640** of the surgical instrument **600** (or of other devices such as, but not limited to, an endoscope) along the insertion axis **702**. As shown in FIG. **8**, the cannula **900** extends distally from the third link **830** through the patient's body wall **20** via the surgical access location **22**.

As described further herein, in order to facilitate movements of the surgical instrument **600** (and of the end effector **650** in particular), the relative configuration of the links **810**, **820**, and **830** of the manipulator device assembly **800** actively adjust in response to input (e.g., surgeon input using the surgeon console **40** and processor **43** as described in reference to FIG. **2**). It can be said, therefore, that the manipulator device assembly **800** is configured to actuate pitch, roll, and yaw motions of the surgical instrument **600** as a whole in response to actuation input. Moreover, as described further herein, the manipulator device assembly **800** is configured to actuate such pitch, roll, and yaw motions of the surgical instrument **600** without creating excessive lateral motion of the body wall access cannula **900**, which might tend to stress or tear the tissues adjacent the surgical access location **22** or to enlarge the access site inadvertently.

In the depicted embodiment, the manipulator device assembly **800** is designed with a hardware-constrained remote center of motion (RCM) **902** so that pitch, roll, and yaw motions of the surgical instrument **600** as a whole can be implemented by the manipulator device **800** without creating excessive lateral motion of the body wall access cannula **900**. The RCM **902** is a point in space around which the roll, pitch, and yaw motions described above are made. In the depicted embodiment, the RCM **902** is a point on the insertion axis **702** that is fixed at a particular longitudinal position along the cannula **900**. As the relative configuration of the links **810**, **820**, and **830** of the manipulator device assembly **800** actively adjust in response to user input, the RCM **902** remains fixed in space. Therefore, while pitch, roll, and yaw motions of the surgical instrument **600** as a whole are implemented by the manipulator device **800**, excessive lateral motion of the body wall access cannula **900** that might tend to stress or tear the tissues adjacent the surgical access location **22** or to enlarge the access site inadvertently is avoided. In some embodiments, the RCM can be located at other points (e.g., at a particular distance away from the insertion axis **702**). In some embodiments, the manipulator device assembly **800** can be implemented using a software-constrained RCM rather than, or in addition to, a hardware-constrained RCM.

Referring to FIGS. **10**-**13**, it can be seen that first link **810** has a proximal end **810***a* and a distal end **810***b*. First link **810**'s straight longitudinal axis **821** extends through and is defined by its proximal and distal ends. It can further be seen that second link **820** has a proximal end **820***a* and a distal end **820***b*. Second link **820** also has an actuator housing portion **820***c* that extends proximally beyond proximal end **820***a* to a proximal actuator housing portion end **820***d*.

Still referring to FIGS. **10**-**13**, the distal end **810***b* of first link **810** is rotatably coupled to the proximal end **820***a* of second link **820** at a revolute joint **815**. The axis of rotation of revolute joint **815** defines a longitudinal axis of second link **820**. The longitudinal axes of the first and second links are coincident, and these coincident axes are illustrated by axis **821** as shown. Accordingly, the second link **820** can rotate in relation to the first link **810** about an axis that is defined by the rotary joint **815**, which may be considered a yaw joint (the term "yaw" is arbitrary and does not indicate a unique coordinate system). It can be seen that as second link **820** rotates in relation to first link **810**, second link **820**'s housing portion **820***c* and its distal end **820***d* orbit around first link **810**. It can further be seen that an axis through housing portion proximal end **820***d* and second link distal end **820***b* sweeps along a section of a conical surface having an axis coincident with the longitudinal axis of second link **820**.

The second link **820** is rotatably coupled to the third link **830** at a revolute pivot joint **825**, which may be considered a pitch joint (the term "pitch" is arbitrary and does not indicate a unique coordinate system). Accordingly, the third link **830** can pivot in relation to the second link **820** about an axis that is defined by the revolute pivot joint **825**. At any combination of relative orientation between the links **810**, **820**, and **830** and motions of the links **810**, **820**, and **830**, the RCM **902** remains fixed in space because of the manipulator device assembly **800** is designed with a hardware-constrained RCM.

Referring to FIGS. **12** and **13**, here the first link **810** is shown transparently so that the mechanisms by which the second link **820** is rotatable in relation to the first link **810** can be visualized. In the depicted embodiment, a motor **812** is included in the first link **810**. A drive gear **814** is fixed to the drive shaft of the motor **812**. Rotation of the motor **812** therefore rotates the drive gear **814**. As shown, motor **812** extends proximally from drive gear **814** (i.e., proximally from joint **815**).

The drive gear **814** is meshed with a driven gear **822**. The driven gear **822** is fixed to the second link **820**. Therefore, rotary motion of the driven gear **822** result in corresponding rotary motion of the second link **820**. Motor **812** and drive gear **814** are illustrative of various yaw drive assemblies that may be used. As shown, with reference to first link **820**'s longitudinal axis **821**, motor **812**'s axis of rotation is non-parallel, non-intersecting, and at a shallow acute angle. In other implementations motor **812**'s axis of rotation may, for example, parallel to or coincident with longitudinal axis **821**.

Because the first link **810** is constrained in relation to a set-up structure (e.g., set-up structure **172**, FIG. **8**), rotation of the drive gear **814** causes the driven gear **822** to rotate around its axis **821**. Because the driven gear **822** is fixed to the second link **820**, rotation of the driven gear around the axis **821** causes the entire second link **820** to rotate about the axis **821**.

The first link **810** also includes a bearing **816**. The outer race of the bearing **816** is captured in a stationary relationship to the housing of the first link **810**. The inner race of the bearing **816** is coupled with a stub shaft (projecting from the second link **820**) that the driven gear **822** is also coupled to. Therefore, the entire second link **820** rotates in relation to the first link **810** about the axis **821** as the motor **812** is actuated. In the depicted embodiment, the axis **821** is defined by the bearing **816** and is coaxial with the driven gear **822**. The axis **821** projects through the RCM **902** (FIGS. **10** and **11**) and functions as an instrument yaw axis of the manipulator assembly.

Referring also to FIGS. **14** and **15**, here the manipulator device assembly **800** is shown in relation to a simulated portion of a patient's body wall **20**. The difference between FIG. **14** and FIG. **15** is the rotational orientation of the second link **820** in relation to the first link **810**. As described above, the second link **820** is rotatable in relation to the first link **810** about the axis **821** as depicted by arrow **804**. In some cases, the axis **821** may also be referred to as the yaw axis **821**, and rotations of the second link **820** in relation to the first link **810** may be referred to as yaw motions, or simply "yaw." The yaw axis **821** projects through the RCM **902**.

One advantageous feature of the manipulator device assembly **800** is that it is designed to facilitate a wide range of yaw motion without contacting the patient's body (e.g., without contacting a surface **23**, which may be a skin surface, for example, or without intersecting a plane that includes the RCM **902** and that is perpendicular to the instrument insertion axis **702**). In general, yaw range of motion is limited by second link **820**'s proximity to surface **23** at one extreme (see e.g., FIG. **15**) and third link **830**'s proximity to surface **23** at the other extreme (see e.g., FIG. **14**). For example, in some embodiments the second link **820** can be rotated in relation to the first link **810** through an arc (as depicted by arrow **804**) that is in a range of about 90° to about (110°±10°), or about 100° to about 120° (110°±10°), or about 110° to about 130° (120°±10°), or about 120° to about 140° (130°±10°), or about 130° to about 150° (140°±10°), or about 110° to about 120° (115°±5°), or about 115° to about 125° (120°±5°), or about 120° to about 130° (125°±5°) without contacting the patient's body and/or without intersecting the plane that includes the RCM **902**. It should also be understood that these ranges of rotational motion of the second link **820** in relation to the first link **810** can be realized throughout all possible rotational orientations of the third link **830** in relation to the second link **820** when pivoted at pivot joint **825**.

Another advantageous feature of the manipulator device assembly **800** is its operative usability for computer-assisted teleoperated surgery while positioned at a low angle in relation to the surface **23**. Such low-angle positioning can provide advantages such as enhanced patient access by the surgical team, greater visualization of the patient, and facilitated communications between the surgical team members because they can more easily see each other. For example, in some embodiments the manipulator device assembly **800** can be oriented such that the angle between the yaw axis **821** and the surface **23** (or, for example, between the yaw axis **821** and a plane that includes the RCM **902**) is in a range between about 10° to about 30° (20°±10°), or about 20° to about 40° (30°±10°), or about 30° to about 50° (40°±10°), or about 15° to about 25°(20°±5°), or about 20° to about 30° (25°±5°), or about 25° to about 35° (30°±5°), or about 30° to about 40° (35°±5)°. Moreover, the manipulator device assembly **800** can be oriented at these low angles while also allowing for the second link **820** to be rotated in relation to the first link **810** through the arc ranges described above without intersecting the patient's body (or intersecting the plane that includes the RCM **902**).

Referring to FIGS. **16** and **17**, the second link **820** is shown transparently so that the mechanisms by which the third link **830** is rotatable in relation to the second link **820** can be visualized. In the depicted embodiment, a motor **824** is included in the second link **820**. A lead screw **826** is coupled to the drive shaft of the motor **824**. Rotation of the motor **824** therefore rotates the lead screw **826**.

A nut **828** is threadably coupled to the lead screw **826**. The nut **828** is constrained from rotating in relation to the housing of the second link **820**. Therefore, as the motor **824** drives rotation of the lead screw **826**, the nut **828** is caused to translate along the longitudinal axis of the lead screw **826**.

A pitch drive link **829** has a first end that is pivotably coupled to the nut **828** and a second end that is pivotably coupled to the third link **830** at a pivot joint **832**. The pivot joint **832** is spaced apart from the pivot joint **825**. Therefore, as the motor **824** drives rotation of the lead screw **826**, the nut **828** is caused to translate along the longitudinal axis of the lead screw **826**, and the link **829** causes the third link **830** to pivot about the pivot joint **825** in relation to the second link **820**. The pivoting motion of the third link **830** in relation to the second link **820** is depicted by arrow **806**. The entire third link **830** pivots in relation to second link **820** about the axis **831** as the motor **824** is actuated. In the depicted embodiment, the axis **831** is defined by the pivot joint **825** (which acts as a hinge between the second link **820** and the third link **830**). The axis **831** projects through the RCM **902** and functions as an instrument pitch axis of the manipulator assembly.

The motor **824**, lead screw **826**, and nut **828** are illustrative of various linear actuators that may be used, including ball screw, chain, belt, hydraulic, pneumatic, electromagnetic, and the like. Such linear actuators and the pitch drive link **829** are illustrative of various pitch drive assemblies that may be used to rotate third link **830** around pitch axis **831**.

It should be understood that in the context of manipulator device assembly **800**, the rotational motion between the first link **810** and the second link **820** is a different type of motion than the rotational motion between the second link **820** and the third link **830**. The third link **830** pivots in relation to the second link **820** because the links are conjoined at the pivot joint **825** (which acts like a hinge), and so third link **830** generally orbits around axis **831**. The second link **820** rotates in relation to the first link **810** because the links are conjoined at the rotary joint **815** which allows the second link **820** to rotate in relation to the first link **810** generally in-line around axis **821**.

Referring also to FIGS. **18** and **19**, the manipulator device assembly **800** is shown in relation to a simulated portion of a patient's body wall **20**. The difference between FIG. **18** and FIG. **19** is the rotational orientation of the third link **830** in relation to the second link **820**. As described above, the third link **830** is pivotable in relation to the second link **820** about the axis **831**, as depicted by arrow **806**. In some cases, the axis **831** may also be referred to as the pitch axis **831**, and pivotal motions of the third link **830** in relation to the second link **820** may be referred to as pitch motions, or simply "pitch." The pitch axis **831** projects through the RCM **902**.

In the depicted embodiment, the pitch axis **831** is non-orthogonal to the insertion axis **702**. The pitch axis **831** remains non-orthogonal to the insertion axis **702** throughout all rotational orientations of the second link **820** around yaw axis **821** in relation to the first link **810**, throughout all rotational orientations of the third link **830** around pitch axis **831** in relation to the second link **820**, and throughout all combinations thereof. In some embodiments, the angle between the pitch axis **831** and the insertion axis **702** is in a range between about 10° to about 30°, or about 20° to about 40°, or about 30° to about 50°, or about 15° to about 25°, or about 20° to about 25, or about 25° to about 35°, or about 30° to about 40°, or about 25° to about 30°, or about 30° to about 35°.

It can be seen that as the third link **830** pivots in relation to the second link **820**, insertion axis **702** sweeps across a portion of a conical surface having an apex at RCM **902**. It can also be seen that at a unique rotational orientation of the third link **830** around the pitch axis **831** with reference to the second link **820**, instrument insertion axis **702** will be perpendicular to yaw axis **821**. And so at this unique rotational orientation around pitch axis **831**, rotation of the second link **820** around yaw axis **821** with reference to the first link **810** sweeps the instrument insertion axis **702** across a circular sector surface having a center at RCM **902**. It can also be seen that at rotational orientations of the third link **830** around the pitch axis **831** with reference to the second link **820** other than this unique rotational orientation around pitch axis **831**, rotation of the second link **820** around the yaw axis **821** with reference to the first link **810** sweeps the instrument insertion axis **702** across a portion of a conical surface having an apex at RCM **902**. The portions of the conical surfaces across which instrument insertion axis **702** is swept by rotation around the yaw axis **821** and rotation around the pitch axis **831** are different from each other.

Thus it can be seen that RCM **902** is constrained by manipulator device assembly **800**'s hardware, and it is defined by the intersection of insertion axis **702**, yaw axis **821**, and pitch axis **831**. As the surgeon commands the instrument end effector **650** to move in various directions at the surgical site by moving a master input device **42**, the controller illustrated by processor **43** correspondingly controls rotation of the instrument as a whole along axis **702**, around axis **821**, and around axis **831** to place the end effector at the desired position in space at the surgical site. Similarly, the controller controls orientation of end effector **650** by controlling rotation around axis **702**, and by moving the end effector in pitch and yaw with reference to instrument shaft **640**. Manipulator device assembly **800** provides a compact, low profile, large range of motion teleoperated manipulator for use during telesurgery.

In some embodiments, the manipulator device assembly **800** may include electronic sensors and the like for various advantageous purposes. For example, encoders may be coupled to the drive trains of the motorized pitch, roll, and/or yaw drive (adjustment) mechanisms. In some embodiments, position sensors may be used that can positively identify the locations of the movable components of the manipulator device **800**.

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

Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system modules and components in the embodiments described herein should not be understood as requiring such separation in all embodiments, and it should be understood that the described program components and systems can generally be integrated together in a single product or packaged into multiple products.

Particular embodiments of the subject matter have been described. Other embodiments are within the scope of the following claims. For example, the actions recited in the claims can be performed in a different order and still achieve desirable results. As one example, the processes depicted in the accompanying figures do not necessarily require the particular order shown, or sequential order, to achieve desirable results. In certain implementations, multitasking and parallel processing may be advantageous.

We claim:

1. A teleoperated surgical system comprising:

a first link;

a second link rotatably coupled to the first link at a revolute yaw joint having an axis of rotation that defines an instrument yaw axis; and

a third link rotatably coupled to the second link at a revolute pitch joint having an axis of rotation that defines a pitch axis, the third link defining an instrument insertion axis,

wherein the yaw axis, the pitch axis, and the instrument insertion axis intersect at a remote center of motion, and

wherein rotation of the third link around the pitch axis with reference to the second link sweeps the instrument insertion axis to trace a portion of a first conical shape having an apex at the remote center of motion.

2. The teleoperated surgical system of claim **1**, wherein the first link comprises a proximal end, a distal end, and a longitudinal axis defined between the proximal and distal ends of the first link.

3. The teleoperated surgical system of claim **2**, wherein the instrument yaw axis is coincident with the longitudinal axis of the first link.

4. The teleoperated surgical system of claim **1**, further comprising a surgical instrument actuator coupled to the third link, the instrument actuator comprising a proximal end and a distal end, wherein the instrument insertion axis defined by the third link is positioned between the proximal and distal ends of the instrument actuator.

5. The teleoperated surgical system of claim **4**, wherein the surgical instrument actuator is coupled to the third link at the distal end of the surgical instrument actuator.

6. The teleoperated surgical system of claim **4**, wherein the surgical instrument actuator is releasably coupled to and is readily detachable from the third link such that the surgical instrument actuator can be interchanged with a second surgical instrument actuator.

7. The teleoperated surgical system of claim **4**, further comprising a revolute roll joint, wherein the surgical instrument actuator is coupled to the third link via the roll joint, the roll joint defines an axis of rotation coincident with the instrument insertion axis, and the surgical instrument actuator rotates at the roll joint with reference to the third link around the instrument insertion axis.

8. The teleoperated surgical system of claim **4**, further comprising a roll drive assembly coupled to the third link, wherein the roll drive assembly is engaged with the surgical instrument actuator and drives rotation of the surgical instrument actuator around the instrument insertion axis.

9. The teleoperated surgical system of claim **4**, further comprising a user control unit comprising a user input device and a controller,

wherein the first link, the second link, the third link, and the surgical instrument actuator together comprise a teleoperated surgical manipulator, and

wherein user inputs at the user input device teleoperate the manipulator via the controller to move a surgical instrument with reference to the yaw axis, the pitch axis, and the instrument insertion axis.

10. The teleoperated surgical system of claim **1**, wherein the yaw axis, the pitch axis, and the instrument insertion axis are retained in movable orientations relative to each other.

11. The teleoperated surgical system of claim **1**, wherein at a particular first rotational orientation of the third link around the pitch axis with reference to the second link, rotation of the second link around the yaw axis with reference to the first link sweeps the instrument insertion axis across a circular sector surface having a center at the remote center of motion.

12. The teleoperated surgical system of claim **1**, wherein at rotational orientations of the third link around the pitch axis with reference to the second link other than the first rotational orientation, rotation of the second link around the yaw axis with reference to the first link sweeps the instrument insertion axis to trace a second conical shape having an apex at the remote center of motion.

13. The teleoperated surgical system of claim **1**, wherein:

the second link comprises a pitch drive assembly;

the pitch drive assembly comprises a linear actuator and a pitch drive link coupled to the linear actuator; and

the pitch drive assembly is coupled between the second link and the third link and drives rotation of the third link around the pitch axis.

14. The teleoperated surgical system of claim **1**, further comprising a yaw drive assembly coupled to the second link, wherein the yaw drive assembly is engaged with the first link and drives rotation of the second link around the yaw axis.

15. The teleoperated surgical system of claim **1**, wherein the teleoperated surgical system is configured to have a range of motion around the yaw axis of at least 140° during surgery.

16. The teleoperated surgical system of claim **1**, wherein the teleoperated surgical system is configured to operate during surgery with the yaw axis at 10° with reference to a plane defined by the remote center of motion and a plane perpendicular to the instrument insertion axis.

17. The teleoperated surgical system of claim **1**, wherein the first link comprises a proximal end, a distal end, and a longitudinal axis defined between the proximal and distal ends of the first link, and wherein the proximal end of the first link is configured to couple with a non-teleoperated setup structure.

18. The teleoperated surgical system of claim **1**, wherein the third link is configured to removably couple with an instrument cannula aligned with the insertion axis.

19. The teleoperated surgical system of claim **1**, further comprising a setup structure having a proximal end and a distal end, wherein the distal end of the setup structure is directly coupled to the proximal end of the first link, and wherein the proximal end of the setup structure is directly coupled to a mechanical ground.

20. The teleoperated surgical system of claim **19**, wherein the mechanical ground comprises an operating room table.

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