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Witte et al.

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(45) Date of Patent: Aug. 19, 2025

(54) INSERTION COUPLED INSERTING SURGICAL INSTRUMENTS

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(72) Inventors: **Spencer Witte**, San Francisco, CA (US); **Benjamin Dickerson**, San Francisco, CA (US); **Aren Calder Hill**, Mountain View, CA (US); **Trent Michael Callan**, San Francisco, CA (US); **Dillon Carey**, Mountain View, CA (US)

(73) Assignee: **Cilag GmbH International**, Zug (CH)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 681 days.

(21) Appl. No.: **17/730,021**

(22) Filed: **Apr. 26, 2022**

(65) **Prior Publication Data**

US 2023/0338103 A1 Oct. 26, 2023

(51) **Int. Cl.**
A61B 34/00 (2016.01)
A61B 34/30 (2016.01)

(52) **U.S. Cl.**
CPC ***A61B 34/71*** (2016.02); ***A61B 34/30*** (2016.02); *A61B 2034/305* (2016.02)

(58) **Field of Classification Search**
None
See application file for complete search history.

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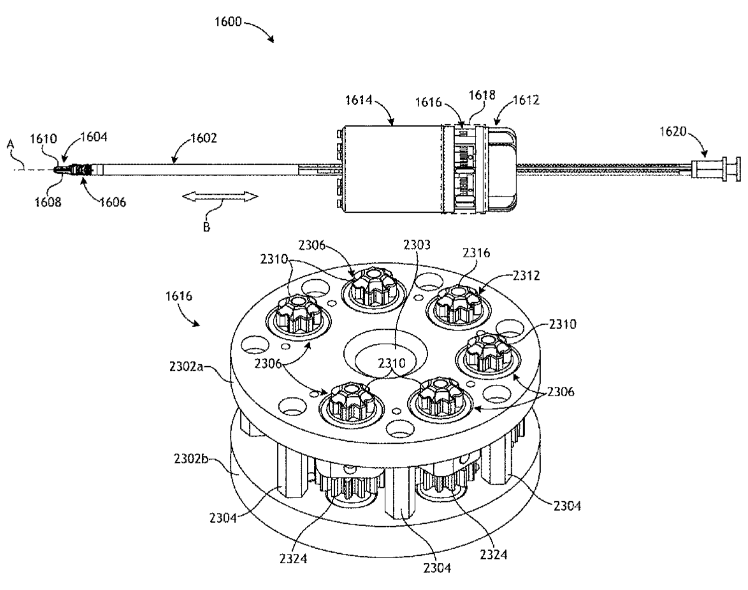
Assistant Examiner — James Moss
(74) *Attorney, Agent, or Firm* — Vorys, Sater, Seymour and Pease LLP

(57) **ABSTRACT**

A robotic surgical tool includes a handle providing drive inputs and a shaft drive input, an instrument driver providing drive outputs and a shaft drive output, an elongate shaft extendable through the handle and the instrument driver, an end effector and a wrist arranged at a distal end of the shaft, a decoupler interposing the handle and the instrument driver, an insertion assembly mounted to the decoupler housing, and a differential gear train extending between the insertion assembly and each differential assembly included in the decoupler such that actuation of the insertion assembly correspondingly actuates each differential assembly as the shaft moves.

20 Claims, 37 Drawing Sheets



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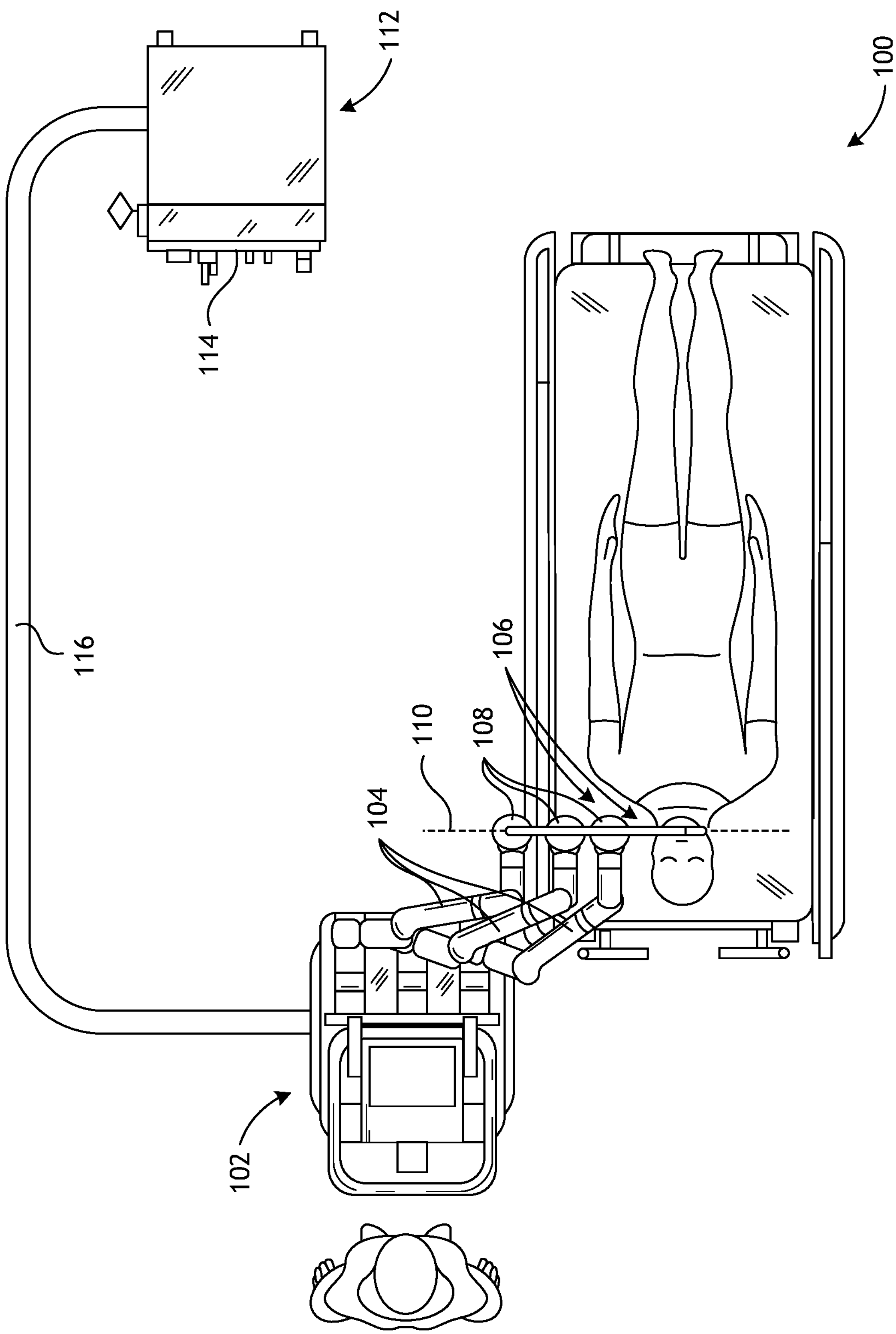


FIG. 1

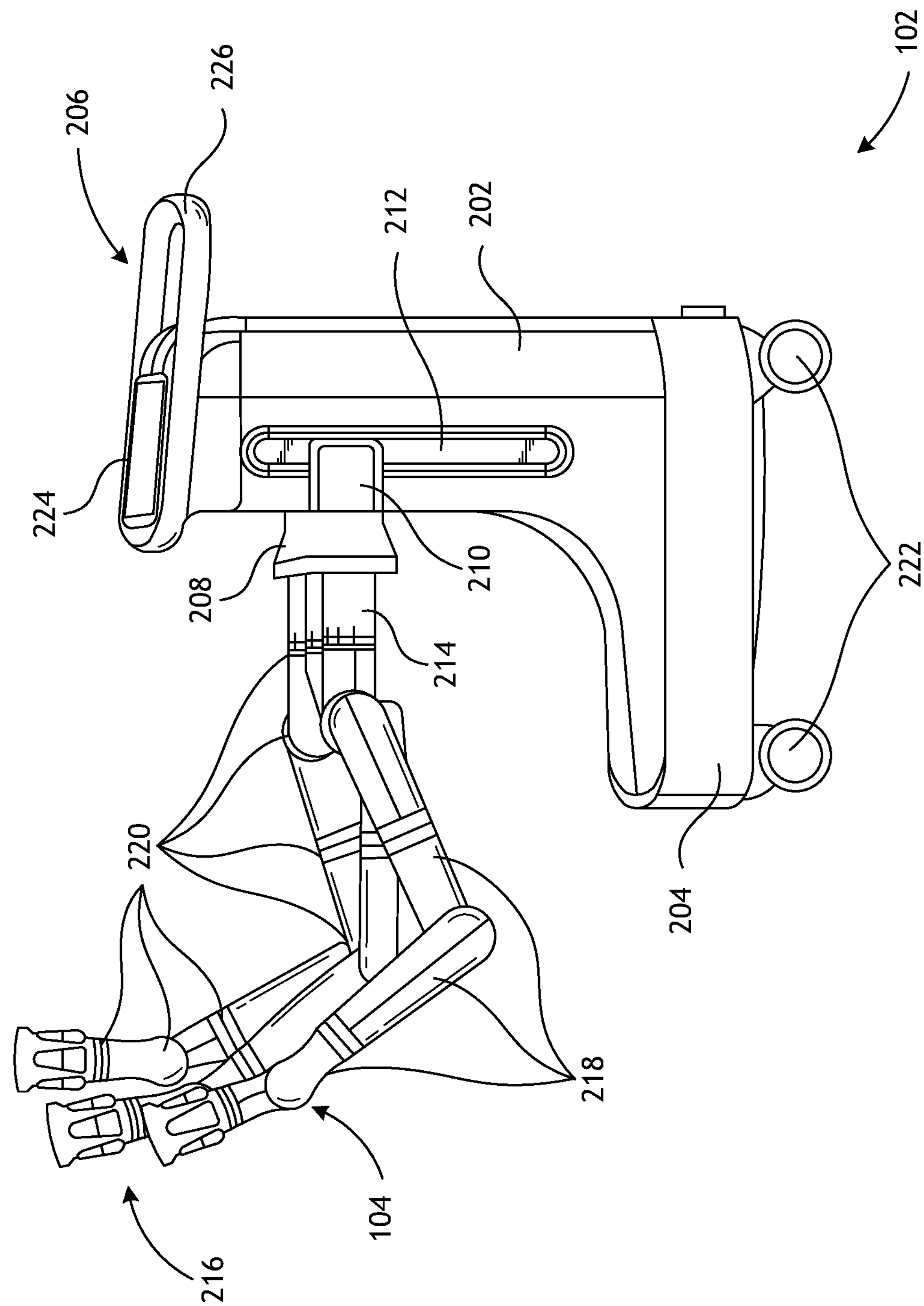


FIG. 2

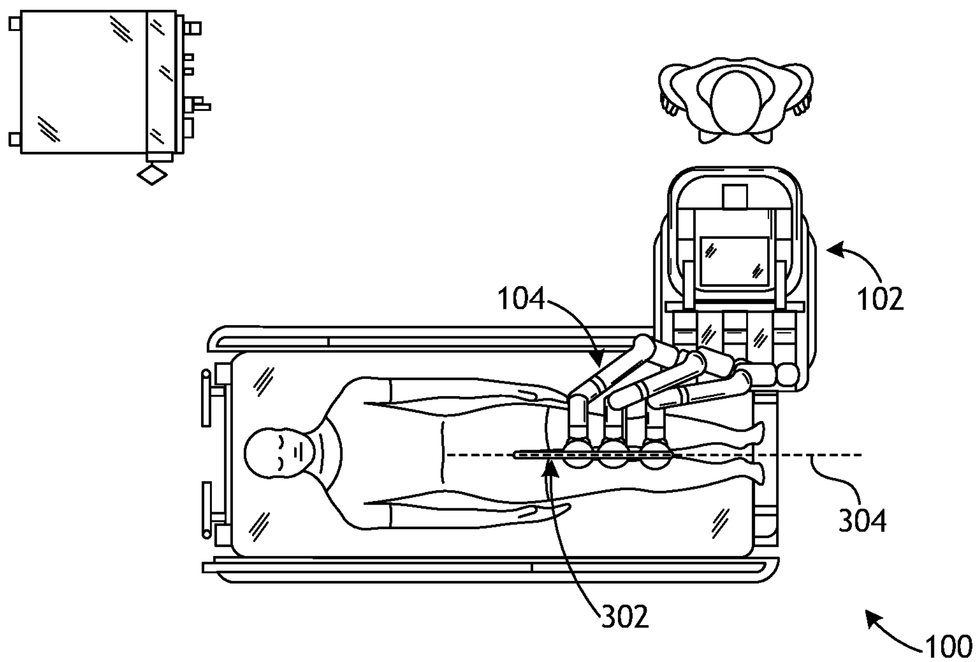


FIG. 3A

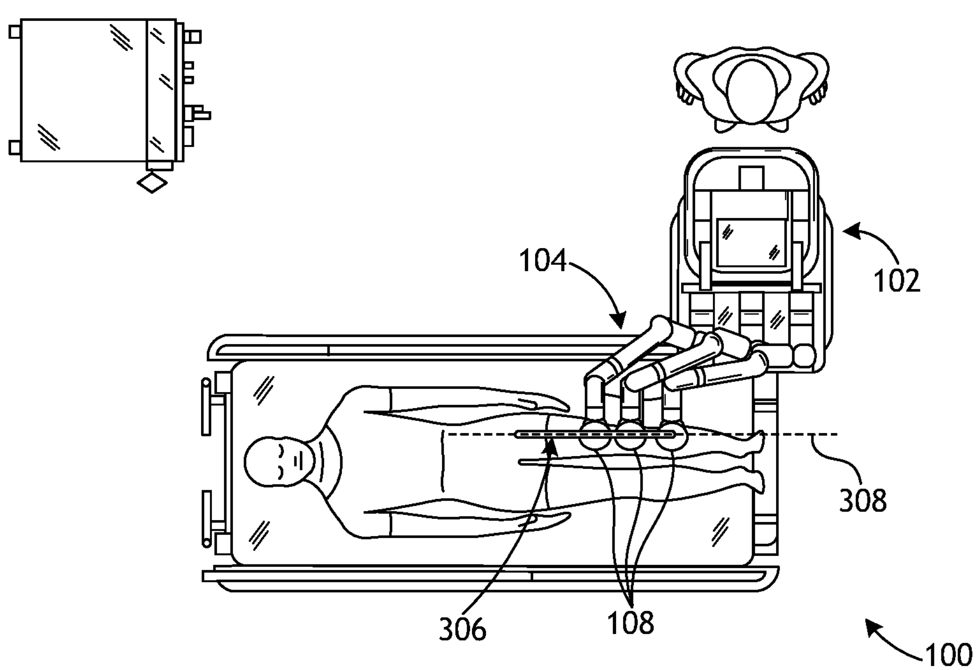


FIG. 3B

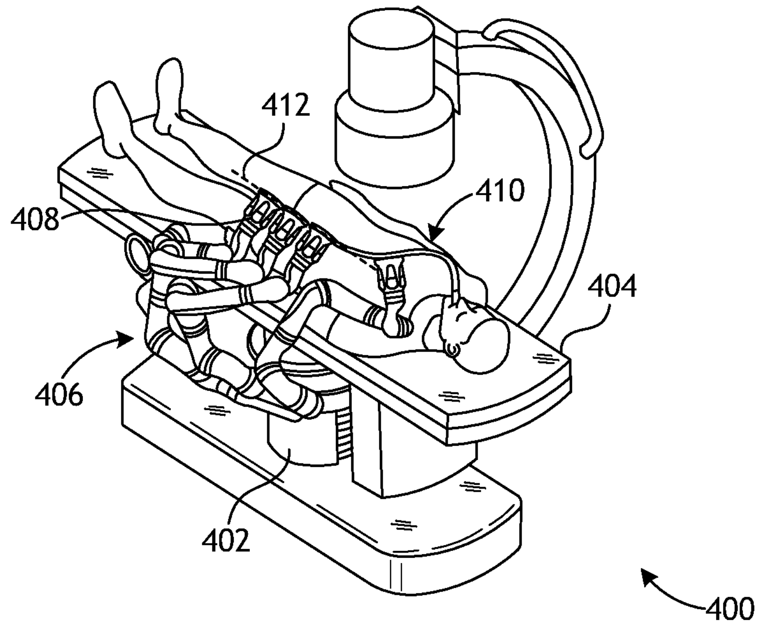


FIG. 4

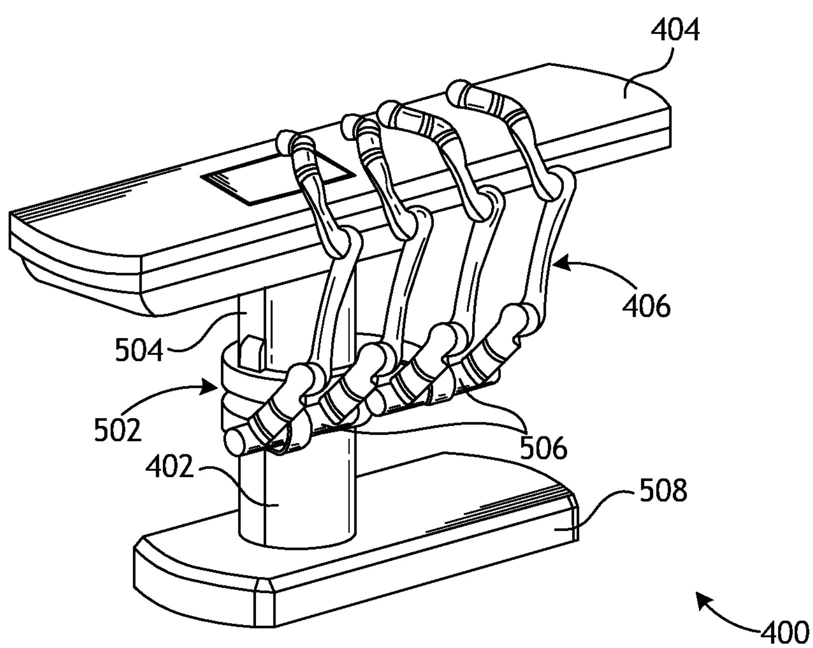
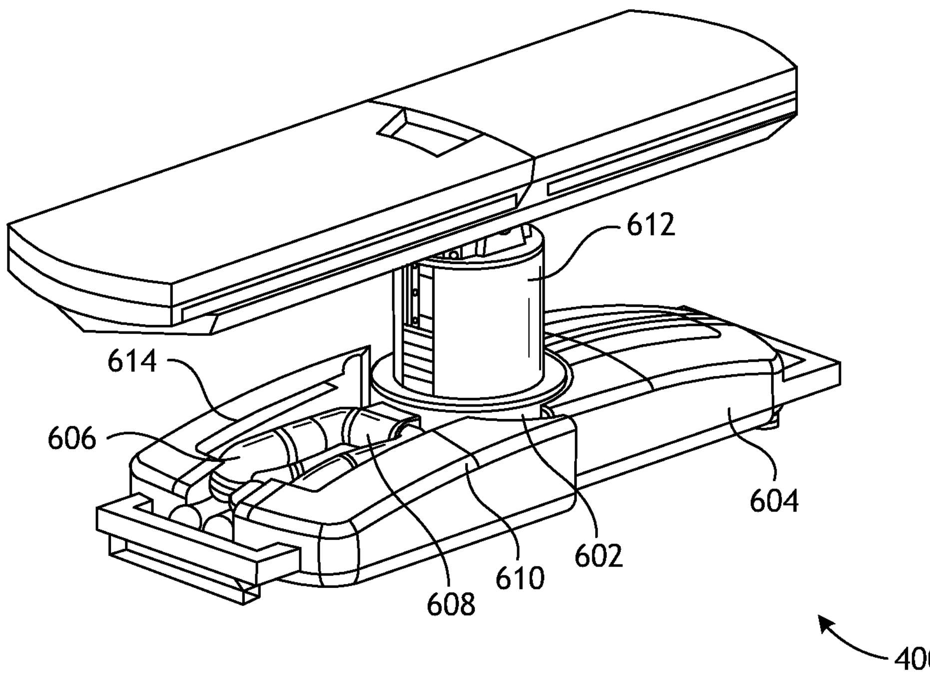


FIG. 5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602
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FIG. 6

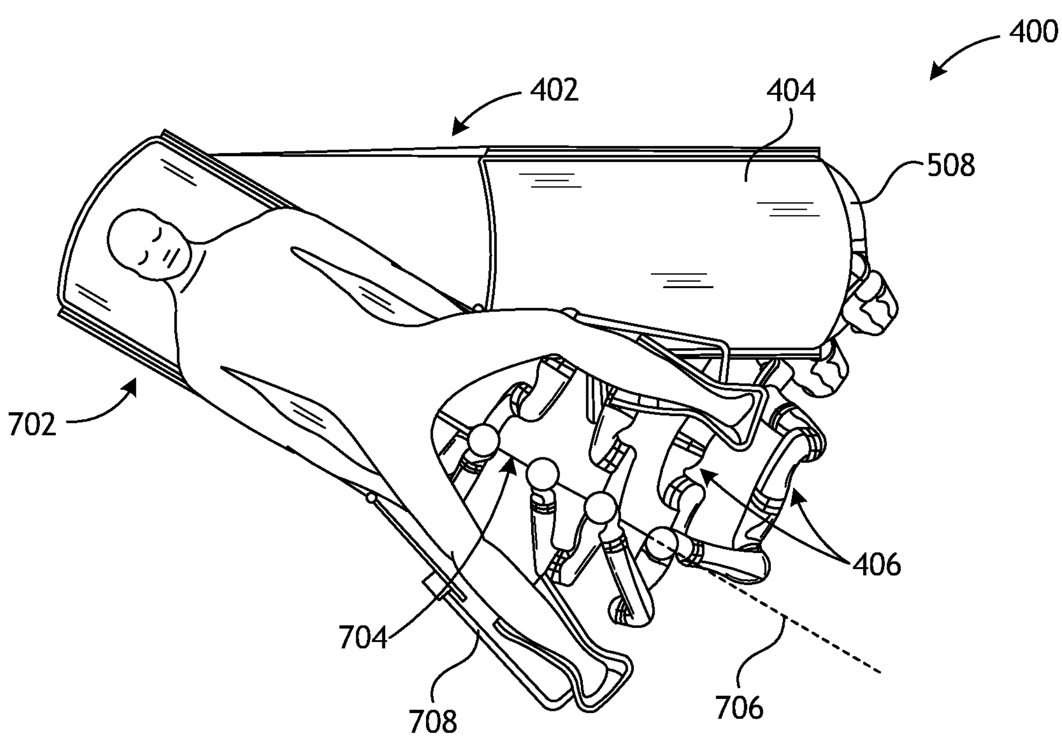
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FIG. 7A

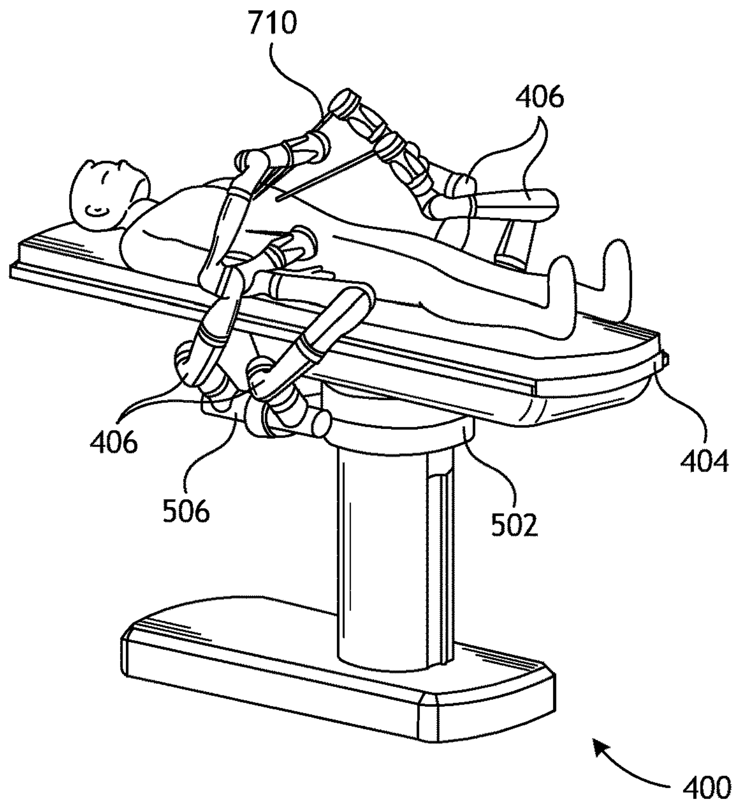


FIG. 7B

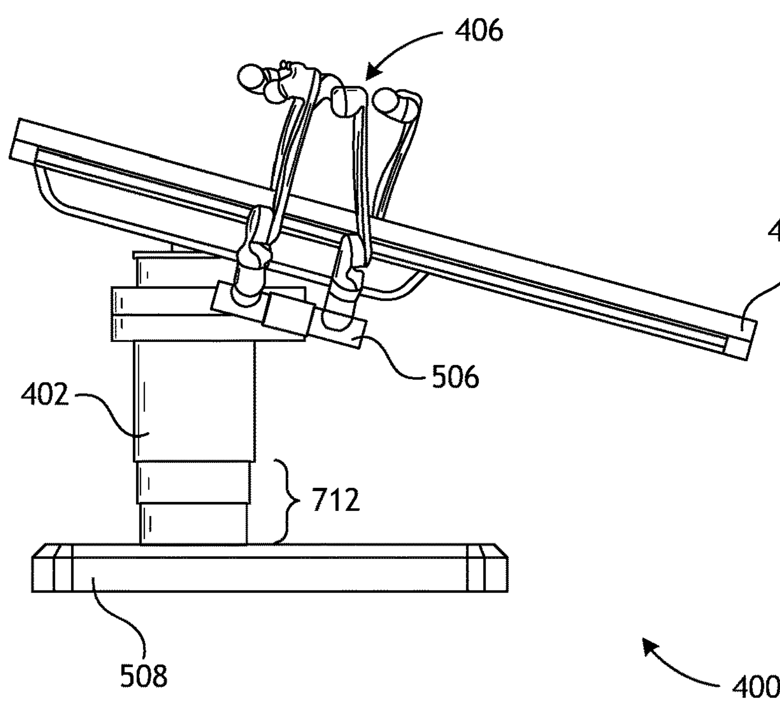


FIG. 7C

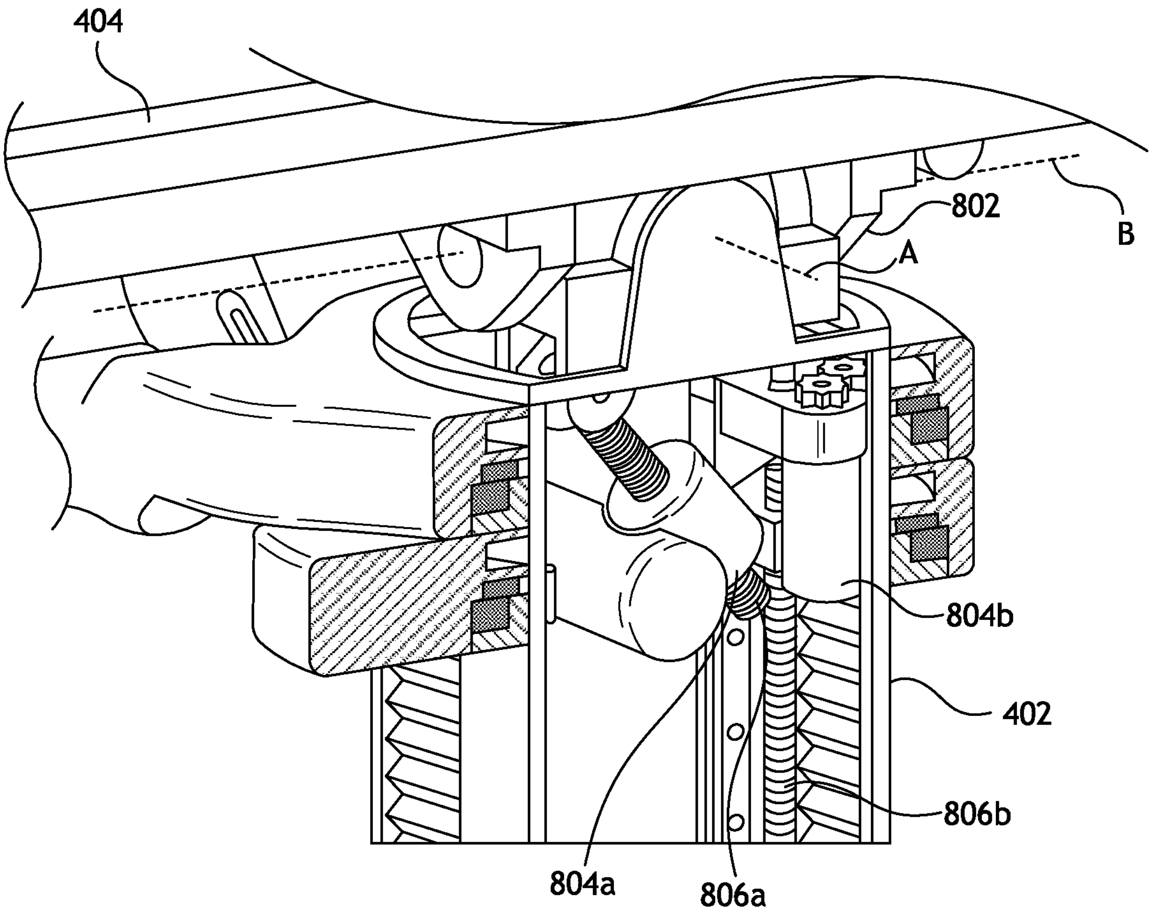
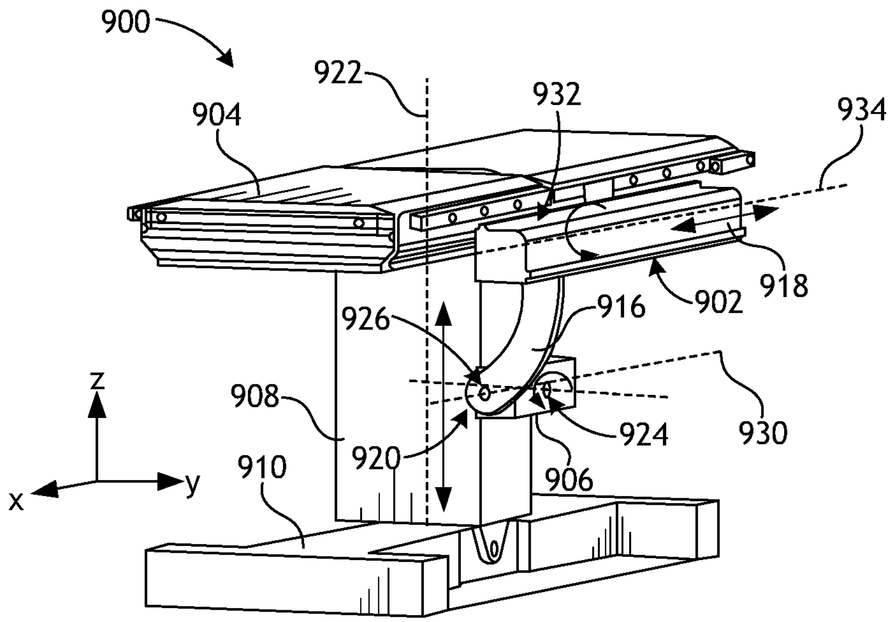


FIG. 8



900
922
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902
916
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z
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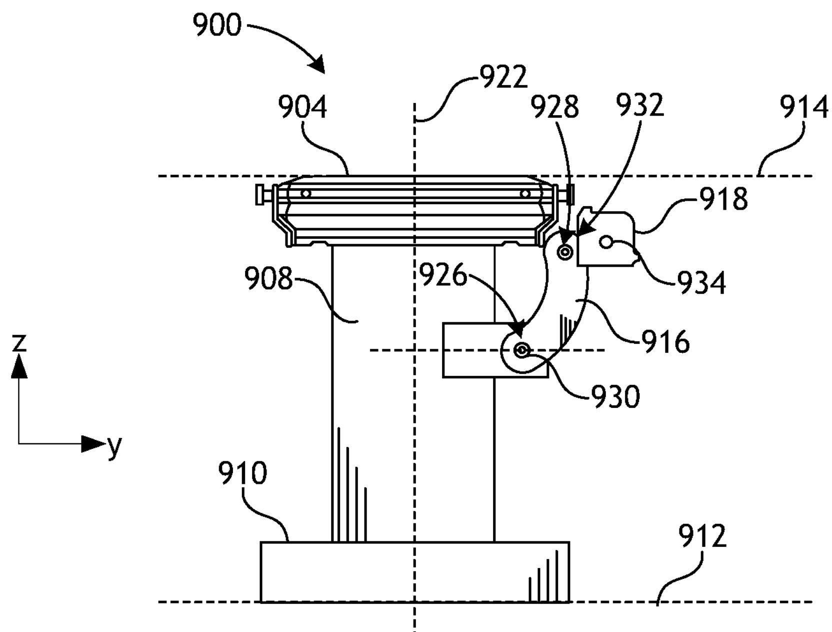
920
924
930
x
y
910
906

FIG. 9A



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934
908
926
916
z
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y
910
912

FIG. 9B

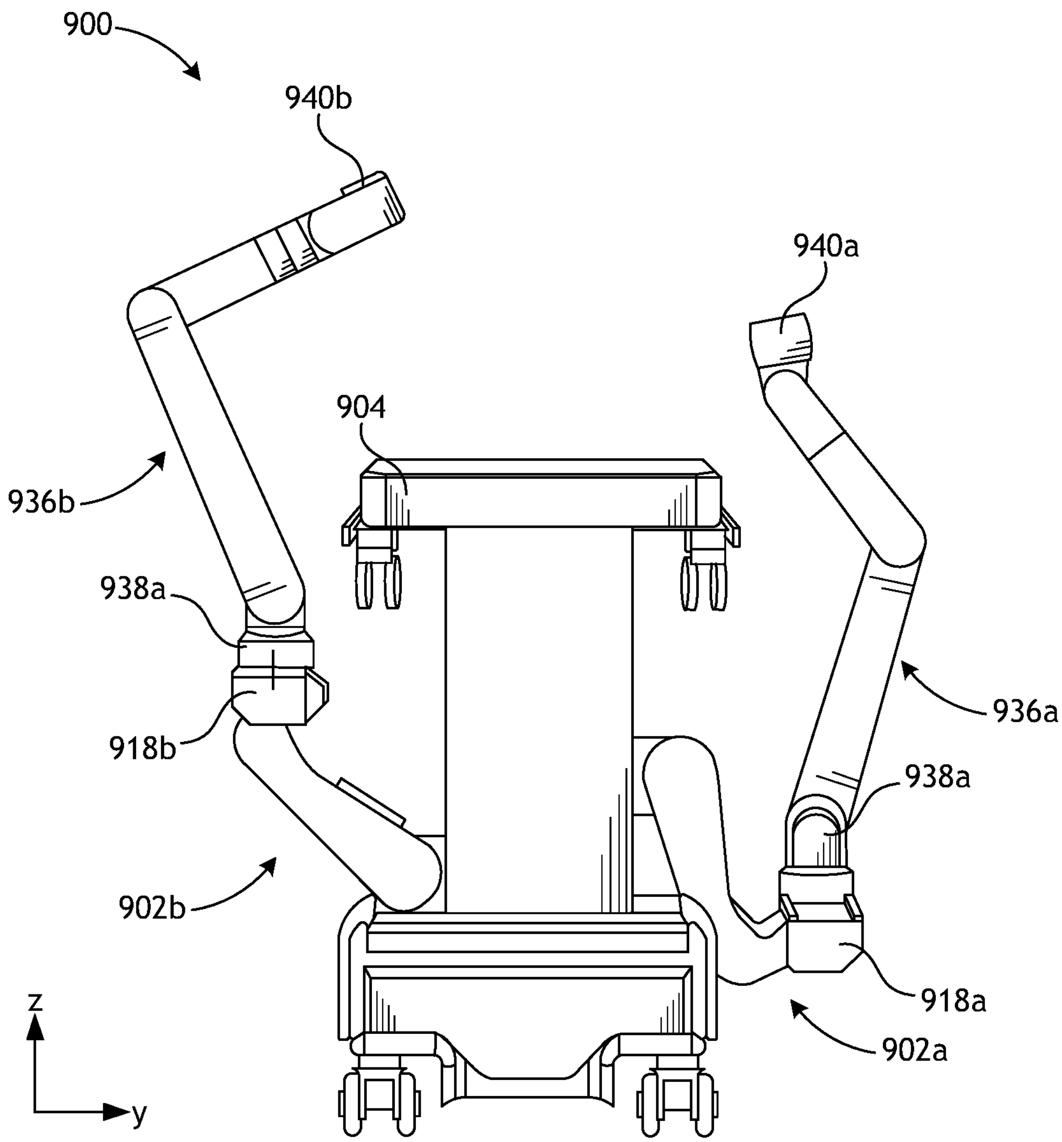

FIG. 9C

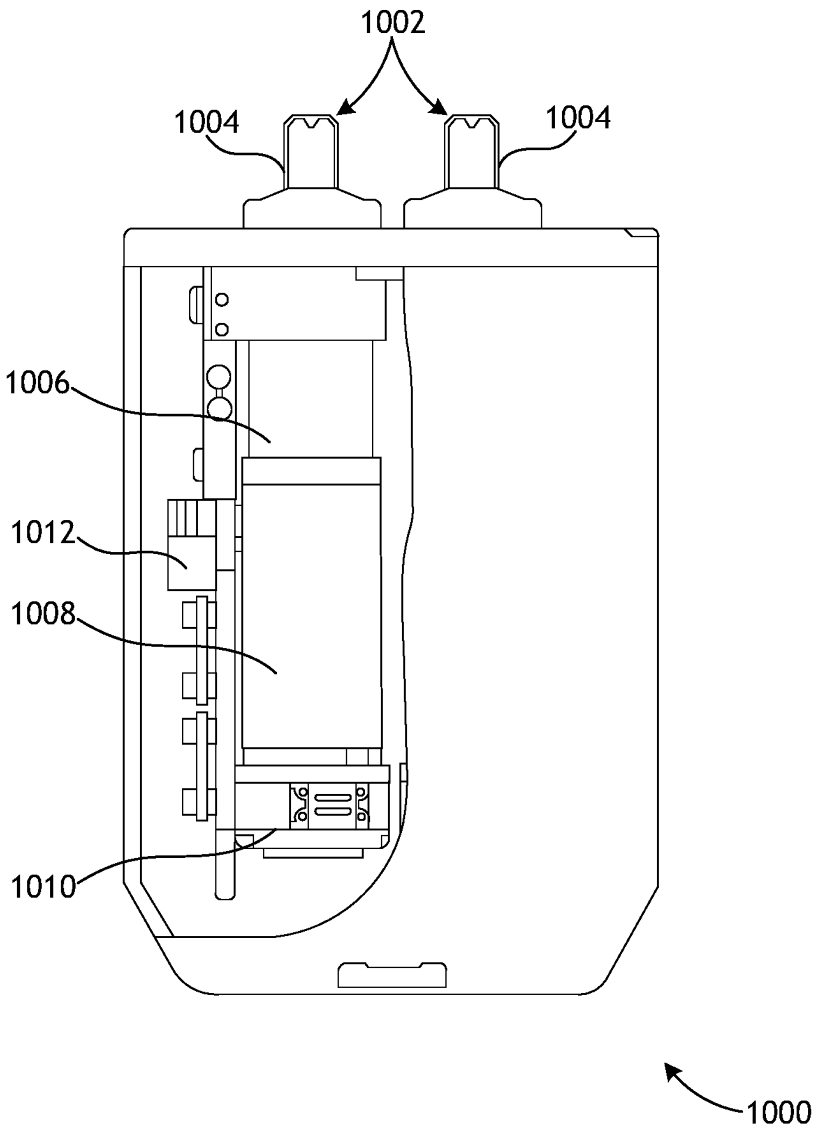

FIG. 10

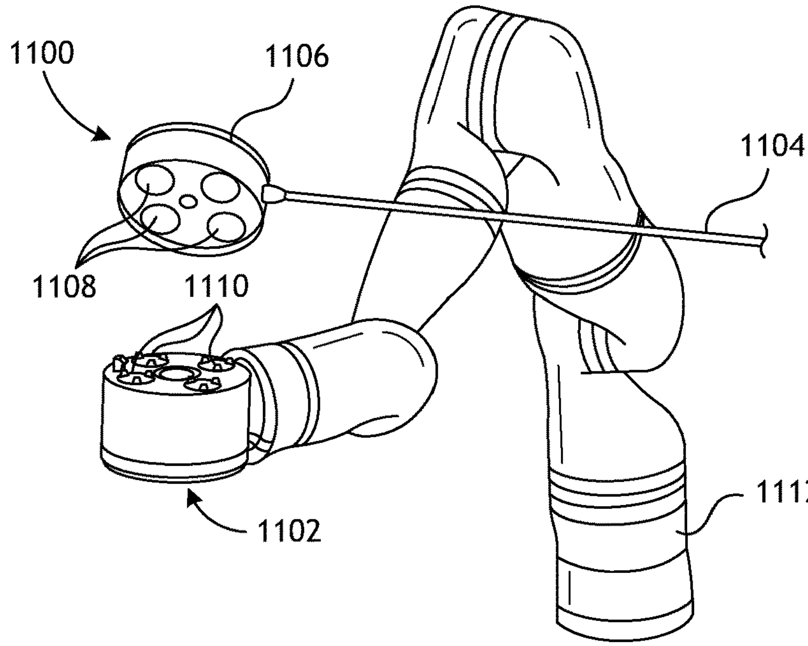
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FIG. 11

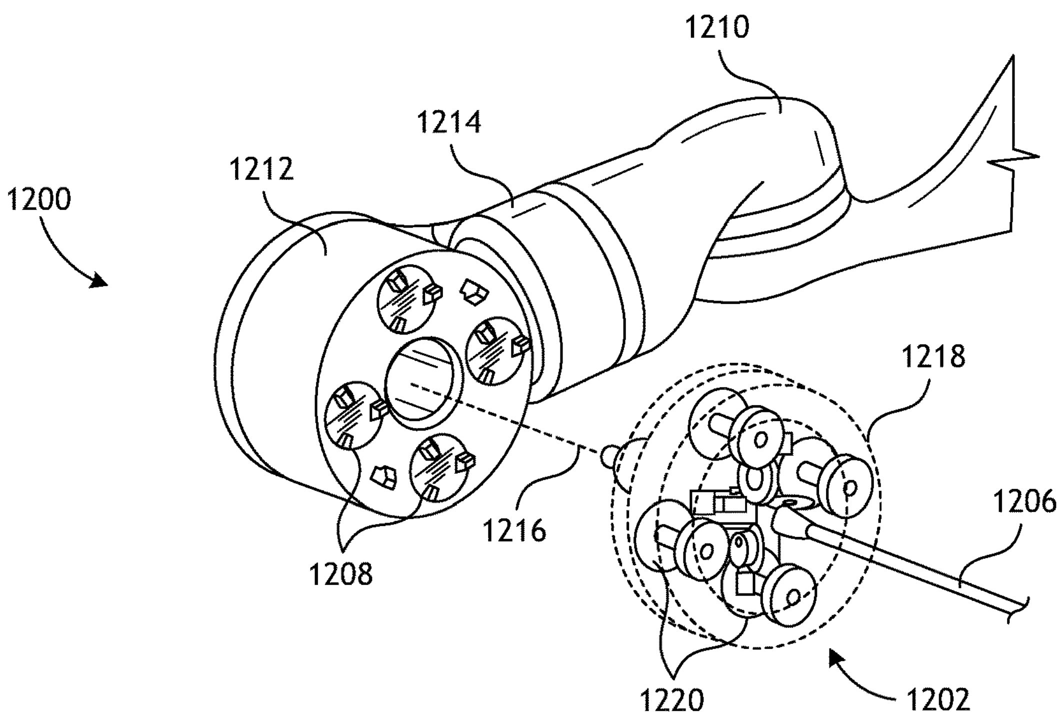
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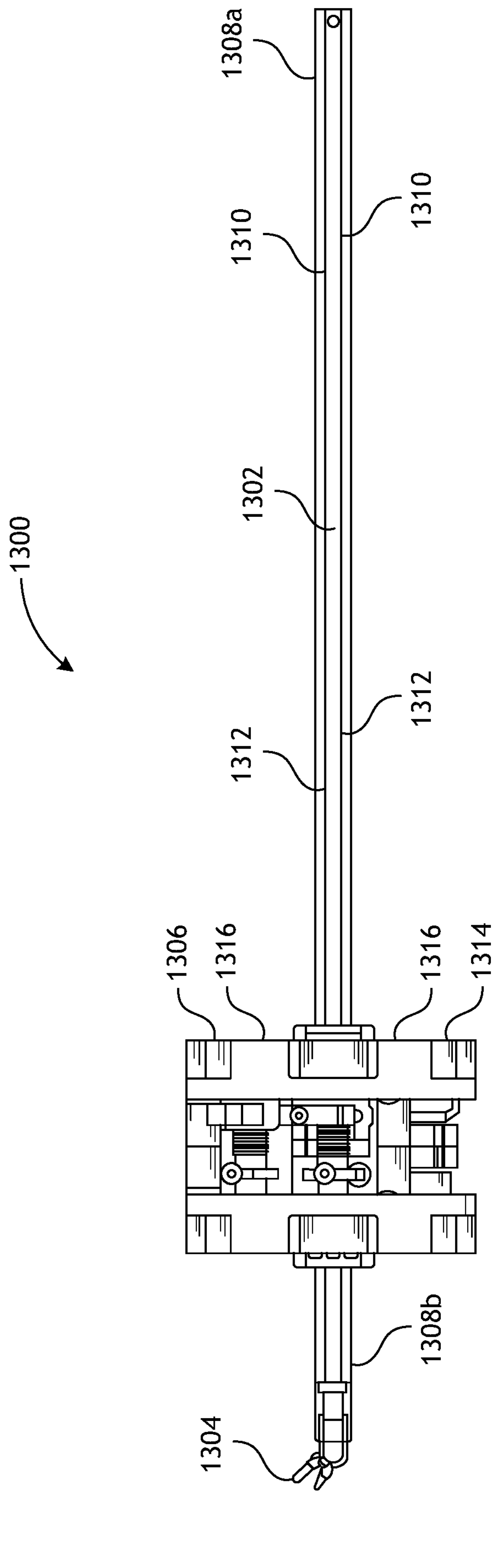
FIG. 12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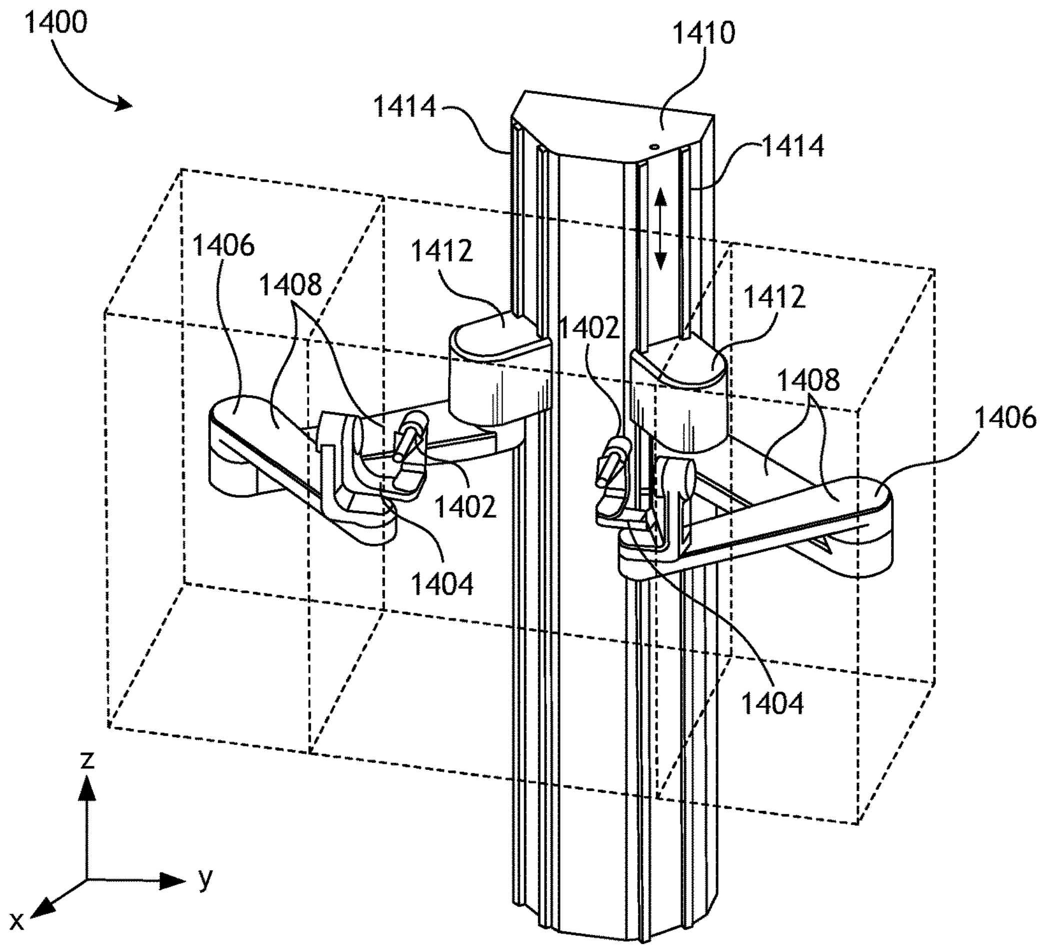
1308b
1304

FIG. 13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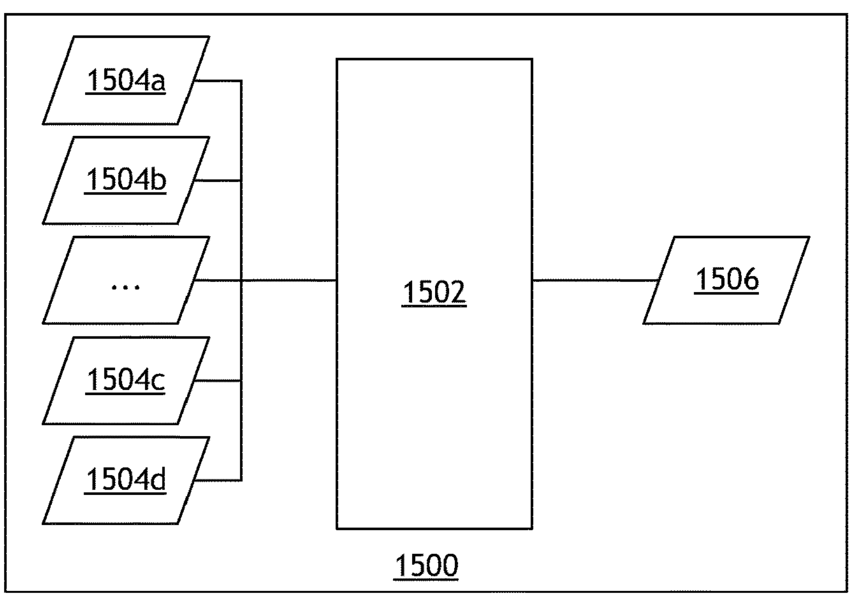
1408
1406
1402
1404
1404
z
y
x

FIG. 14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1506
1500

FIG. 15

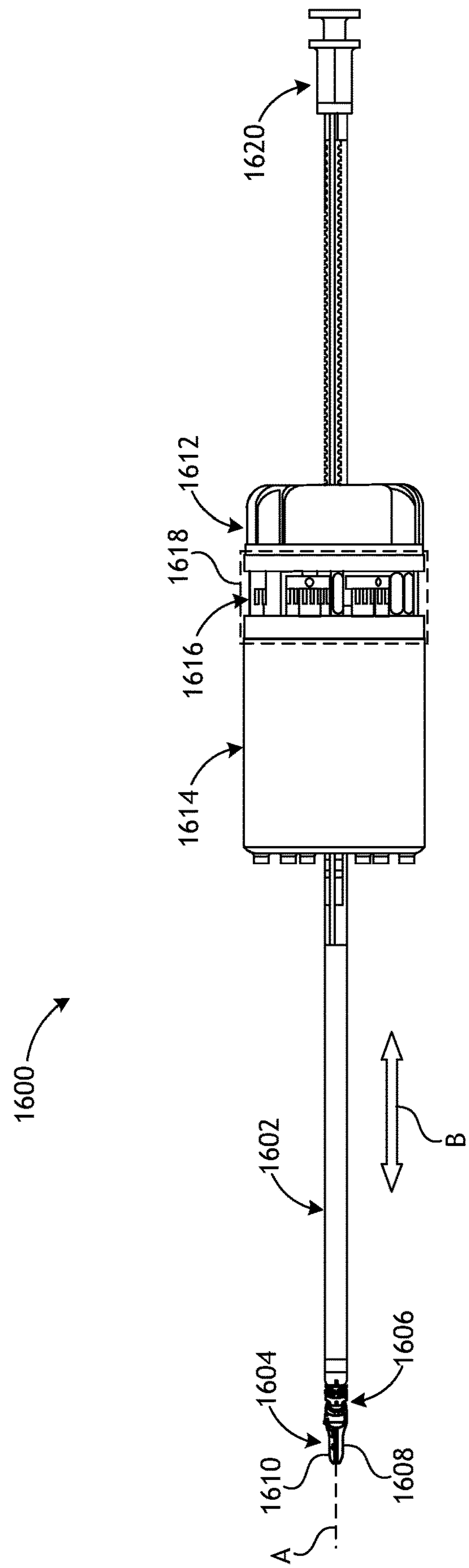


FIG. 16

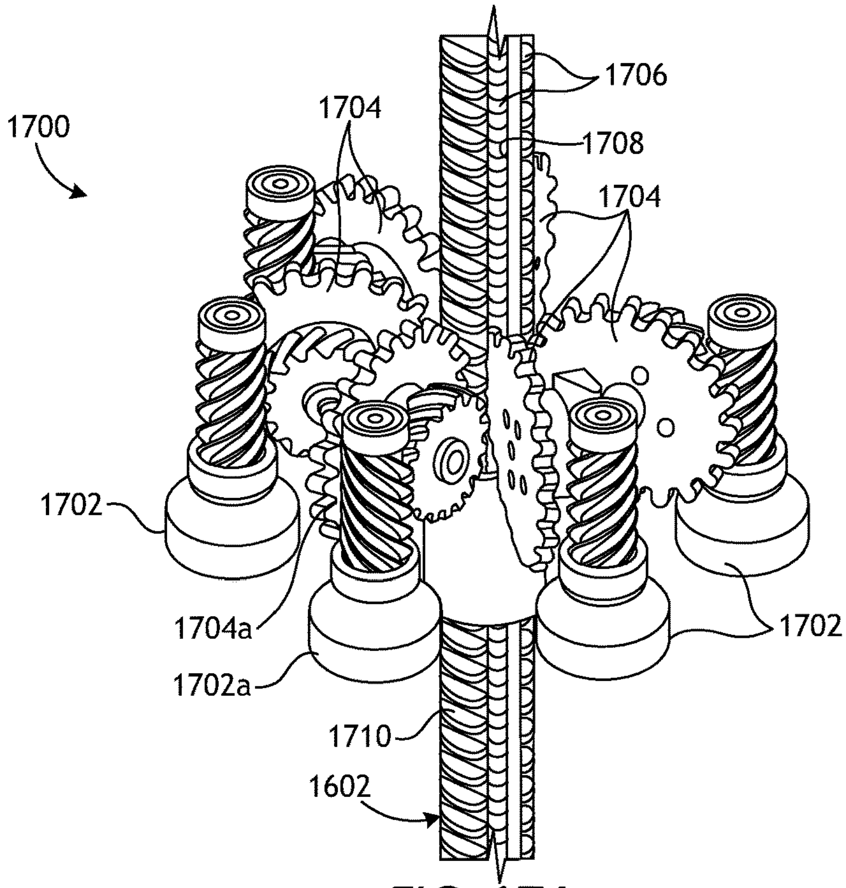


FIG. 17A

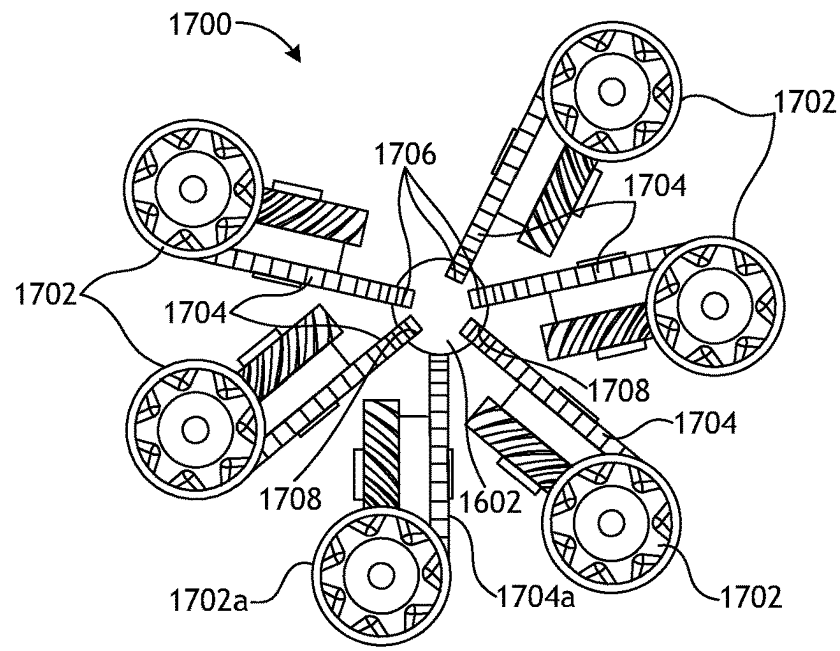


FIG. 17B

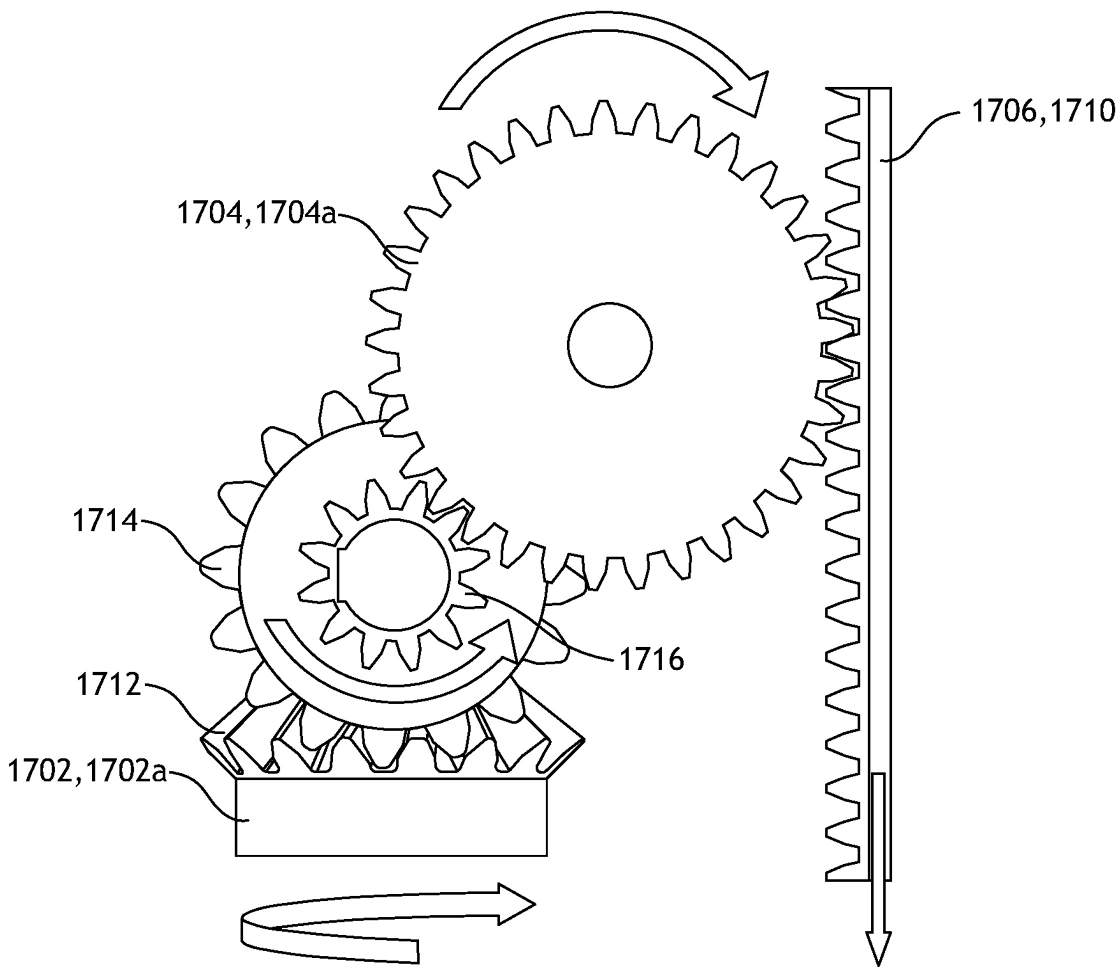


FIG. 17C

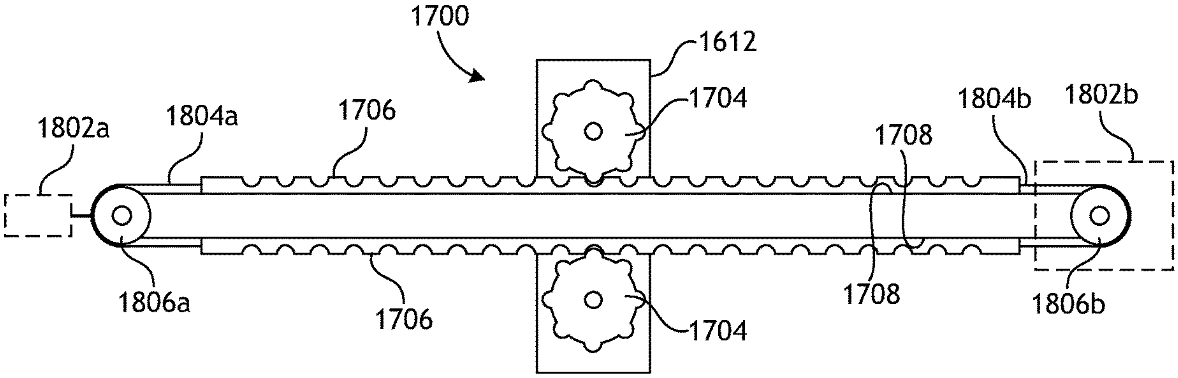


FIG. 18A

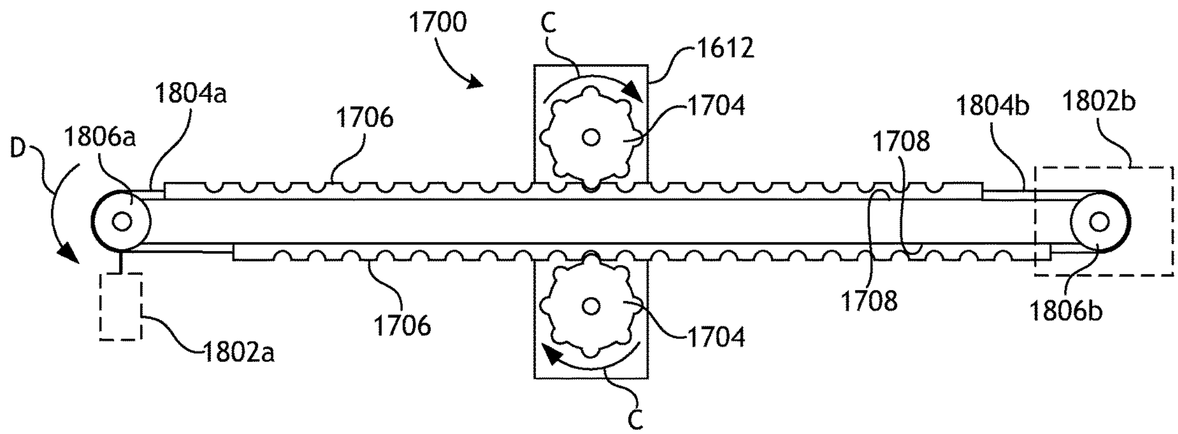


FIG. 18B

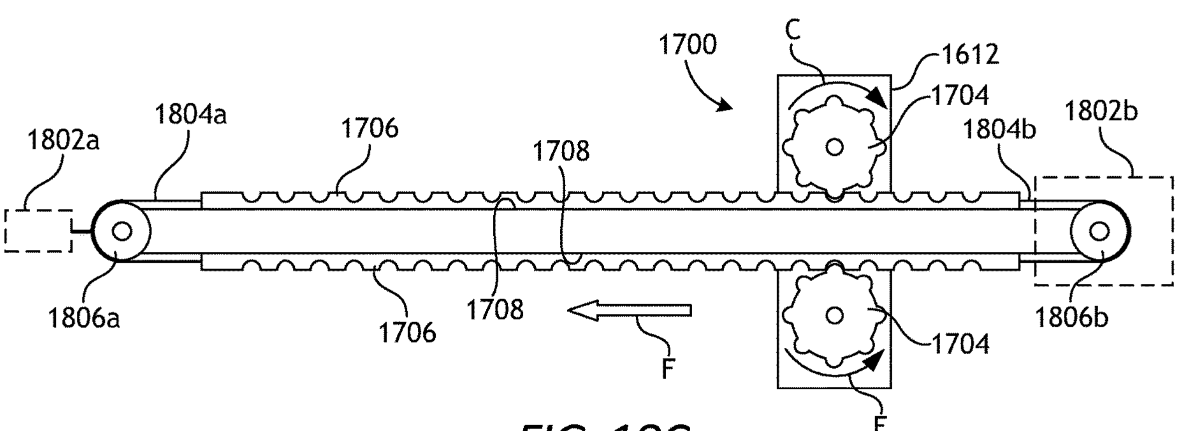


FIG. 18C

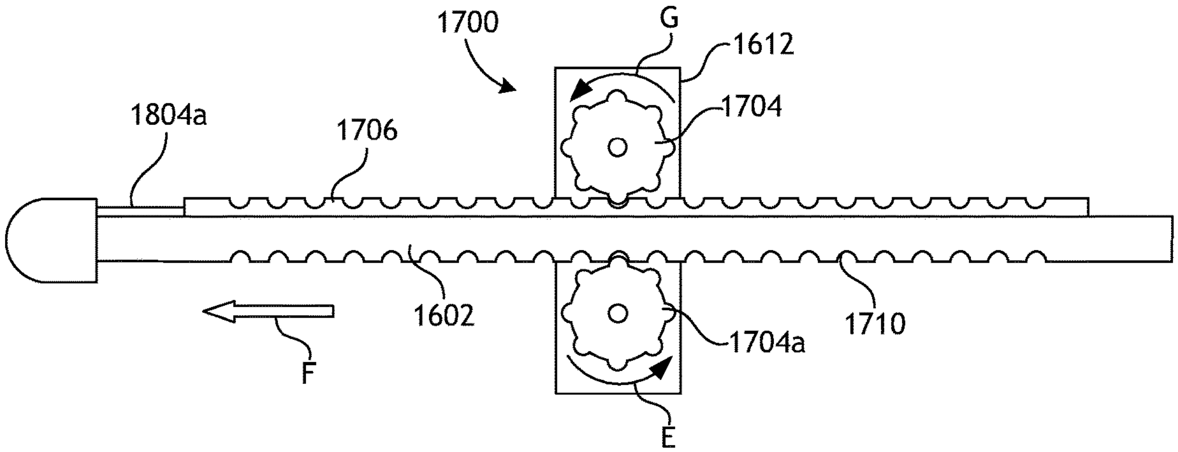


FIG. 18D

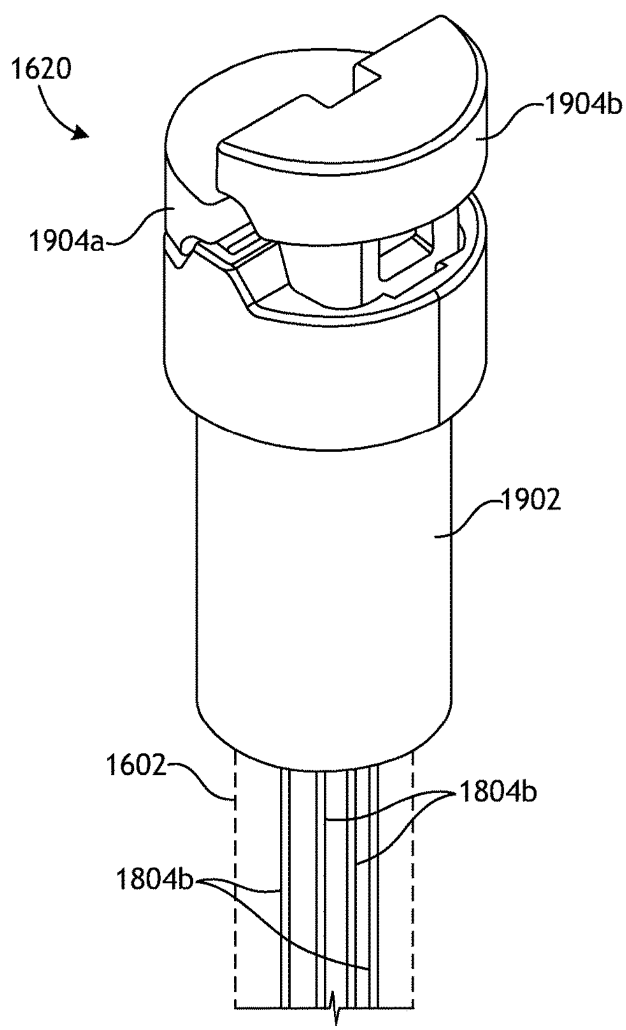


FIG. 19

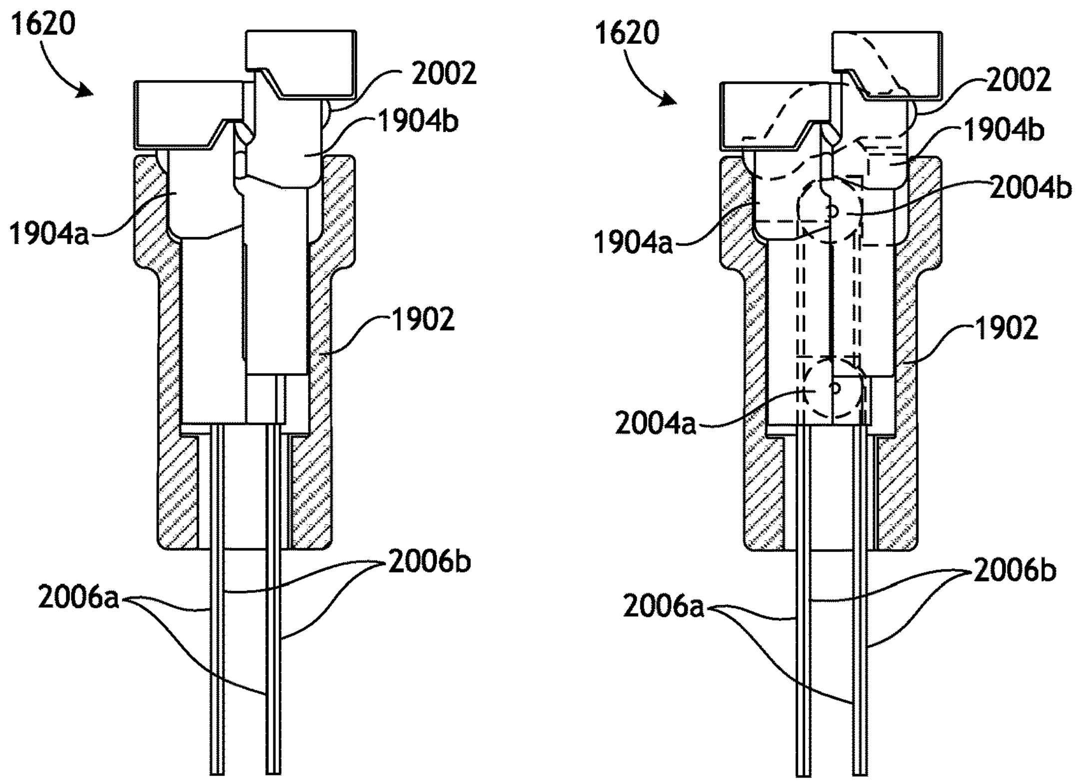


FIG. 20A

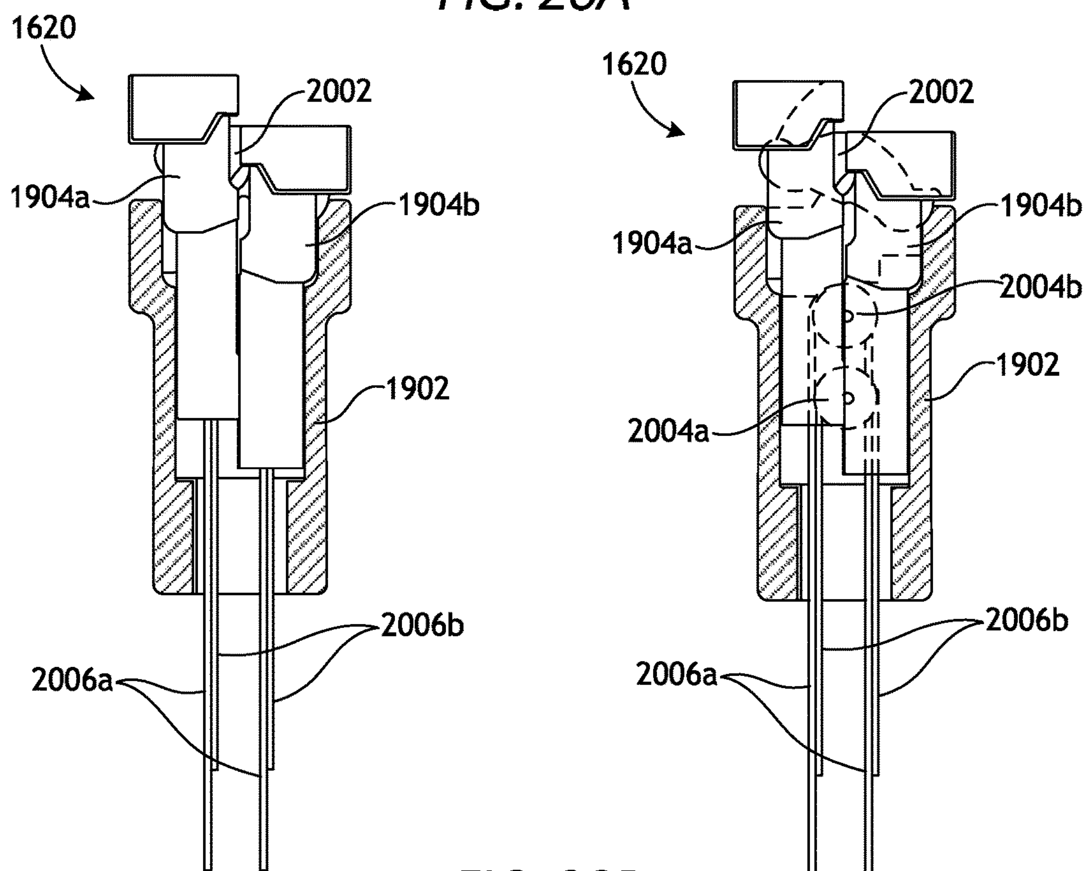
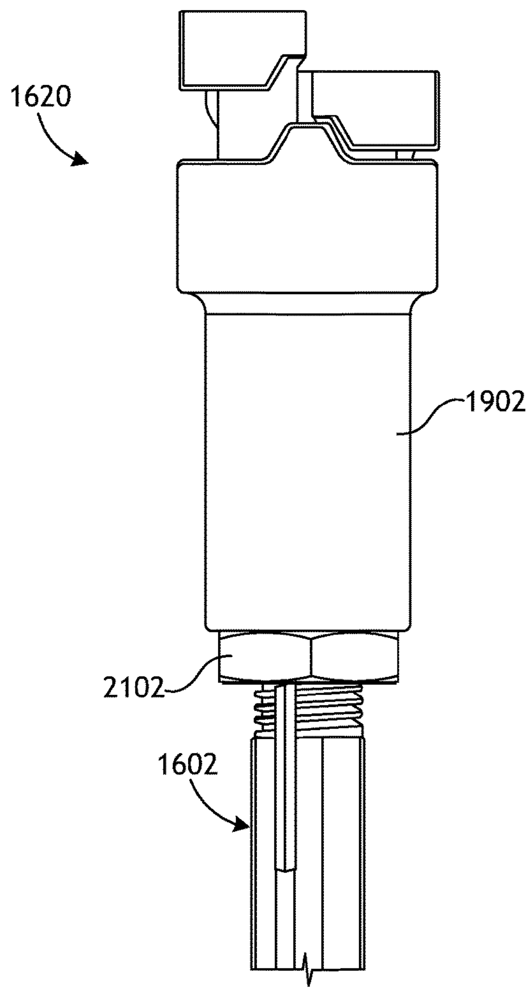


FIG. 20B


1620
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2102
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FIG. 21

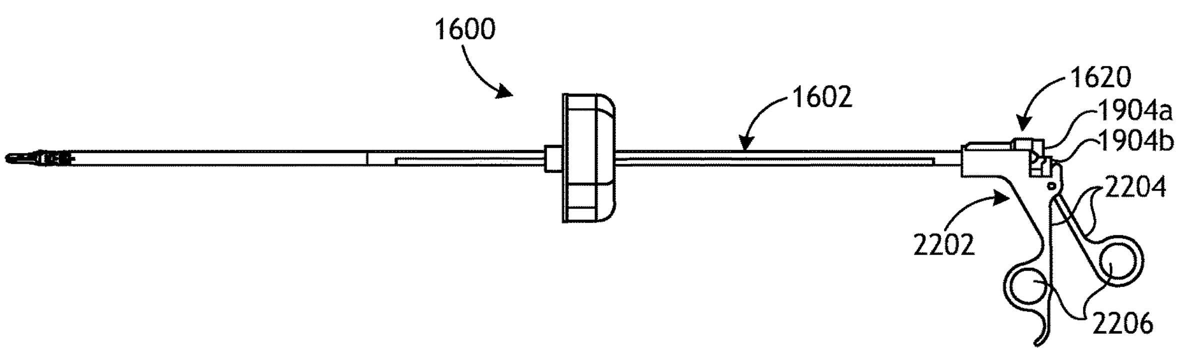
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FIG. 22

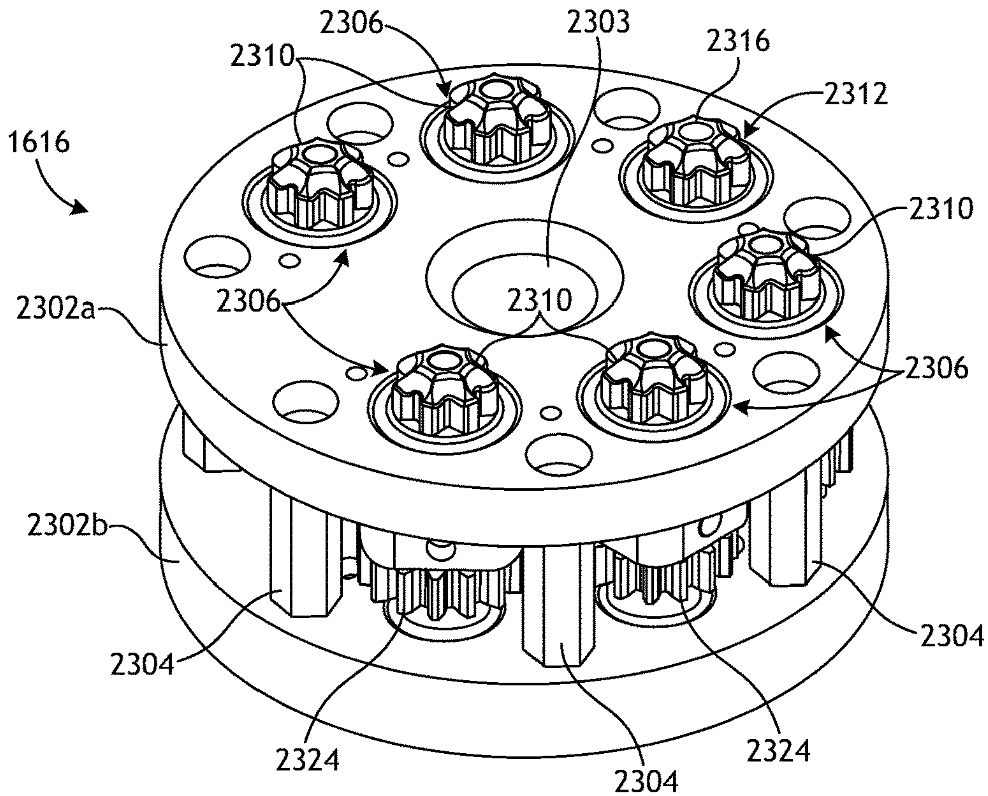

FIG. 23A

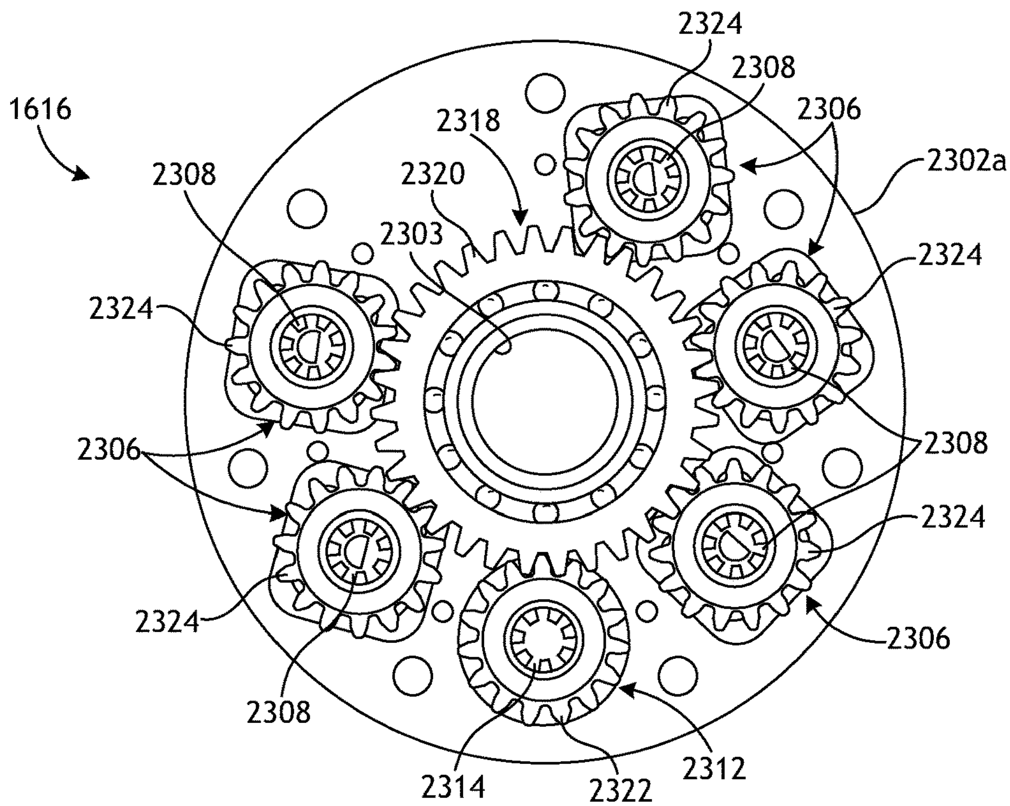

FIG. 23B

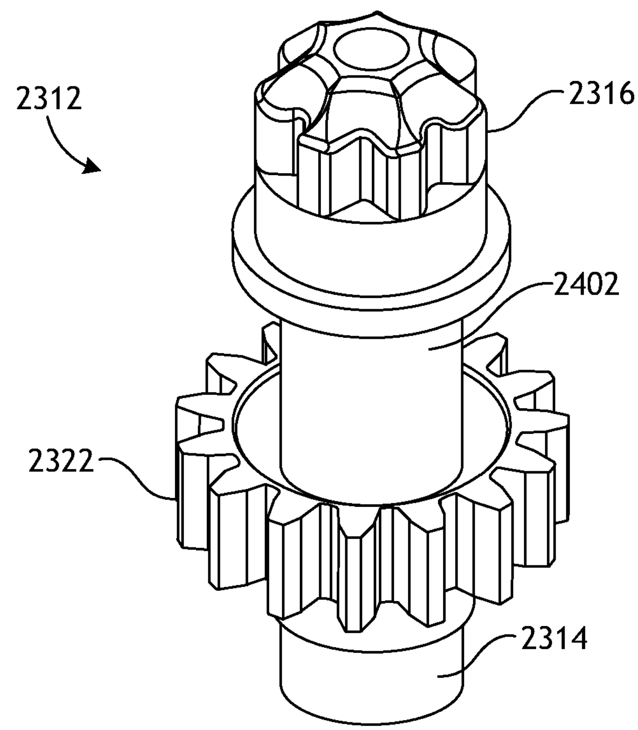

FIG. 24

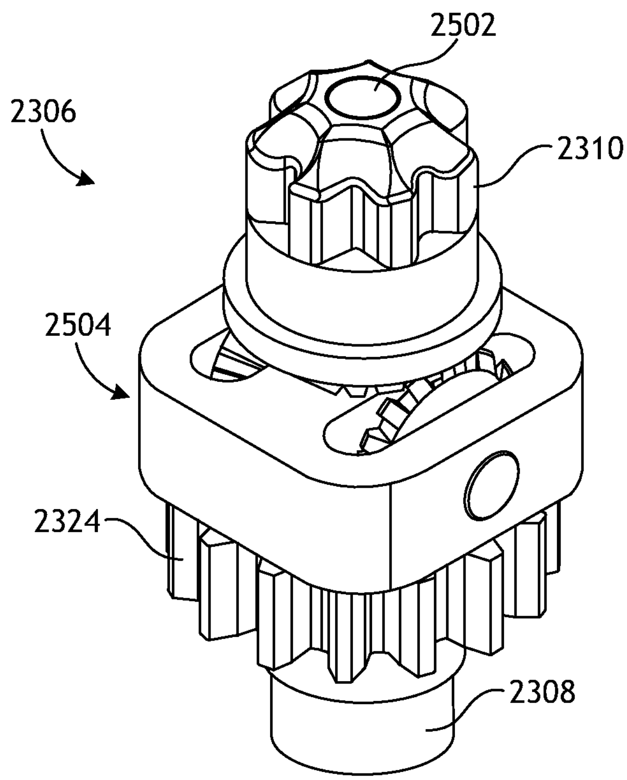

FIG. 25

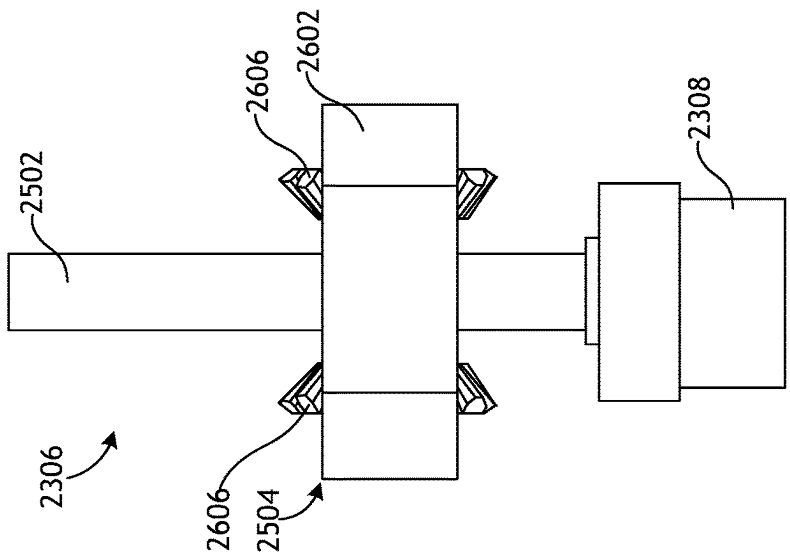

FIG. 26C

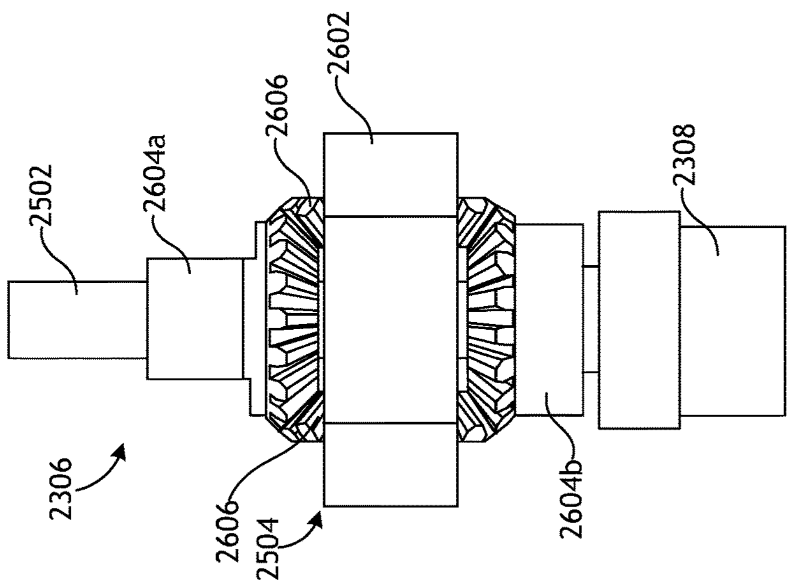

FIG. 26B

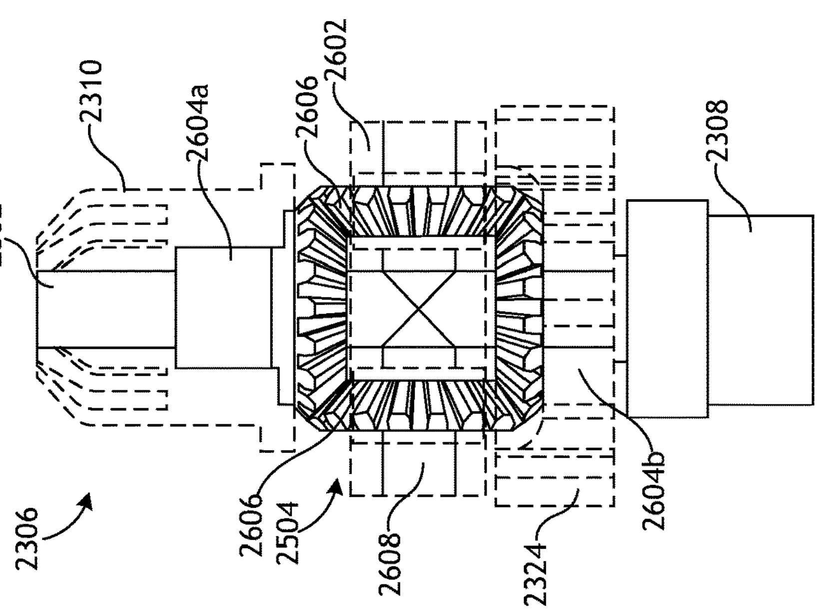

FIG. 26A

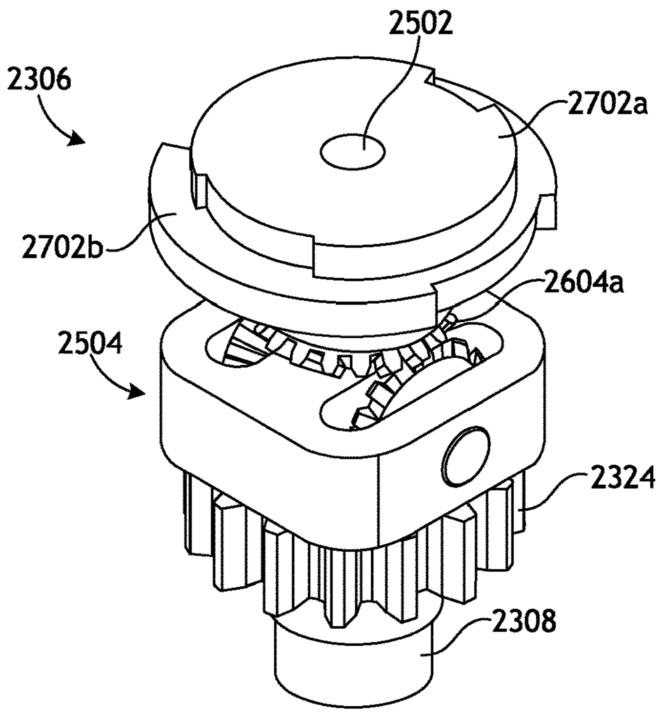

FIG. 27A

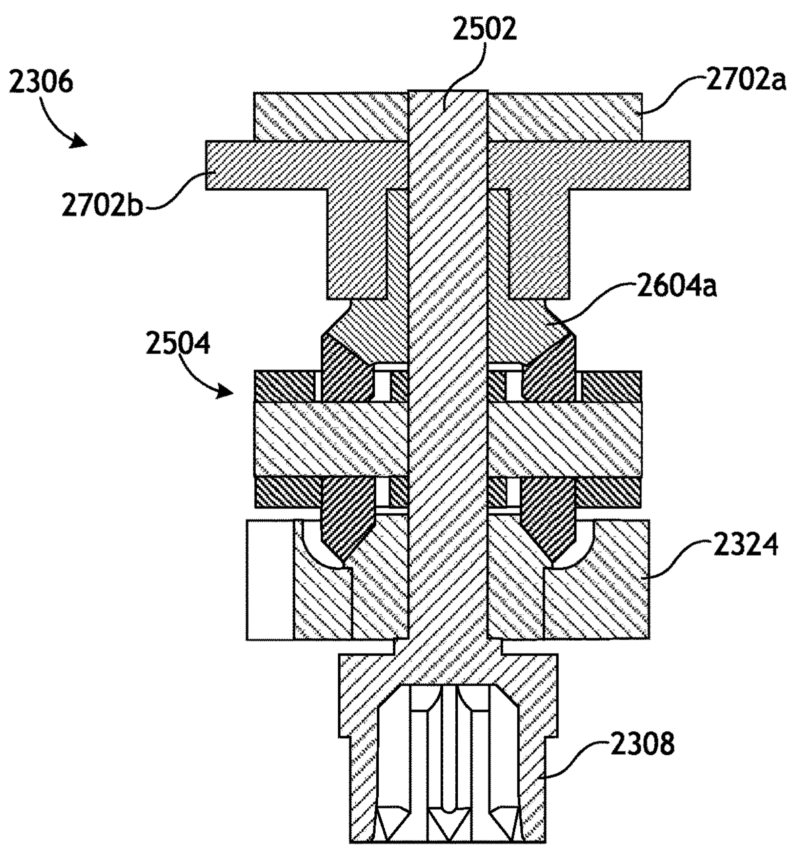

FIG. 27B

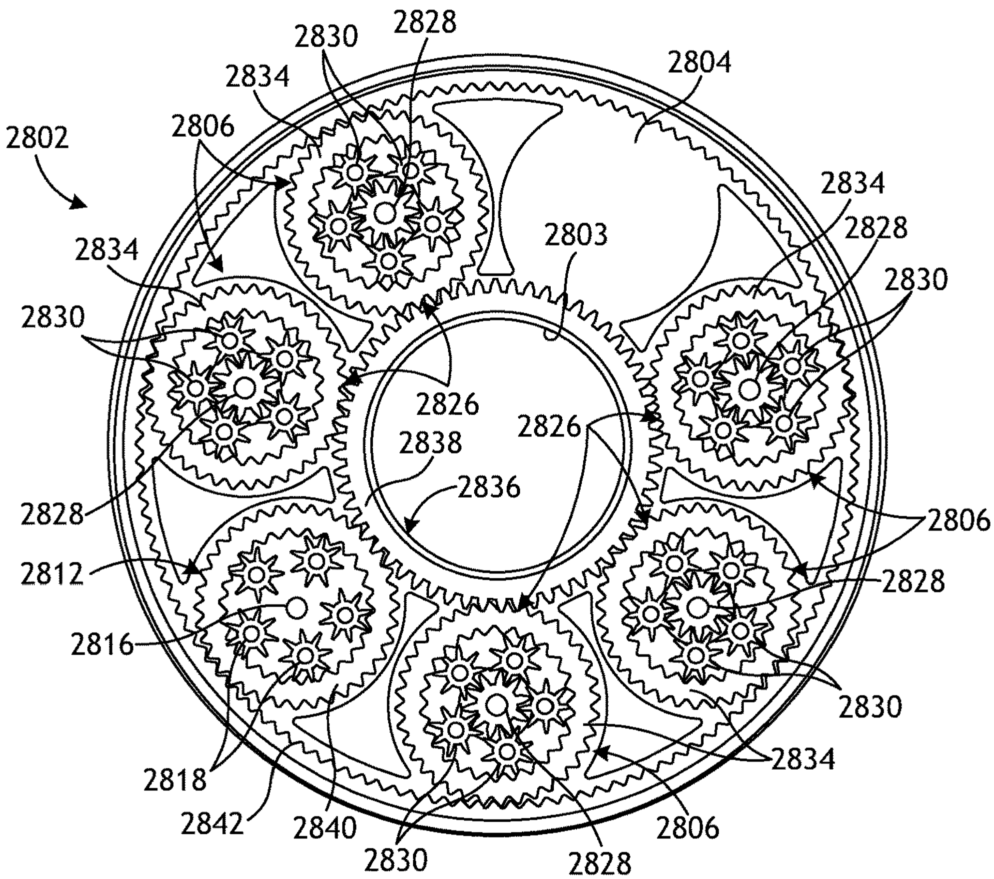
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FIG. 28

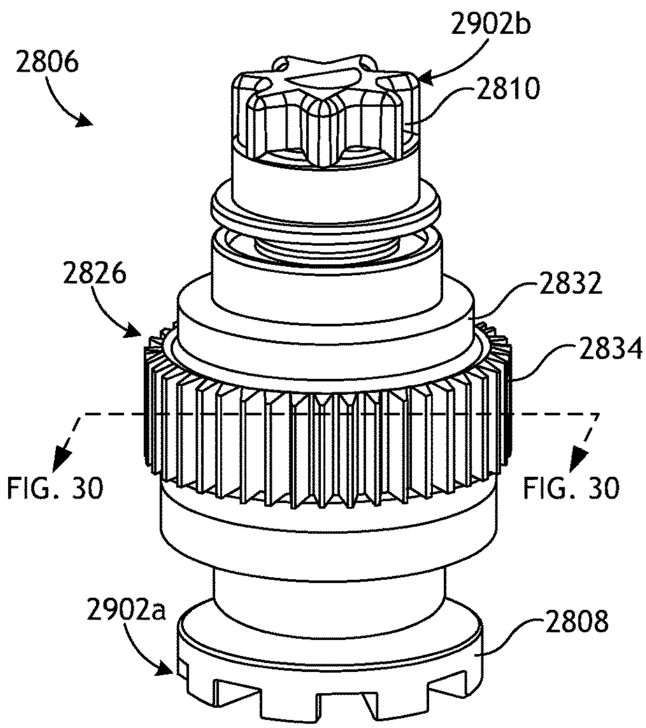
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FIG. 30
FIG. 30
2902a
2808

FIG. 29

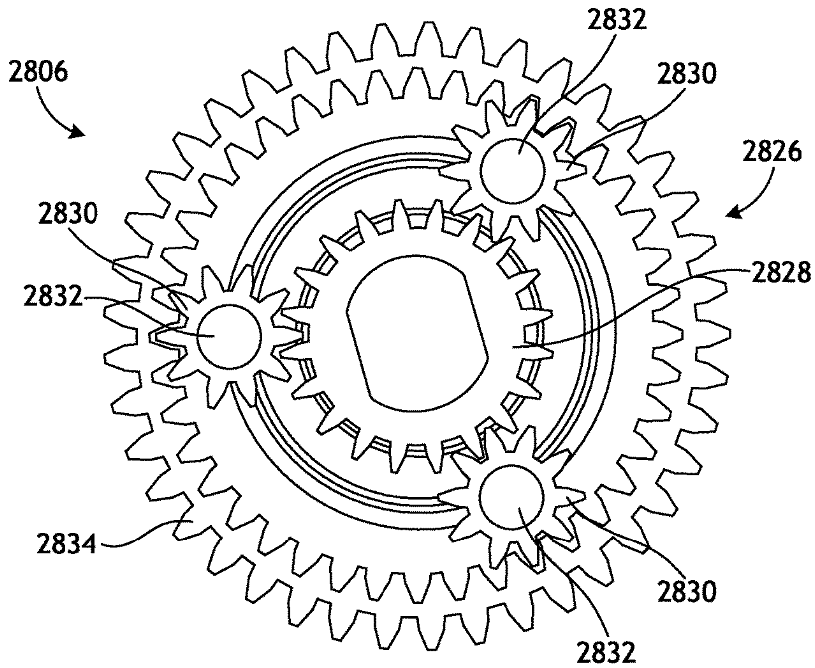


FIG. 30

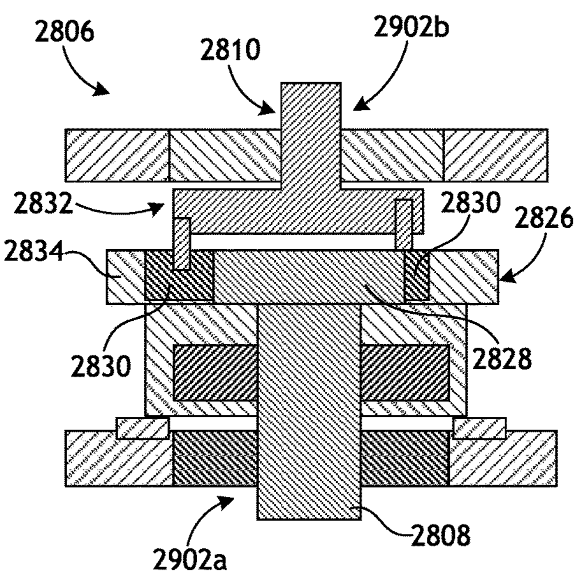


FIG. 31

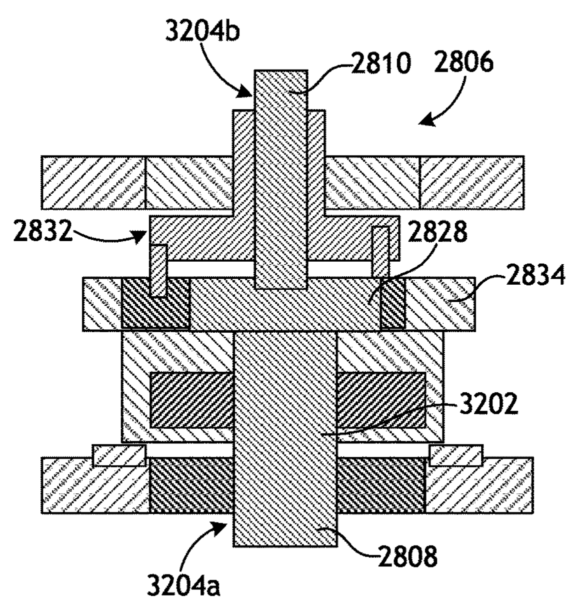
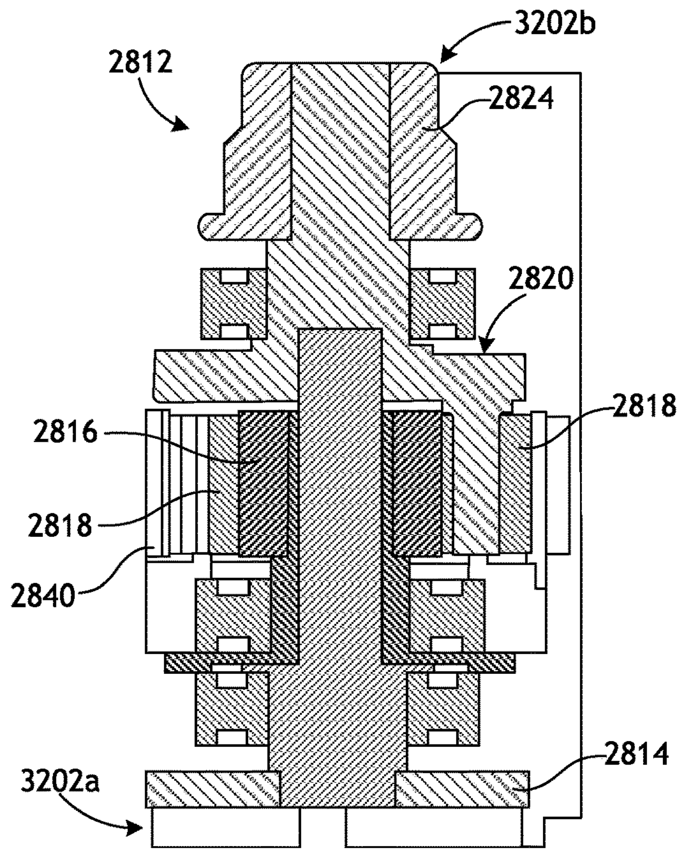


FIG. 32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3202a

FIG. 33

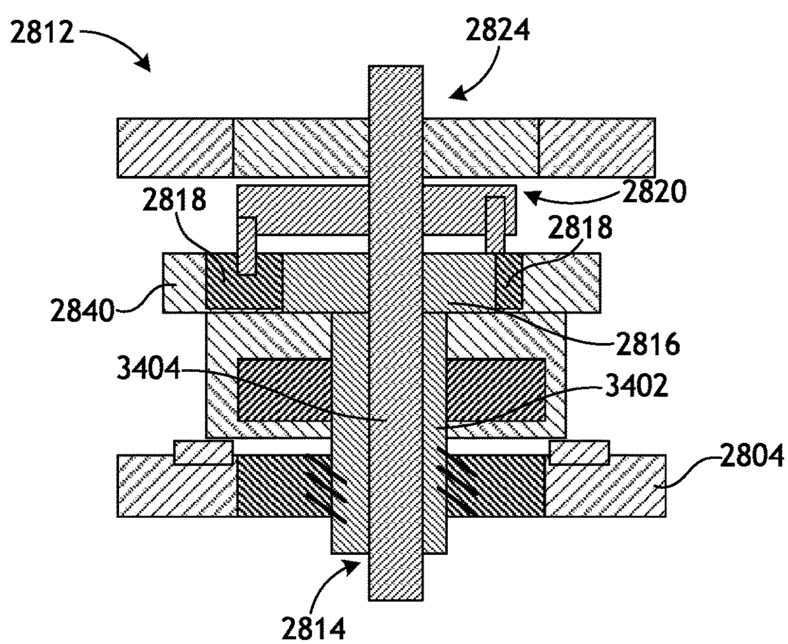
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FIG. 34

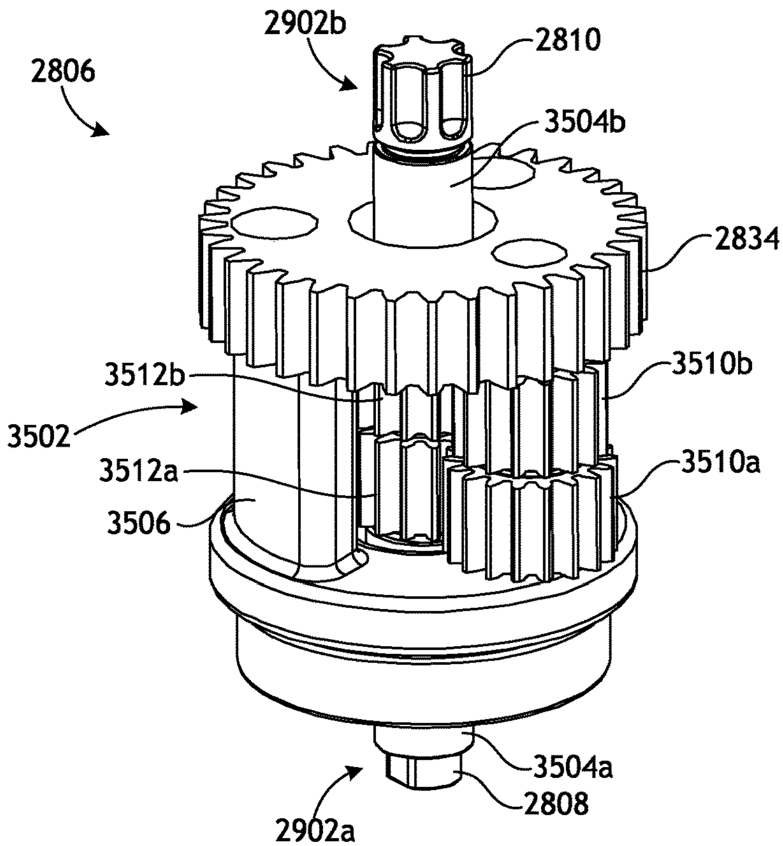

FIG. 35A

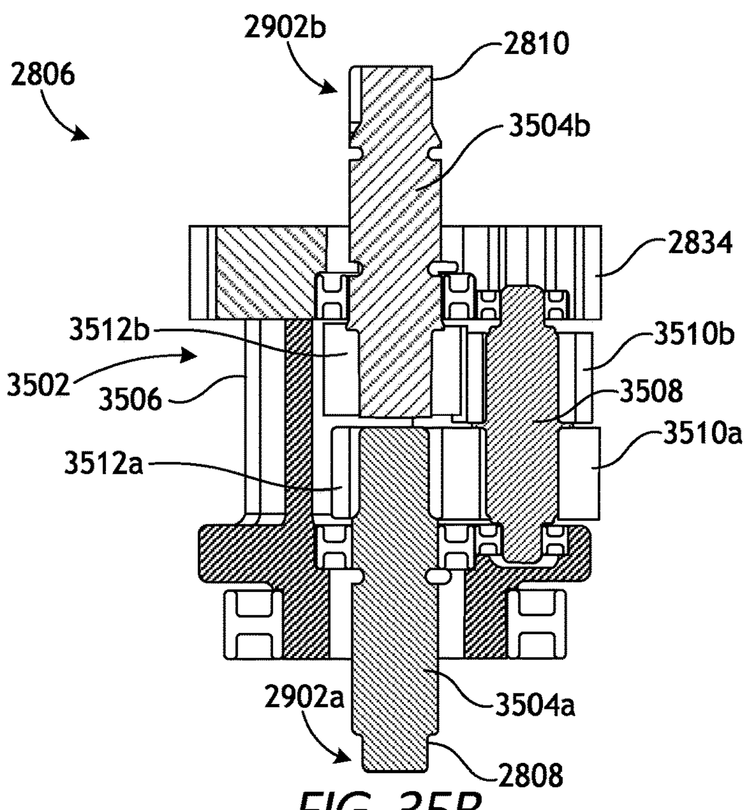

FIG. 35B

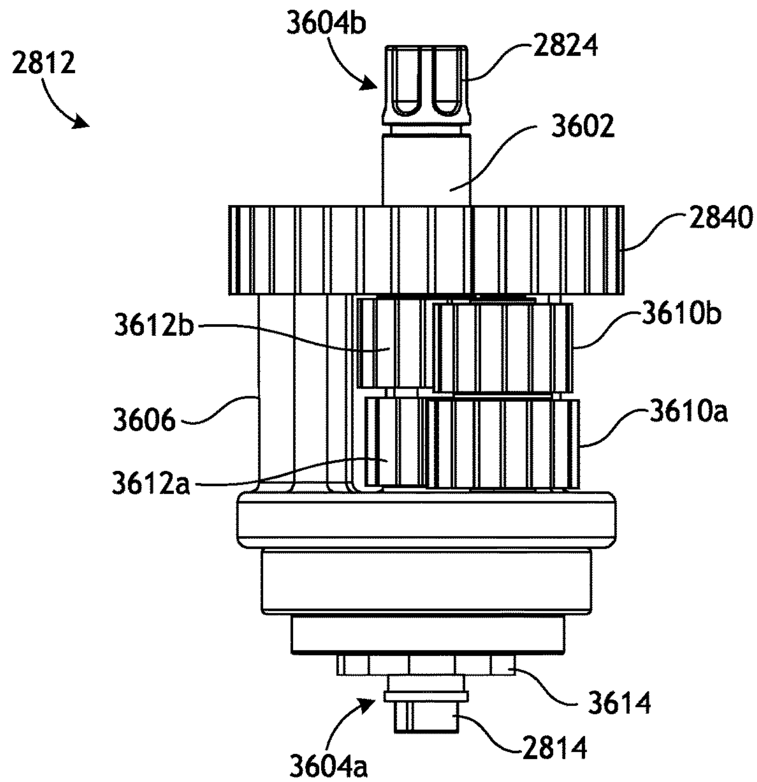

FIG. 36A

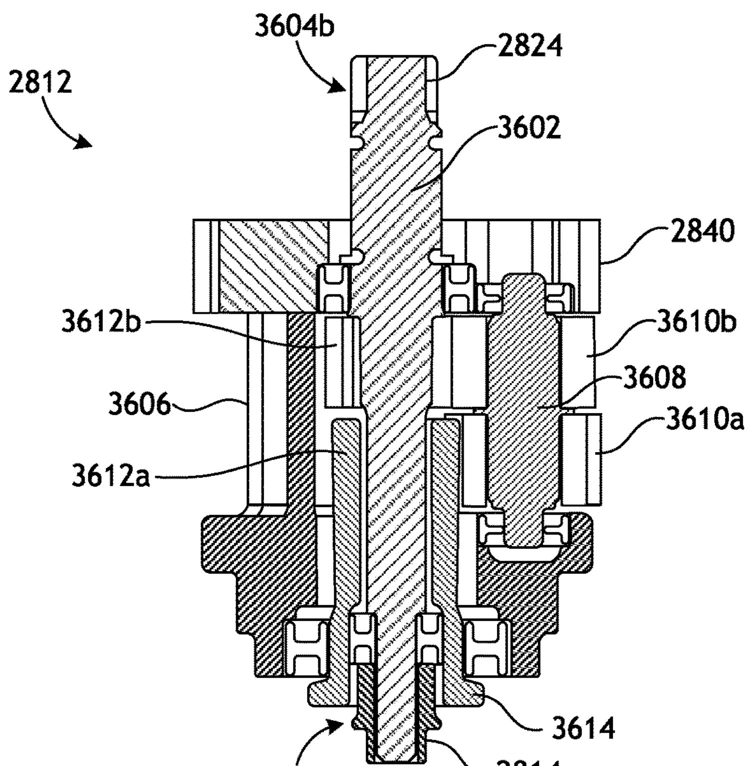

FIG. 36B

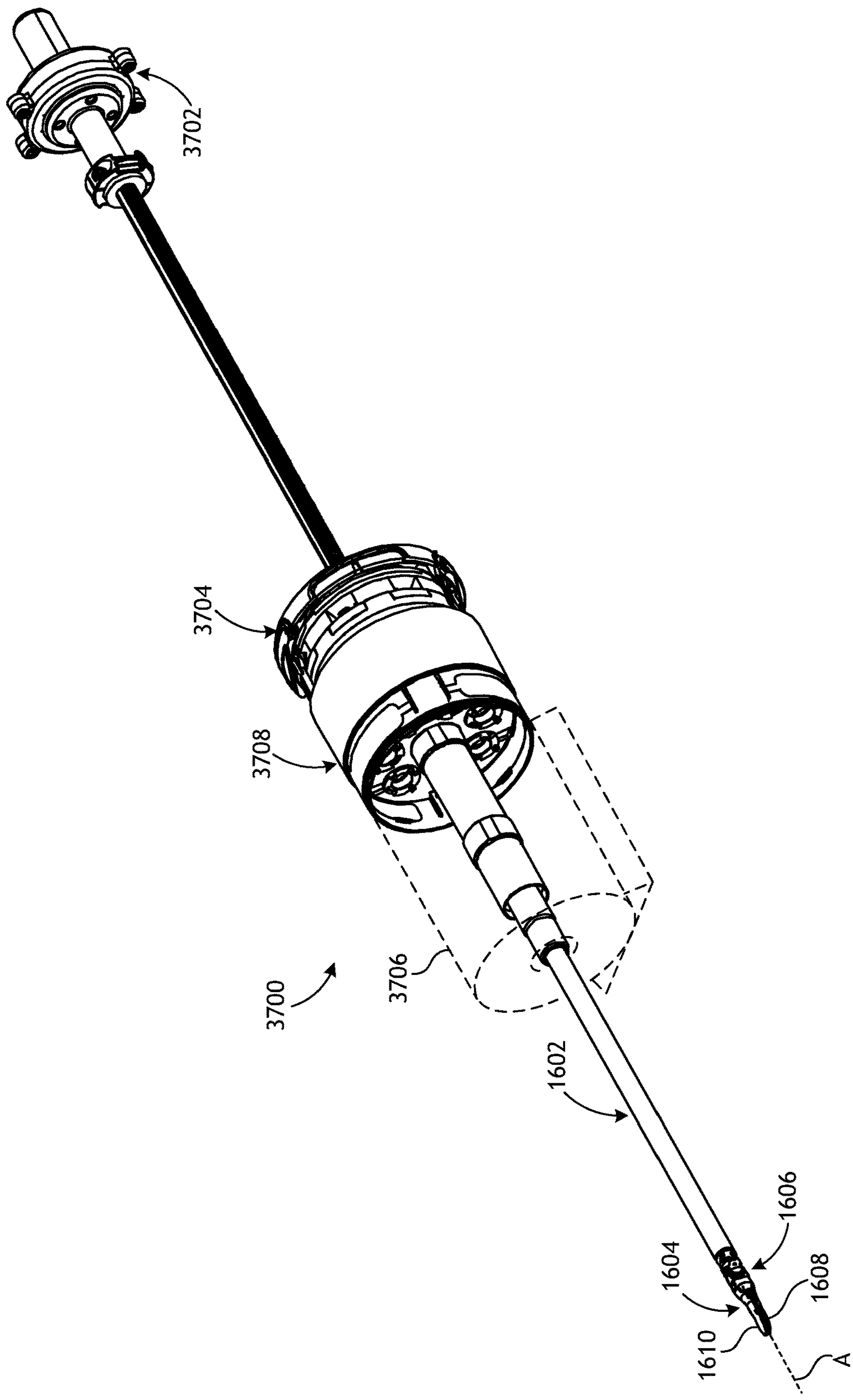

FIG. 37

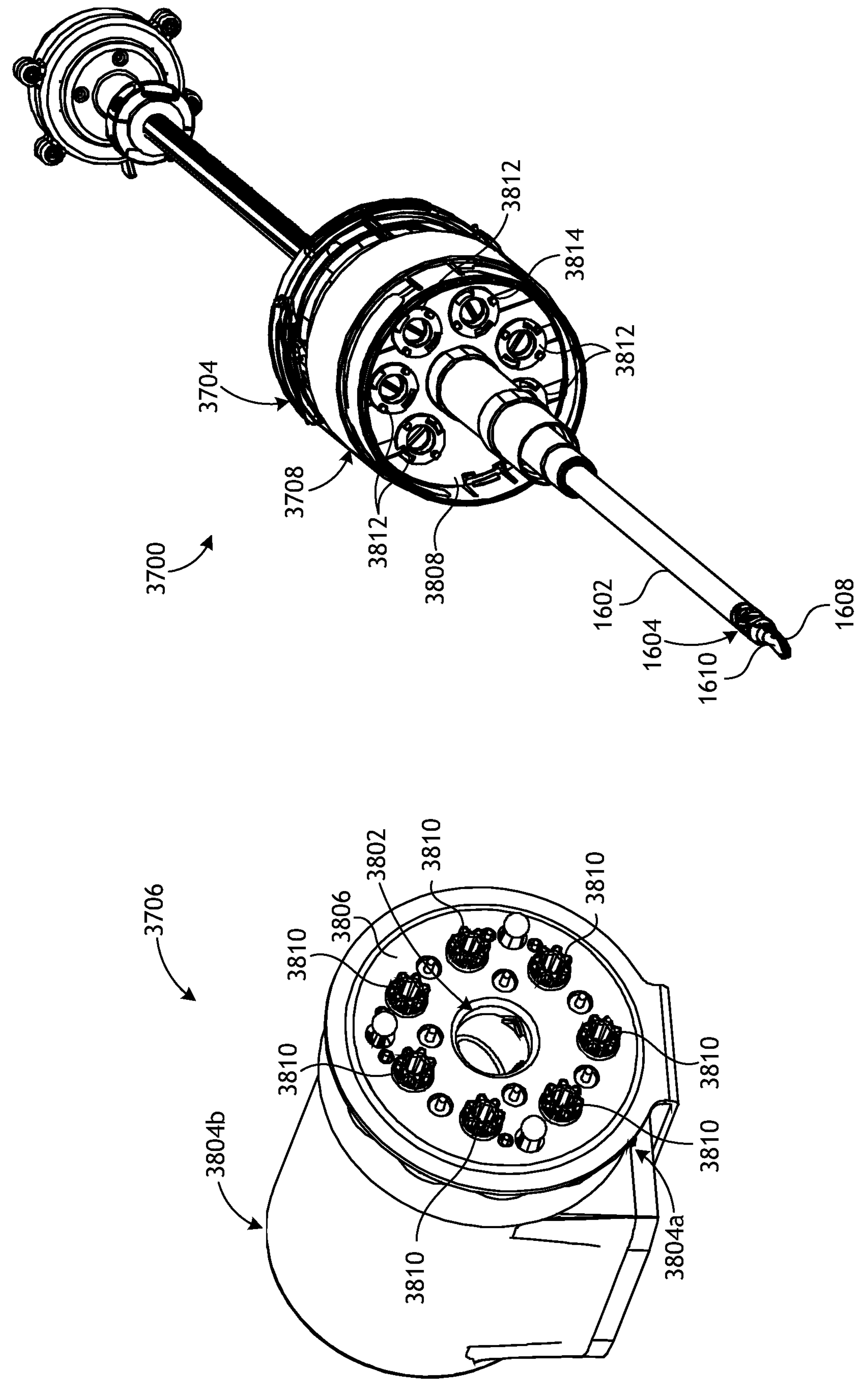
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FIG. 38

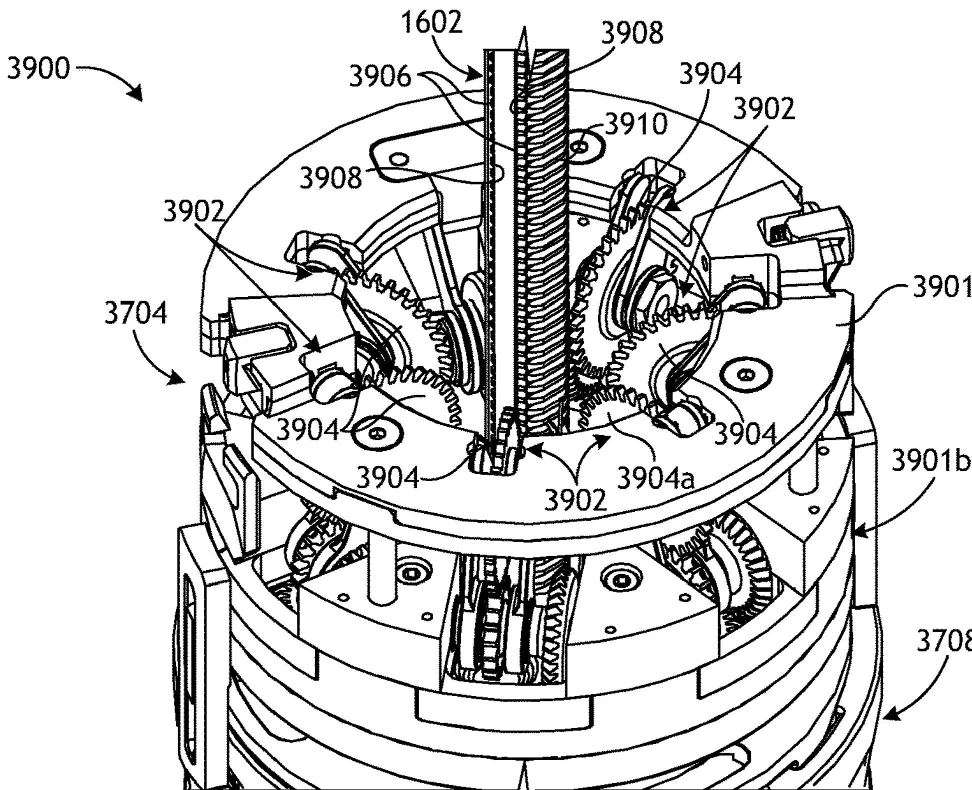

FIG. 39A

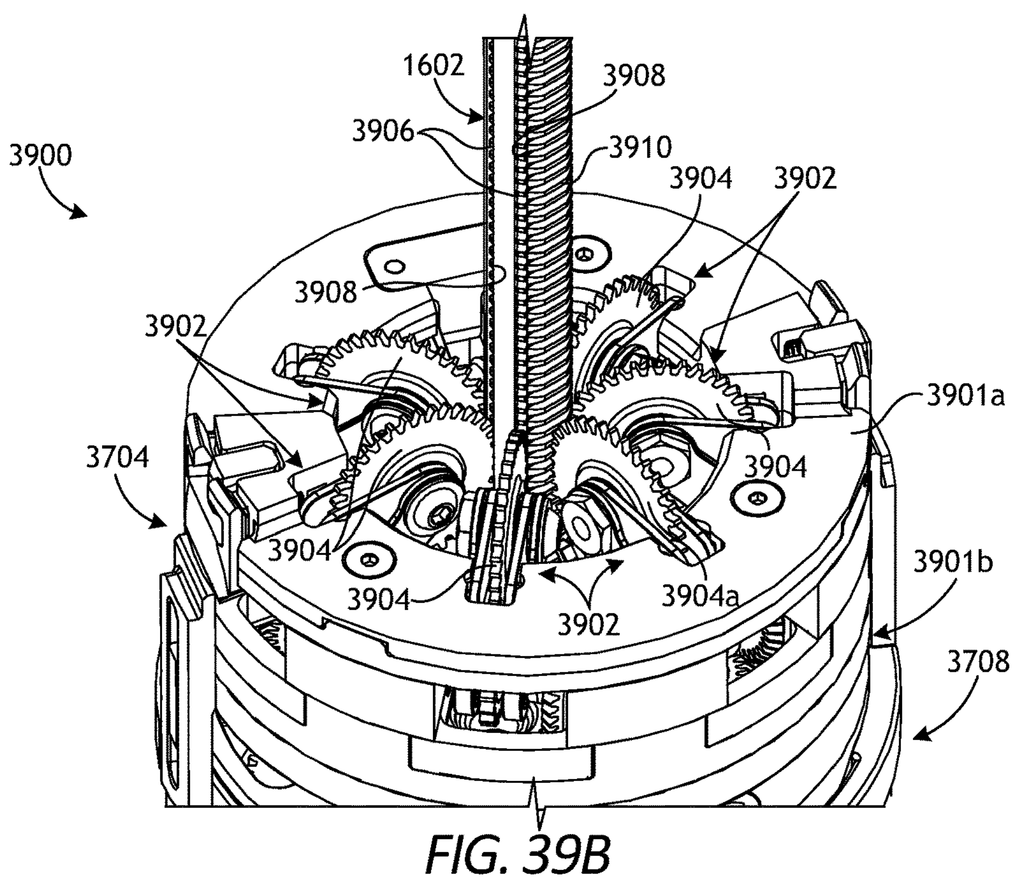

FIG. 39B

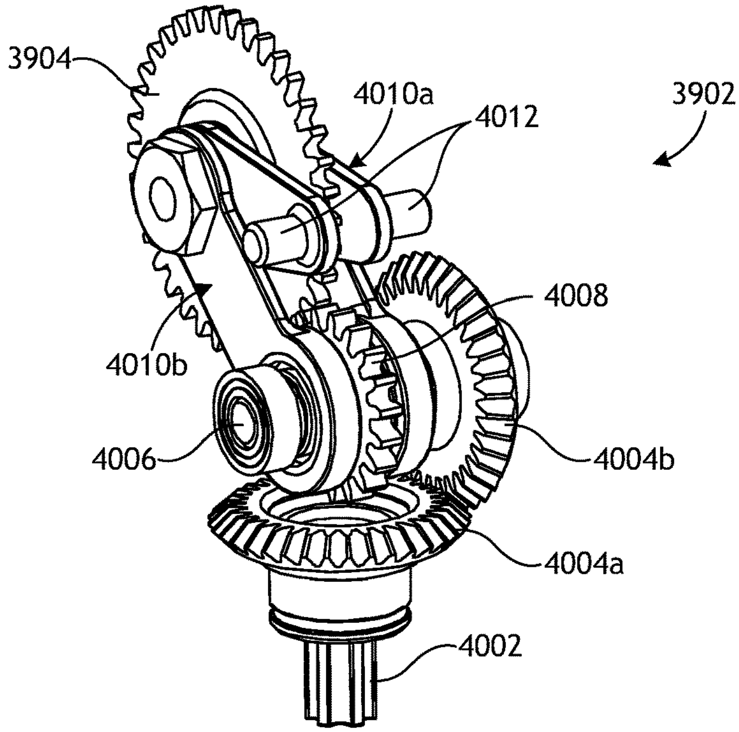
3904
4010a
4012
3902
4008
4010b
4006
4004b
4004a
4002

FIG. 40

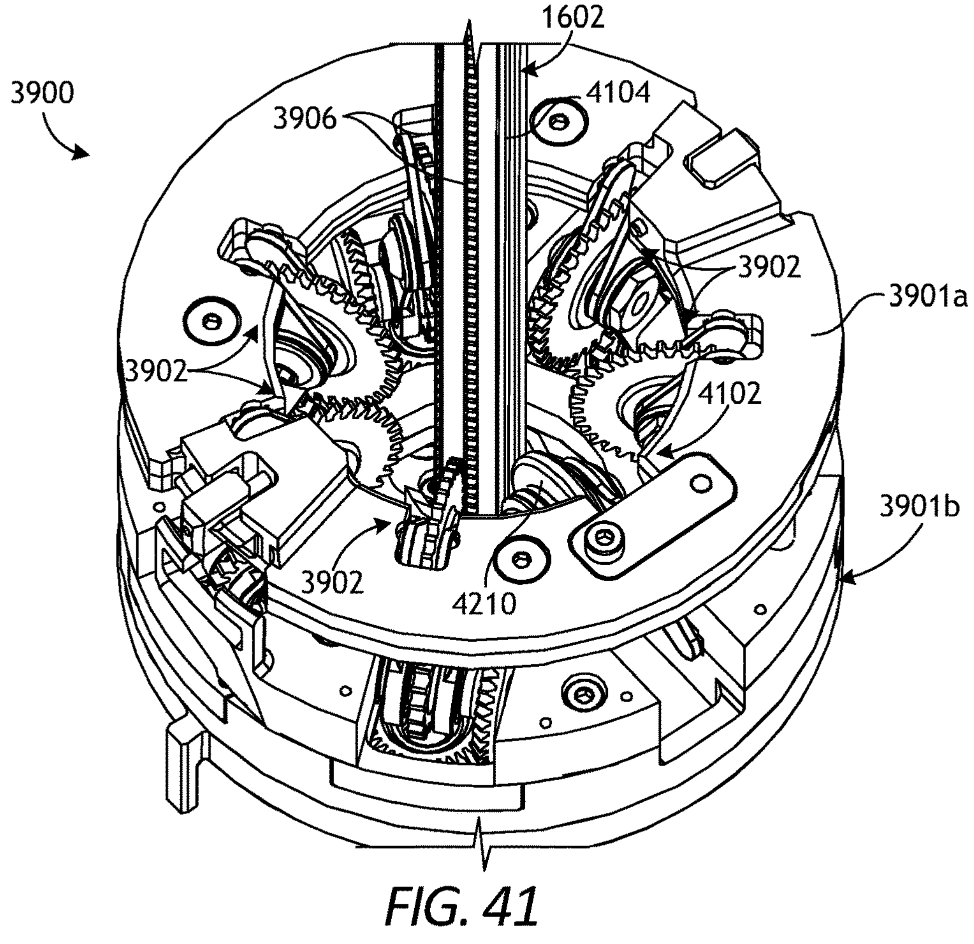
1602
3900
4104
3906
3902
3901a
3902
4102
3901b
3902
4210

FIG. 41

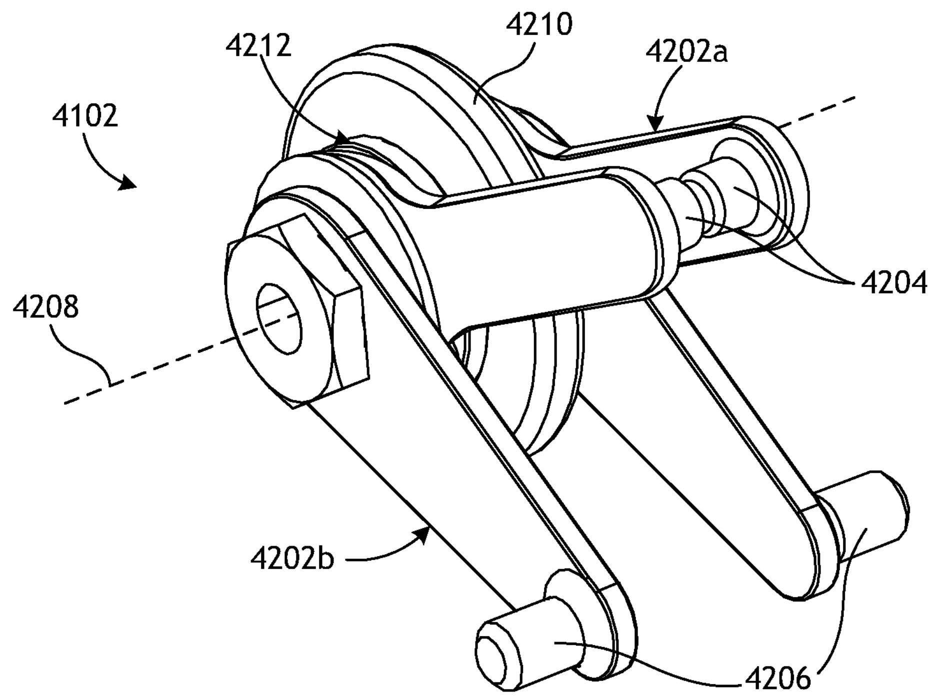
4210
4212
4202a
4102
4204
4208
4202b
4206

FIG. 42

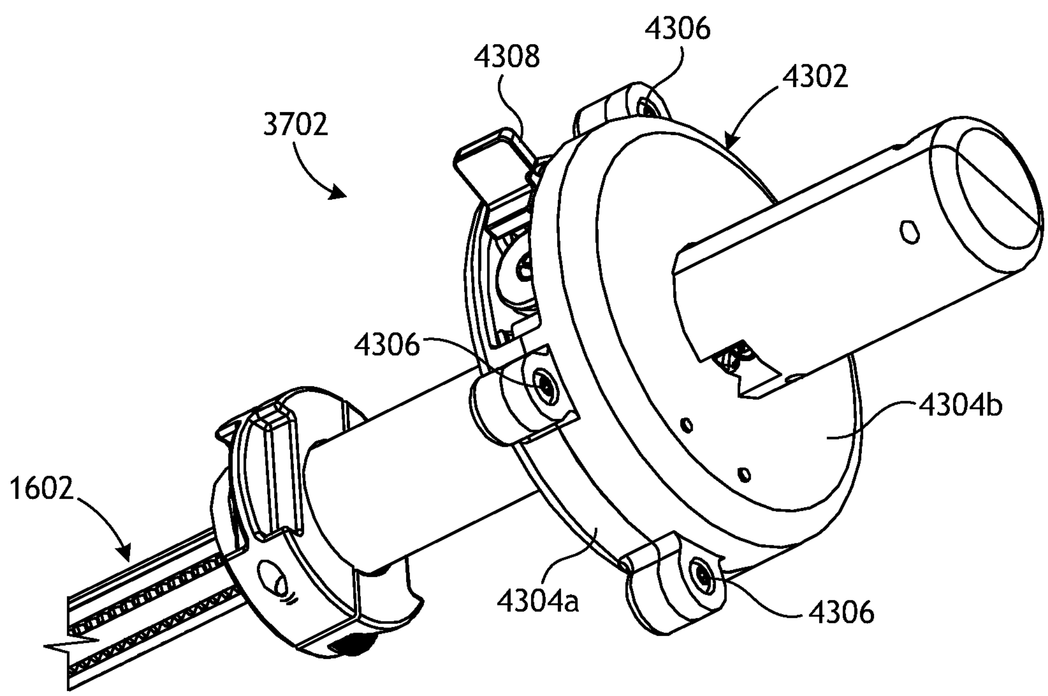
4306
4308
4302
3702
4306
4304b
1602
4304a
4306

FIG. 43

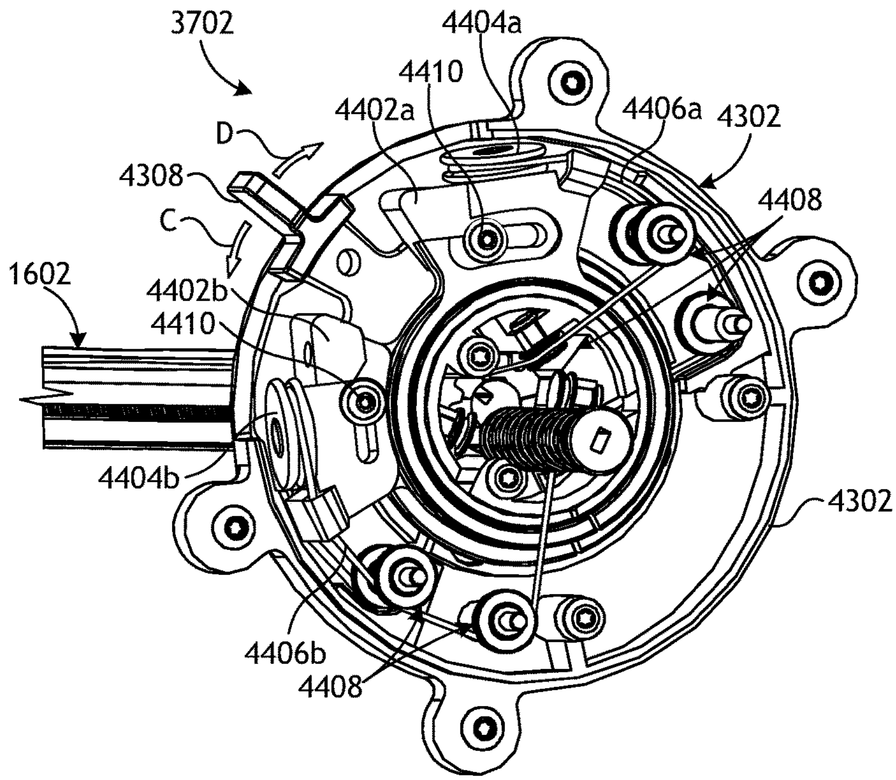
3702
4404a
4410
4402a
4406a
4302
D
4308
4408
C
1602
4402b
4410
4404b
4302
4406b
4408

FIG. 44

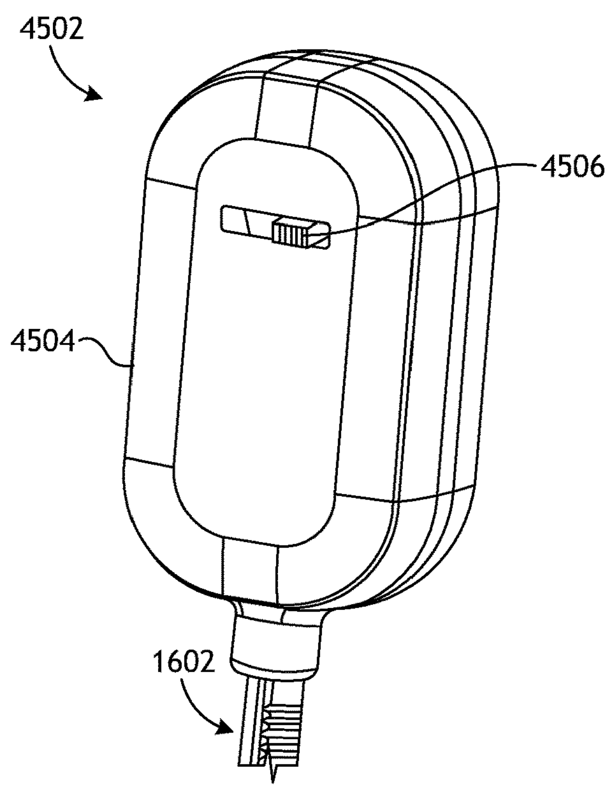
4502
4506
4504
1602

FIG. 45

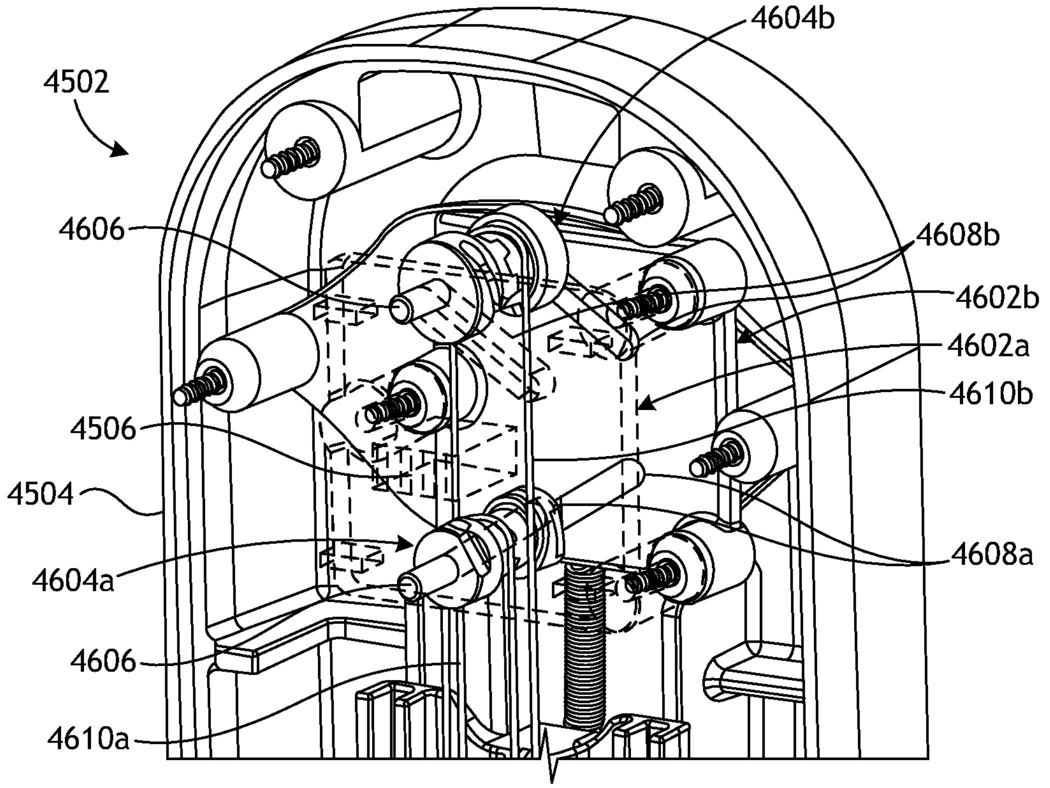

FIG. 46A

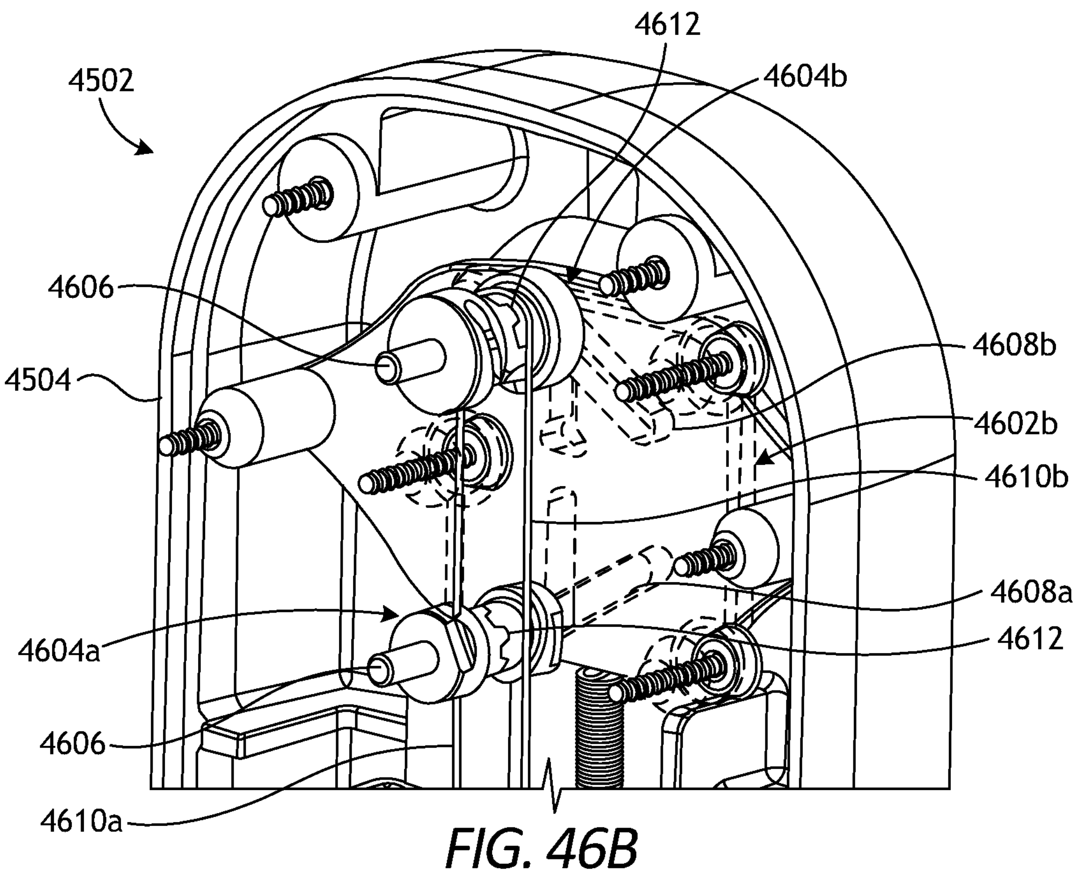

FIG. 46B

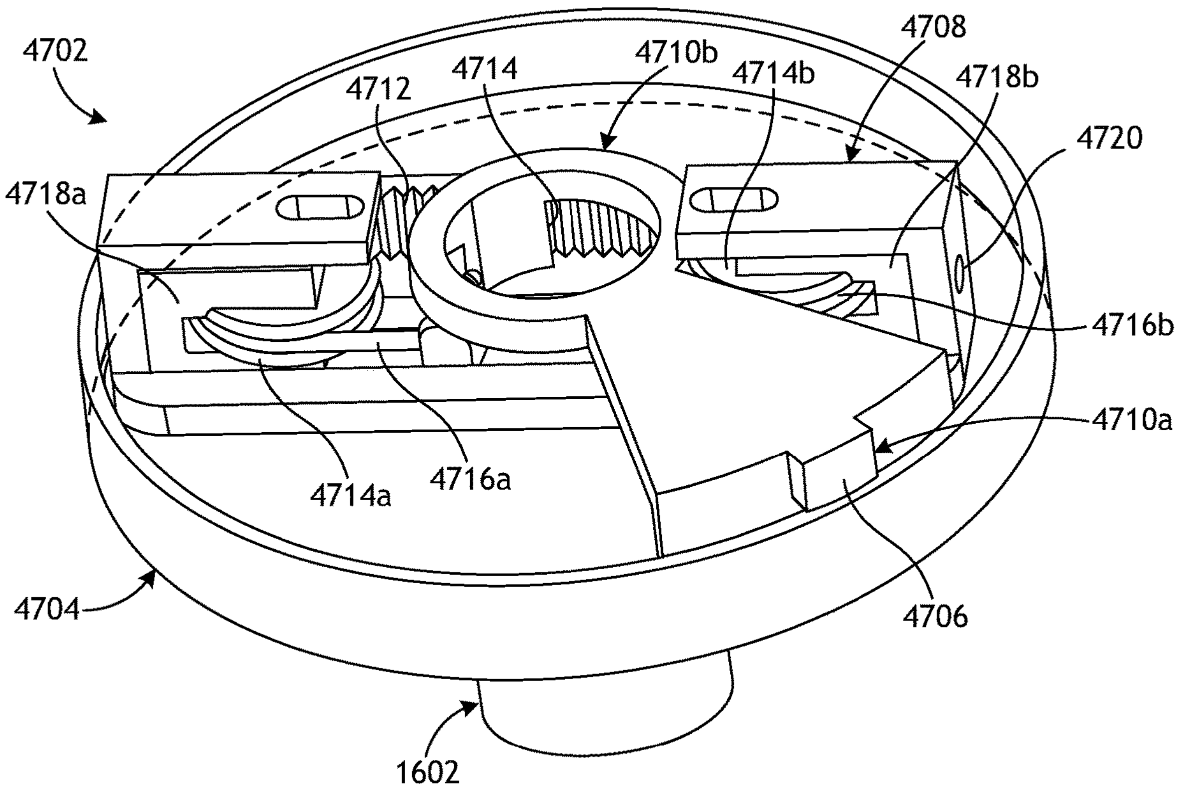
4702
4712
4714
4710b
4714b
4708
4718b
4720
4718a
4716b
4710a
4714a
4716a
4704
4706
1602

FIG. 47

INSERTION COUPLED INSERTING SURGICAL INSTRUMENTS

TECHNICAL FIELD

The systems and methods disclosed herein are directed to robotic surgical tools and, more particularly to, inserting architecture where the insertion motion is coupled with wrist motions.

BACKGROUND

Minimally invasive surgical (MIS) instruments are often preferred over traditional open surgical devices due to the reduced post-operative recovery time and minimal scarring. The most common MIS procedure may be endoscopy, and the most common form of endoscopy is laparoscopy, in which one or more small incisions are formed in the abdomen of a patient and a trocar is inserted through the incision to form a pathway that provides access to the abdominal cavity. The cannula and sealing system of the trocar are used to introduce various instruments and tools into the abdominal cavity, as well as to provide insufflation to elevate the abdominal wall above the organs. The instruments can be used to engage and/or treat tissue in a number of ways to achieve a diagnostic or therapeutic effect.

Various robotic systems have recently been developed to assist in MIS procedures. Robotic systems can allow for more instinctive hand movements by maintaining natural eye-hand axis. Robotic systems can also allow for more degrees of freedom in movement by including an articulable "wrist" joint that creates a more natural hand-like articulation. In such systems, an end effector positioned at the distal end of the instrument can be articulated (moved) using a cable driven motion system having one or more drive cables (or other elongate members) that extend through the wrist joint. A user (e.g., a surgeon) is able to remotely operate the end effector by grasping and manipulating in space one or more controllers that communicate with a tool driver coupled to the surgical instrument. User inputs are processed by a computer system incorporated into the robotic surgical system, and the tool driver responds by actuating the cable driven motion system and thereby actively controlling the tension balance in the drive cables. Moving the drive cables articulates the end effector to desired angular positions and configurations.

Improvements to robotically-enabled medical systems will provide physicians with the ability to perform endoscopic and laparoscopic procedures more effectively and with improved ease.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosed aspects will hereinafter be described in conjunction with the appended drawings, provided to illustrate and not to limit the disclosed aspects, wherein like designations denote like elements.

FIG. **1** illustrates an embodiment of a cart-based robotic system arranged for diagnostic and/or therapeutic bronchoscopy procedure(s).

FIG. **2** depicts further aspects of the robotic system of FIG. **1**.

FIG. **3**A illustrates an embodiment of the robotic system of FIG. **1** arranged for ureteroscopy.

FIG. **3**B illustrates an embodiment of the robotic system of FIG. **1** arranged for a vascular procedure.

FIG. **4** illustrates an embodiment of a table-based robotic system arranged for a bronchoscopy procedure.

FIG. **5** provides an alternative view of the robotic system of FIG. **4**.

FIG. **6** illustrates an example system configured to stow robotic arm(s).

FIG. **7**A illustrates an embodiment of a table-based robotic system configured for a ureteroscopy procedure.

FIG. **7**B illustrates an embodiment of a table-based robotic system configured for a laparoscopic procedure.

FIG. **7**C illustrates an embodiment of the table-based robotic system of FIGS. **4-7**B with pitch or tilt adjustment.

FIG. **8** provides a detailed illustration of the interface between the table and the column of the table-based robotic system of FIGS. **4-7**.

FIG. **9**A illustrates an alternative embodiment of a table-based robotic system.

FIG. **9**B illustrates an end view of the table-based robotic system of FIG. **9**A.

FIG. **9**C illustrates an end view of a table-based robotic system with robotic arms attached thereto.

FIG. **10** illustrates an exemplary instrument driver.

FIG. **11** illustrates an exemplary medical instrument with a paired instrument driver.

FIG. **12** illustrates an alternative design for an instrument driver and instrument where the axes of the drive units are parallel to the axis of the elongated shaft of the instrument.

FIG. **13** illustrates an instrument having an instrument-based insertion architecture.

FIG. **14** illustrates an exemplary controller.

FIG. **15** depicts a block diagram illustrating a localization system that estimates a location of one or more elements of the robotic systems of FIGS. **1-7**C, such as the location of the instrument of FIGS. **11-13**, in accordance to an example embodiment.

FIG. **16** is a side view of an example surgical tool that may incorporate some or all of the principles of the present disclosure.

FIGS. **17**A and **17**B are isometric and bottom views, respectively, of an example actuation system, according to one or more embodiments.

FIG. **17**C is another example of a gear train that may be used to transfer rotational torque from the drive inputs to the rack gears.

FIGS. **18**A-**18**D are schematic diagrams of example operation of the actuation system of FIGS. **17**A-**17**B, according to one or more embodiments.

FIG. **19** is an isometric view of one example of the tailpiece of FIG. **16**, according to one or more embodiments.

FIGS. **20**A and **20**B show example operation of the tailpiece (pantograph) of FIG. **19**, according to one or more embodiments.

FIG. **21** is an enlarged side view of the tailpiece (pantograph) of FIG. **19**, according to one or more embodiments.

FIG. **22** is a side view of the surgical tool of FIG. **16**, according to one or more additional embodiments.

FIGS. **23**A and **23**B are isometric and bottom views, respectively, of one example of the decoupler of FIG. **16**, according to one or more embodiments.

FIG. **24** is an isometric view of one example of the insertion assembly of FIGS. **23**A-**23**B, according to one or more embodiments.

FIG. **25** is an isometric view of an example differential assembly of FIGS. **23**A-**23**B, according to one or more embodiments.

FIGS. **26**A-**26**C are side views of the differential assembly of FIG. **25** in various stages of deconstruction, according to one or more embodiments.

FIGS. **27**A and **27**B are isometric and cross-sectional side views, respectively, of another example differential assembly of FIG. **25**, according to one or more additional embodiments.

FIG. **28** is a top view of another example of the decoupler of FIG. **16**, according to one or more additional embodiments.

FIG. **29** is an isometric view of an example differential assembly.

FIG. **30** is a cross-sectional top view of the differential assembly of FIG. **29** taken along the lines shown in FIG. **29**.

FIG. **31** is a schematic cross-sectional side view of the differential assembly of FIG. **29**, according to one or more embodiments.

FIG. **32** is a schematic, cross-sectional side view of yet another example of the differential assembly of FIG. **28**, according to one or more additional embodiments.

FIG. **33** is a cross-sectional side view of one example of the insertion assembly of FIG. **28**, according to one or more embodiments.

FIG. **34** is a schematic, cross-sectional side view of another example of the insertion assembly of FIG. **28**, according to one or more additional embodiments.

FIGS. **35**A and **35**B are isometric and cross-sectional side views of another example of the differential assembly of FIG. **28**, according to one or more additional embodiments.

FIGS. **36**A and **36**B are isometric and cross-sectional side views, respectively, of another example of the insertion assembly of FIG. **28**, according to one or more additional embodiments.

FIG. **37** is an isometric view of another example surgical tool that may incorporate some or all of the principles of the present disclosure.

FIG. **38** depicts separated isometric end views of the instrument driver and the surgical tool of FIG. **37**.

FIGS. **39**A and **39**B are isometric open (disengaged) and closed (engaged) views, respectively, of another example actuation system, according to one or more additional embodiments.

FIG. **40** is an isometric view of an example spur linkage subassembly, according to one or more embodiments.

FIG. **41** is another isometric view of the actuation system of FIGS. **39**A-**39**B, according to one or more additional embodiments.

FIG. **42** is an enlarged, isometric view of one example of the clocking wheel linkage subassembly, according to one or more embodiments.

FIG. **43** is an enlarged isometric view of the tailpiece of FIG. **37**, according to one or more embodiments.

FIG. **44** is an isometric view of the interior of the tailpiece of FIG. **43**, according to one or more embodiments.

FIG. **45** is an isometric view of another embodiment of the tailpiece of FIG. **37**, according to one or more additional embodiments.

FIGS. **46**A and **46**B are isometric views of the interior of the tailpiece of FIG. **45**, according to one or more embodiments.

FIG. **47** is an enlarged isometric view of another example tailpiece, according to one or more additional embodiments.

DETAILED DESCRIPTION

1. Overview

Aspects of the present disclosure may be integrated into a robotically-enabled medical system capable of performing

a variety of medical procedures, including both minimally invasive (e.g., laparoscopy) and non-invasive (e.g., endoscopy) procedures. Among endoscopy procedures, the system may be capable of performing bronchoscopy, ureteroscopy, gastroscopy, etc.

In addition to performing the breadth of procedures, the system may provide additional benefits, such as enhanced imaging and guidance, to assist the physician. Additionally, the system may provide the physician with the ability to perform the procedure from an ergonomic position without the need for awkward arm motions and positions. Still further, the system may provide the physician with the ability to perform the procedure with improved ease of use such that one or more of the instruments of the system can be controlled by a single user.

Various embodiments will be described below in conjunction with the drawings for purposes of illustration. It should be appreciated that many other implementations of the disclosed concepts are possible, and various advantages can be achieved with the disclosed implementations. Headings are included herein for reference and to aid in locating various sections. These headings are not intended to limit the scope of the concepts described with respect thereto, as such concepts may have applicability throughout the entire specification.

A. Robotic System—Cart.

The robotically-enabled medical system may be configured in a variety of ways depending on the particular procedure. FIG. **1** illustrates an embodiment of a cart-based robotically-enabled system **100** arranged for a diagnostic and/or therapeutic bronchoscopy procedure. For a bronchoscopy procedure, the robotic system **100** may include a cart **102** having one or more robotic arms **104** (three shown) to deliver a medical instrument (alternately referred to as a "surgical tool"), such as a steerable endoscope **106** (e.g., a procedure-specific bronchoscope for bronchoscopy), to a natural orifice access point (i.e., the mouth of the patient) to deliver diagnostic and/or therapeutic tools. As shown, the cart **102** may be positioned proximate to the patient's upper torso in order to provide access to the access point. Similarly, the robotic arms **104** may be actuated to position the bronchoscope relative to the access point. The arrangement in FIG. **1** may also be utilized when performing a gastro-intestinal (GI) procedure with a gastroscope, a specialized endoscope for GI procedures.

Once the cart **102** is properly positioned adjacent the patient, the robotic arms **104** are operated to insert the steerable endoscope **106** into the patient robotically, manually, or a combination thereof. The steerable endoscope **106** may comprise at least two telescoping parts, such as an inner leader portion and an outer sheath portion, where each portion is coupled to a separate instrument driver of a set of instrument drivers **108**. As illustrated, each instrument driver **108** is coupled to the distal end of a corresponding one of the robotic arms **104**. This linear arrangement of the instrument drivers **108**, which facilitates coaxially aligning the leader portion with the sheath portion, creates a "virtual rail" **110** that may be repositioned in space by manipulating the robotic arms **104** into different angles and/or positions. Translation of the instrument drivers **108** along the virtual rail **110** telescopes the inner leader portion relative to the outer sheath portion, thus effectively advancing or retracting the endoscope **106** relative to the patient.

As illustrated, the virtual rail **110** (and other virtual rails described herein) is depicted in the drawings using dashed lines, thus not constituting any physical structure of the system **100**. The angle of the virtual rail **110** may be adjusted, translated, and pivoted based on clinical application or physician preference. For example, in bronchoscopy, the angle and position of the virtual rail **110** as shown represents a compromise between providing physician access to the endoscope **106** while minimizing friction that results from bending the endoscope **106** into the patient's mouth.

After insertion into the patient's mouth, the endoscope **106** may be directed down the patient's trachea and lungs using precise commands from the robotic system **100** until reaching a target destination or operative site. In order to enhance navigation through the patient's lung network and/or reach the desired target, the endoscope **106** may be manipulated to telescopically extend the inner leader portion from the outer sheath portion to obtain enhanced articulation and greater bend radius. The use of separate instrument drivers **108** also allows the leader portion and sheath portion to be driven independent of each other.

For example, the endoscope **106** may be directed to deliver a biopsy needle to a target, such as, for example, a lesion or nodule within the lungs of a patient. The needle may be deployed down a working channel that runs the length of the endoscope **106** to obtain a tissue sample to be analyzed by a pathologist. Depending on the pathology results, additional tools may be deployed down the working channel of the endoscope for additional biopsies. After identifying a tissue sample to be malignant, the endoscope **106** may endoscopically deliver tools to resect the potentially cancerous tissue. In some instances, diagnostic and therapeutic treatments can be delivered in separate procedures. In those circumstances, the endoscope **106** may also be used to deliver a fiducial marker to "mark" the location of a target nodule as well. In other instances, diagnostic and therapeutic treatments may be delivered during the same procedure.

The system **100** may also include a movable tower **112**, which may be connected via support cables to the cart **102** to provide support for controls, electronics, fluidics, optics, sensors, and/or power to the cart **102**. Placing such functionality in the tower **112** allows for a smaller form factor cart **102** that may be more easily adjusted and/or repositioned by an operating physician and his/her staff. Additionally, the division of functionality between the cart/table and the support tower **112** reduces operating room clutter and facilitates improving clinical workflow. While the cart **102** may be positioned close to the patient, the tower **112** may alternatively be stowed in a remote location to stay out of the way during a procedure.

In support of the robotic systems described above, the tower **112** may include component(s) of a computer-based control system that stores computer program instructions, for example, within a non-transitory computer-readable storage medium such as a persistent magnetic storage drive, solid state drive, etc. The execution of those instructions, whether the execution occurs in the tower **112** or the cart **102**, may control the entire system or sub-system(s) thereof. For example, when executed by a processor of the computer system, the instructions may cause the components of the robotics system to actuate the relevant carriages and arm mounts, actuate the robotics arms, and control the medical instruments. For example, in response to receiving the control signal, motors in the joints of the robotic arms **104** may position the arms into a certain posture or angular orientation.

The tower **112** may also include one or more of a pump, flow meter, valve control, and/or fluid access in order to provide controlled irrigation and aspiration capabilities to the system **100** that may be deployed through the endoscope **106**. These components may also be controlled using the computer system of the tower **112**. In some embodiments, irrigation and aspiration capabilities may be delivered directly to the endoscope **106** through separate cable(s).

The tower **112** may include a voltage and surge protector designed to provide filtered and protected electrical power to the cart **102**, thereby avoiding placement of a power transformer and other auxiliary power components in the cart **102**, resulting in a smaller, more moveable cart **102**.

The tower **112** may also include support equipment for sensors deployed throughout the robotic system **100**. For example, the tower **112** may include opto-electronics equipment for detecting, receiving, and processing data received from optical sensors or cameras throughout the robotic system **100**. In combination with the control system, such opto-electronics equipment may be used to generate real-time images for display in any number of consoles deployed throughout the system, including in the tower **112**. Similarly, the tower **112** may also include an electronic subsystem for receiving and processing signals received from deployed electromagnetic (EM) sensors. The tower **112** may also be used to house and position an EM field generator for detection by EM sensors in or on the medical instrument.

The tower **112** may also include a console **114** in addition to other consoles available in the rest of the system, e.g., a console mounted to the cart **102**. The console **114** may include a user interface and a display screen (e.g., a touchscreen) for the physician operator. Consoles in the system **100** are generally designed to provide both robotic controls as well as pre-operative and real-time information of the procedure, such as navigational and localization information of the endoscope **106**. When the console **114** is not the only console available to the physician, it may be used by a second operator, such as a nurse, to monitor the health or vitals of the patient and the operation of system, as well as provide procedure-specific data, such as navigational and localization information. In other embodiments, the console **114** may be housed in a body separate from the tower **112**.

The tower **112** may be coupled to the cart **102** and endoscope **106** through one or more cables **116** connections. In some embodiments, support functionality from the tower **112** may be provided through a single cable **116** extending to the cart **102**, thus simplifying and de-cluttering the operating room. In other embodiments, specific functionality may be coupled in separate cabling and connections. For example, while power may be provided through a single power cable to the cart **102**, support for controls, optics, fluidics, and/or navigation may be provided through one or more separate cables.

FIG. **2** provides a detailed illustration of an embodiment of the cart **102** from the cart-based robotically-enabled system **100** of FIG. **1**. The cart **102** generally includes an elongated support structure **202** (also referred to as a "column"), a cart base **204**, and a console **206** at the top of the column **202**. The column **202** may include one or more carriages, such as a carriage **208** (alternatively "arm support") for supporting the deployment of the robotic arms **104**. The carriage **208** may include individually configurable arm mounts that rotate along a perpendicular axis to adjust the base **214** of the robotic arms **104** for better positioning relative to the patient. The carriage **208** also includes a carriage interface **210** that allows the carriage **208** to vertically translate along the column **202**.

The carriage interface **210** is connected to the column **202** through slots, such as slot **212**, that are positioned on opposite sides of the column **202** to guide the vertical translation of the carriage **208**. The slot **212** contains a vertical translation interface to position and hold the carriage **208** at various vertical heights relative to the cart base **204**. Vertical translation of the carriage **208** allows the cart **102** to adjust the reach of the robotic arms **104** to meet a variety of table heights, patient sizes, and physician preferences. Similarly, the individually configurable arm mounts on the carriage **208** allow a base **214** of the robotic arms **104** to be angled in a variety of configurations.

In some embodiments, the slot **212** may be supplemented with slot covers (not shown) that are flush and parallel to the slot surface to prevent dirt and fluid ingress into the internal chambers of the column **202** and the vertical translation interface as the carriage **208** vertically translates. The slot covers may be deployed through pairs of spring spools positioned near the vertical top and bottom of the slot **212**. The covers are coiled within the spools until deployed to extend and retract from their coiled state as the carriage **208** vertically translates up and down. The spring-loading of the spools provides force to retract the cover into a spool when carriage **208** translates towards the spool, while also maintaining a tight seal when the carriage **208** translates away from the spool. The covers may be connected to the carriage **208** using, for example, brackets in the carriage interface **210** to ensure proper extension and retraction of the cover as the carriage **208** translates.

The column **202** may internally comprise mechanisms, such as gears and motors, which are designed to use a vertically aligned lead screw to translate the carriage **208** in a mechanized fashion in response to control signals generated in response to user inputs, e.g., inputs from the console **206**.

The robotic arms **104** may generally comprise robotic arm bases **214** and end effectors **216** (three shown), separated by a series of linkages **218** connected by a corresponding series of joints **220**, each joint **220** including an independent actuator, and each actuator including an independently controllable motor. Each independently controllable joint **220** represents an independent degree of freedom available to the corresponding robotic arm **104**. In the illustrated embodiment, each arm **104** has seven joints **220**, thus providing seven degrees of freedom. A multitude of joints **220** result in a multitude of degrees of freedom, allowing for "redundant" degrees of freedom. Redundant degrees of freedom allow the robotic arms **104** to position their respective end effectors **216** at a specific position, orientation, and trajectory in space using different linkage positions and joint angles. This allows for the system **100** to position and direct a medical instrument from a desired point in space while allowing the physician to move the arm joints **220** into a clinically advantageous position away from the patient to create greater access, while avoiding arm collisions.

The cart base **204** balances the weight of the column **202**, the carriage **208**, and the arms **104** over the floor. Accordingly, the cart base **204** houses heavier components, such as electronics, motors, power supply, as well as components that either enable movement and/or immobilize the cart. For example, the cart base **204** includes rolling casters **222** that allow for the cart to easily move around the room prior to a procedure. After reaching an appropriate position, the casters **222** may be immobilized using wheel locks to hold the cart **102** in place during the procedure.

Positioned at the vertical end of the column **202**, the console **206** allows for both a user interface for receiving user input and a display screen (or a dual-purpose device such as, for example, a touchscreen **224**) to provide the physician user with both pre-operative and intra-operative data. Potential pre-operative data on the touchscreen **224** may include pre-operative plans, navigation and mapping data derived from pre-operative computerized tomography (CT) scans, and/or notes from pre-operative patient interviews. Intra-operative data on the touchscreen **224** may include optical information provided from the tool, sensor and coordinate information from sensors, as well as vital patient statistics, such as respiration, heart rate, and/or pulse. The console **206** may be positioned and tilted to allow a physician to access the console from the side of the column **202** opposite carriage **208**. From this position, the physician may view the console **206**, the robotic arms **104**, and the patient while operating the console **206** from behind the cart **102**. As shown, the console **206** also includes a handle **226** to assist with maneuvering and stabilizing cart **102**.

FIG. **3**A illustrates an embodiment of the system **100** of FIG. **1** arranged for ureteroscopy. In a ureteroscopic procedure, the cart **102** may be positioned to deliver a ureteroscope **302**, a procedure-specific endoscope designed to traverse a patient's urethra and ureter, to the lower abdominal area of the patient. In ureteroscopy, it may be desirable for the ureteroscope **302** to be directly aligned with the patient's urethra to reduce friction and forces on the sensitive anatomy. As shown, the cart **102** may be aligned at the foot of the table to allow the robotic arms **104** to position the ureteroscope **302** for direct linear access to the patient's urethra. From the foot of the table, the robotic arms **104** may insert the ureteroscope **302** along a virtual rail **304** directly into the patient's lower abdomen through the urethra.

After insertion into the urethra, using similar control techniques as in bronchoscopy, the ureteroscope **302** may be navigated into the bladder, ureters, and/or kidneys for diagnostic and/or therapeutic applications. For example, the ureteroscope **302** may be directed into the ureter and kidneys to break up kidney stone build-up using a laser or ultrasonic lithotripsy device deployed down a working channel of the ureteroscope **302**. After lithotripsy is complete, the resulting stone fragments may be removed using baskets deployed down the working channel of the ureteroscope **302**.

FIG. **3**B illustrates another embodiment of the system **100** of FIG. **1** arranged for a vascular procedure. In a vascular procedure, the system **100** may be configured such that the cart **102** may deliver a medical instrument **306**, such as a steerable catheter, to an access point in the femoral artery in the patient's leg. The femoral artery presents both a larger diameter for navigation as well as a relatively less circuitous and tortuous path to the patient's heart, which simplifies navigation. As in a ureteroscopic procedure, the cart **102** may be positioned towards the patient's legs and lower abdomen to allow the robotic arms **104** to provide a virtual rail **308** with direct linear access to the femoral artery access point in the patient's thigh/hip region. After insertion into the artery, the medical instrument **306** may be directed and advanced by translating the instrument drivers **108**. Alternatively, the cart **102** may be positioned around the patient's upper abdomen in order to reach alternative vascular access points, such as, for example, the carotid and brachial arteries near the patient's shoulder and wrist.

B. Robotic System—Table.

Embodiments of the robotically-enabled medical system may also incorporate the patient's table. Incorporation of the table reduces the amount of capital equipment within the operating room by removing the cart, which allows greater access to the patient. FIG. **4** illustrates an embodiment of such a robotically-enabled system **400** arranged for a bronchoscopy procedure. As illustrated, the system **400** includes a support structure or column **402** for supporting platform

404 (shown as a "table" or "bed") over the floor. Much like in the cart-based systems, the end effectors of the robotic arms **406** of the system **400** comprise instrument drivers **408** that are designed to manipulate an elongated medical instrument, such as a bronchoscope **410**, through or along a virtual rail **412** formed from the linear alignment of the instrument drivers **408**. In practice, a C-arm for providing fluoroscopic imaging may be positioned over the patient's upper abdominal area by placing the emitter and detector around the table **404**.

FIG. **5** provides an alternative view of the system **400** without the patient and medical instrument for discussion purposes. As shown, the column **402** may include one or more carriages **502** shown as ring-shaped in the system **400**, from which the one or more robotic arms **406** may be based. The carriages **502** may translate along a vertical column interface **504** that runs the length (height) of the column **402** to provide different vantage points from which the robotic arms **406** may be positioned to reach the patient. The carriage(s) **502** may rotate around the column **402** using a mechanical motor positioned within the column **402** to allow the robotic arms **406** to have access to multiples sides of the table **404**, such as, for example, both sides of the patient. In embodiments with multiple carriages **502**, the carriages **502** may be individually positioned on the column **402** and may translate and/or rotate independent of the other carriages **502**. While carriages **502** need not surround the column **402** or even be circular, the ring-shape as shown facilitates rotation of the carriages **502** around the column **402** while maintaining structural balance. Rotation and translation of the carriages **502** allows the system **400** to align medical instruments, such as endoscopes and laparoscopes, into different access points on the patient.

In other embodiments (discussed in greater detail below with respect to FIG. **9**A), the system **400** can include a patient table or bed with adjustable arm supports in the form of bars or rails extending alongside it. One or more robotic arms **406** (e.g., via a shoulder with an elbow joint) can be attached to the adjustable arm supports, which can be vertically adjusted. By providing vertical adjustment, the robotic arms **406** are advantageously capable of being stowed compactly beneath the patient table or bed, and subsequently raised during a procedure.

The arms **406** may be mounted on the carriages **502** through a set of arm mounts **506** comprising a series of joints that may individually rotate and/or telescopically extend to provide additional configurability to the robotic arms **406**. Additionally, the arm mounts **506** may be positioned on the carriages **502** such that when the carriages **502** are appropriately rotated, the arm mounts **506** may be positioned on either the same side of the table **404** (as shown in FIG. **5**), on opposite sides of table **404** (as shown in FIG. 7B), or on adjacent sides of the table **404** (not shown).

The column **402** structurally provides support for the table **404**, and a path for vertical translation of the carriages **502**. Internally, the column **402** may be equipped with lead screws for guiding vertical translation of the carriages, and motors to mechanize the translation of said carriages based the lead screws. The column **402** may also convey power and control signals to the carriage **502** and robotic arms **406** mounted thereon.

A table base **508** serves a similar function as the cart base **204** of the cart **102** shown in FIG. **2**, housing heavier components to balance the table/bed **404**, the column **402**, the carriages **502**, and the robotic arms **406**. The table base **508** may also incorporate rigid casters to provide stability during procedures. Deployed from the bottom of the table base **508**, the casters may extend in opposite directions on both sides of the base **508** and retract when the system **400** needs to be moved.

In some embodiments, the system **400** may also include a tower (not shown) that divides the functionality of system **400** between table and tower to reduce the form factor and bulk of the table **404**. As in earlier disclosed embodiments, the tower may provide a variety of support functionalities to the table **404**, such as processing, computing, and control capabilities, power, fluidics, and/or optical and sensor processing. The tower may also be movable to be positioned away from the patient to improve physician access and de-clutter the operating room. Additionally, placing components in the tower allows for more storage space in the table base **508** for potential stowage of the robotic arms **406**. The tower may also include a master controller or console that provides both a user interface for user input, such as keyboard and/or pendant, as well as a display screen (or touchscreen) for pre-operative and intra-operative information, such as real-time imaging, navigation, and tracking information. In some embodiments, the tower may also contain holders for gas tanks to be used for insufflation.

In some embodiments, a table base may stow and store the robotic arms when not in use. FIG. **6** illustrates an embodiment of the system **400** that is configured to stow robotic arms in an embodiment of the table-based system. In the system **400**, one or more carriages **602** (one shown) may be vertically translated into a base **604** to stow one or more robotic arms **606**, one or more arm mounts **608**, and the carriages **602** within the base **604**. Base covers **610** may be translated and retracted open to deploy the carriages **602**, the arm mounts **608**, and the arms **606** around the column **612**, and closed to stow and protect them when not in use. The base covers **610** may be sealed with a membrane **614** along the edges of its opening to prevent dirt and fluid ingress when closed.

FIG. **7**A illustrates an embodiment of the robotically-enabled table-based system **400** configured for a ureteroscopy procedure. In ureteroscopy, the table **404** may include a swivel portion **702** for positioning a patient off-angle from the column **402** and the table base **508**. The swivel portion **702** may rotate or pivot around a pivot point (e.g., located below the patient's head) in order to position the bottom portion of the swivel portion **702** away from the column **402**. For example, the pivoting of the swivel portion **702** allows a C-arm (not shown) to be positioned over the patient's lower abdomen without competing for space with the column (not shown) below table **404**. By rotating the carriage (not shown) around the column **402**, the robotic arms **406** may directly insert a ureteroscope **704** along a virtual rail **706** into the patient's groin area to reach the urethra. In ureteroscopy, stirrups **708** may also be fixed to the swivel portion **702** of the table **404** to support the position of the patient's legs during the procedure and allow clear access to the patient's groin area.

FIG. **7**B illustrates an embodiment of the system **400** configured for a laparoscopic procedure. In a laparoscopic procedure, through small incision(s) in the patient's abdominal wall, minimally invasive instruments may be inserted into the patient's anatomy. In some embodiments, the minimally invasive instruments comprise an elongated rigid member, such as a shaft, which is used to access anatomy within the patient. After inflation of the patient's abdominal cavity, the instruments may be directed to perform surgical or medical tasks, such as grasping, cutting, ablating, suturing, etc. In some embodiments, the instruments can comprise a scope, such as a laparoscope. As shown in FIG. **7**B, the carriages **502** of the system **400** may be rotated and vertically adjusted to position pairs of the robotic arms **406** on opposite sides of the table **404**, such that an instrument **710** may be positioned using the arm mounts **506** to be passed through minimal incisions on both sides of the patient to reach his/her abdominal cavity.

To accommodate laparoscopic procedures, the system **400** may also tilt the platform to a desired angle. FIG. **7**C illustrates an embodiment of the system **400** with pitch or tilt adjustment. As shown in FIG. **7**C, the system **400** may accommodate tilt of the table **404** to position one portion of the table **404** at a greater distance from the floor than the other. Additionally, the arm mounts **506** may rotate to match the tilt such that the arms **406** maintain the same planar relationship with table **404**. To accommodate steeper angles, the column **402** may also include telescoping portions **712** that allow vertical extension of the column **402** to keep the table **404** from touching the floor or colliding with the base **508**.

FIG. **8** provides a detailed illustration of the interface between the table **404** and the column **402**. Pitch rotation mechanism **802** may be configured to alter the pitch angle of the table **404** relative to the column **402** in multiple degrees of freedom. The pitch rotation mechanism **802** may be enabled by the positioning of orthogonal axes A and B at the column-table interface, each axis actuated by a separate motor **804***a* and **804***b* responsive to an electrical pitch angle command. Rotation along one screw **806***a* would enable tilt adjustments in one axis A, while rotation along another screw **806***b* would enable tilt adjustments along the other axis B. In some embodiments, a ball joint can be used to alter the pitch angle of the table **404** relative to the column **402** in multiple degrees of freedom.

For example, pitch adjustments are particularly useful when trying to position the table in a Trendelenburg position, i.e., position the patient's lower abdomen at a higher position from the floor than the patient's lower abdomen, for lower abdominal surgery. The Trendelenburg position causes the patient's internal organs to slide towards his/her upper abdomen through the force of gravity, clearing out the abdominal cavity for minimally invasive tools to enter and perform lower abdominal surgical or medical procedures, such as laparoscopic prostatectomy.

FIGS. **9**A and **9**B illustrate isometric and end views, respectively, of an alternative embodiment of a table-based surgical robotics system **900**. The surgical robotics system **900** includes one or more adjustable arm supports **902** that can be configured to support one or more robotic arms (see, for example, FIG. **9**C) relative to a table **904**. In the illustrated embodiment, a single adjustable arm support **902** is shown, though an additional arm support can be provided on an opposite side of the table **904**. The adjustable arm support **902** can be configured so that it can move relative to the table **904** to adjust and/or vary the position of the adjustable arm support **902** and/or any robotic arms mounted thereto relative to the table **904**. For example, the adjustable arm support **902** may be adjusted in one or more degrees of freedom relative to the table **904**. The adjustable arm support **902** provides high versatility to the system **900**, including the ability to easily stow the one or more adjustable arm supports **902** and any robotics arms attached thereto beneath the table **904**. The adjustable arm support **902** can be elevated from the stowed position to a position below an upper surface of the table **904**. In other embodiments, the adjustable arm support **902** can be elevated from the stowed position to a position above an upper surface of the table **904**.

The adjustable arm support **902** can provide several degrees of freedom, including lift, lateral translation, tilt, etc. In the illustrated embodiment of FIGS. **9**A and **9**B, the arm support **902** is configured with four degrees of freedom, which are illustrated with arrows in FIG. **9**A. A first degree of freedom allows for adjustment of the adjustable arm support **902** in the z-direction ("Z-lift"). For example, the adjustable arm support **902** can include a carriage **906** configured to move up or down along or relative to a column **908** supporting the table **904**. A second degree of freedom can allow the adjustable arm support **902** to tilt. For example, the adjustable arm support **902** can include a rotary joint, which can allow the adjustable arm support **902** to be aligned with the bed in a Trendelenburg position. A third degree of freedom can allow the adjustable arm support **902** to "pivot up," which can be used to adjust a distance between a side of the table **904** and the adjustable arm support **902**. A fourth degree of freedom can permit translation of the adjustable arm support **902** along a longitudinal length of the table.

The surgical robotics system **900** in FIGS. **9**A and **9**B can comprise a table **904** supported by a column **908** that is mounted to a base **910**. The base **910** and the column **908** support the table **904** relative to a support surface. A floor axis **912** and a support axis **914** are shown in FIG. **9**B.

The adjustable arm support **902** can be mounted to the column **908**. In other embodiments, the arm support **902** can be mounted to the table **904** or the base **910**. The adjustable arm support **902** can include a carriage **906**, a bar or rail connector **916** and a bar or rail **918**. In some embodiments, one or more robotic arms mounted to the rail **918** can translate and move relative to one another.

The carriage **906** can be attached to the column **908** by a first joint **920**, which allows the carriage **906** to move relative to the column **908** (e.g., such as up and down a first or vertical axis **922**). The first joint **920** can provide the first degree of freedom ("Z-lift") to the adjustable arm support **902**. The adjustable arm support **902** can include a second joint **924**, which provides the second degree of freedom (tilt) for the adjustable arm support **902**. The adjustable arm support **902** can include a third joint **926**, which can provide the third degree of freedom ("pivot up") for the adjustable arm support **902**. An additional joint **928** (shown in FIG. **9**B) can be provided that mechanically constrains the third joint **926** to maintain an orientation of the rail **918** as the rail connector **916** is rotated about a third axis **930**. The adjustable arm support **902** can include a fourth joint **932**, which can provide a fourth degree of freedom (translation) for the adjustable arm support **902** along a fourth axis **934**.

FIG. **9**C illustrates an end view of the surgical robotics system **900** with two adjustable arm supports **902***a* and **902***b* mounted on opposite sides of the table **904**. A first robotic arm **936***a* is attached to the first bar or rail **918***a* of the first adjustable arm support **902***a*. The first robotic arm **936***a* includes a base **938***a* attached to the first rail **918***a*. The distal end of the first robotic arm **936***a* includes an instrument drive mechanism or input **940***a* that can attach to one or more robotic medical instruments or tools. Similarly, the second robotic arm **936***b* includes a base **938***a* attached to the second rail **918***b*. The distal end of the second robotic arm **936***b* includes an instrument drive mechanism or input **940***b* configured to attach to one or more robotic medical instruments or tools.

In some embodiments, one or more of the robotic arms **936***a,b* comprises an arm with seven or more degrees of freedom. In some embodiments, one or more of the robotic arms **936***a,b* can include eight degrees of freedom, including an insertion axis (1-degree of freedom including insertion), a wrist (3-degrees of freedom including wrist pitch, yaw and roll), an elbow (1-degree of freedom including elbow pitch), a shoulder (2-degrees of freedom including shoulder pitch and yaw), and base **938***a,b* (1-degree of freedom including translation). In some embodiments, the insertion degree of freedom can be provided by the robotic arm **936***a,b*, while in other embodiments, the instrument itself provides insertion via an instrument-based insertion architecture.

C. Instrument Driver & Interface.

The end effectors of a system's robotic arms comprise (i) an instrument driver (alternatively referred to as "tool driver," "instrument drive mechanism," "instrument device manipulator," and "drive input") that incorporate electro-mechanical means for actuating the medical instrument, and (ii) a removable or detachable medical instrument, which may be devoid of any electro-mechanical components, such as motors. This dichotomy may be driven by the need to sterilize medical instruments used in medical procedures, and the inability to adequately sterilize expensive capital equipment due to their intricate mechanical assemblies and sensitive electronics. Accordingly, the medical instruments may be designed to be detached, removed, and interchanged from the instrument driver (and thus the system) for individual sterilization or disposal by the physician or the physician's staff. In contrast, the instrument drivers need not be changed or sterilized, and may be draped for protection.

FIG. **10** illustrates an example instrument driver **1000**, according to one or more embodiments. Positioned at the distal end of a robotic arm, the instrument driver **1000** includes one or more drive outputs **1002** arranged with parallel axes to provide controlled torque to a medical instrument via corresponding drive shafts **1004**. Each drive output **1002** comprises an individual drive shaft **1004** for interacting with the instrument, a gear head **1006** for converting the motor shaft rotation to a desired torque, a motor **1008** for generating the drive torque, and an encoder **1010** to measure the speed of the motor shaft and provide feedback to control circuitry **1012**, which can also be used for receiving control signals and actuating the drive output **1002**. Each drive output **1002** being independently controlled and motorized, the instrument driver **1000** may provide multiple (at least two shown in FIG. **10**) independent drive outputs to the medical instrument. In operation, the control circuitry **1012** receives a control signal, transmits a motor signal to the motor **1008**, compares the resulting motor speed as measured by the encoder **1010** with the desired speed, and modulates the motor signal to generate the desired torque.

For procedures that require a sterile environment, the robotic system may incorporate a drive interface, such as a sterile adapter connected to a sterile drape that sits between the instrument driver and the medical instrument. The chief purpose of the sterile adapter is to transfer angular motion from the drive shafts of the instrument driver to the drive inputs of the instrument while maintaining physical separation, and thus sterility, between the drive shafts and drive inputs. Accordingly, an example sterile adapter may comprise a series of rotational inputs and outputs intended to be mated with the drive shafts of the instrument driver and drive inputs on the instrument. Connected to the sterile adapter, the sterile drape, comprised of a thin, flexible material such as transparent or translucent plastic, is designed to cover the capital equipment, such as the instrument driver, robotic arm, and cart (in a cart-based system) or table (in a table-based system). Use of the drape would allow the capital equipment to be positioned proximate to the patient while still being located in an area not requiring sterilization (i.e., non-sterile field). On the other side of the sterile drape, the medical instrument may interface with the patient in an area requiring sterilization (i.e., sterile field).

D. Medical Instrument.

FIG. **11** illustrates an example medical instrument **1100** with a paired instrument driver **1102**. Like other instruments designed for use with a robotic system, the medical instrument **1100** (alternately referred to as a "surgical tool") comprises an elongated shaft **1104** (or elongate body) and an instrument base **1106**. The instrument base **1106**, also referred to as an "instrument handle" due to its intended design for manual interaction by the physician, may generally comprise rotatable drive inputs **1108**, e.g., receptacles, pulleys or spools, that are designed to be mated with drive outputs **1110** that extend through a drive interface on the instrument driver **1102** at the distal end of a robotic arm **1112**. When physically connected, latched, and/or coupled, the mated drive inputs **1108** of the instrument base **1106** may share axes of rotation with the drive outputs **1110** in the instrument driver **1102** to allow the transfer of torque from the drive outputs **1110** to the drive inputs **1108**. In some embodiments, the drive outputs **1110** may comprise splines that are designed to mate with receptacles on the drive inputs **1108**.

The elongated shaft **1104** is designed to be delivered through either an anatomical opening or lumen, e.g., as in endoscopy, or a minimally invasive incision, e.g., as in laparoscopy. The elongated shaft **1104** may be either flexible (e.g., having properties similar to an endoscope) or rigid (e.g., having properties similar to a laparoscope) or contain a customized combination of both flexible and rigid portions. When designed for laparoscopy, the distal end of the shaft **1104** may be connected to an end effector extending from a jointed wrist formed from a clevis with at least one degree of freedom and a surgical tool or medical instrument, such as, for example, a grasper or scissors, that may be actuated based on force from the tendons as the drive inputs **1008** rotate in response to torque received from the drive outputs **1110** of the instrument driver **1102**. When designed for endoscopy, the distal end of the flexible elongated shaft **1104** may include a steerable or controllable bending section that may be articulated and bent based on torque received from the drive outputs **1110** of the instrument driver **1102**.

In some embodiments, torque from the instrument driver **1102** is transmitted down the elongated shaft **1104** using tendons along the shaft **1104**. These individual tendons, such as pull wires, may be individually anchored to individual drive inputs **1108** within the instrument handle **1106**. From the handle **1106**, the tendons are directed down one or more pull lumens along the elongated shaft **1104** and anchored at the distal portion of the elongated shaft **1104**, or in the wrist at the distal portion of the elongated shaft. During a surgical procedure, such as a laparoscopic, endoscopic, or a hybrid procedure, these tendons may be coupled to a distally mounted end effector, such as a wrist, a grasper, or scissors. Under such an arrangement, torque exerted on the drive inputs **1108** would transfer tension to the tendon, thereby causing the end effector to actuate in some way. In some embodiments, during a surgical procedure, the tendon may cause a joint to rotate about an axis, thereby causing the end effector to move in one direction or another. Alternatively, the tendon may be connected to one or more jaws of a grasper at distal end of the elongated shaft **1104**, where tension from the tendon cause the grasper to close.

In endoscopy, the tendons may be coupled to a bending or articulating section positioned along the elongated shaft

1104 (e.g., at the distal end) via adhesive, control ring, or other mechanical fixation. When fixedly attached to the distal end of a bending section, torque exerted on drive inputs **1108** would be transmitted down the tendons, causing the softer, bending section (sometimes referred to as the articulable section or region) to bend or articulate. Along the non-bending sections, it may be advantageous to spiral or helix the individual pull lumens that direct the individual tendons along (or inside) the walls of the endoscope shaft to balance the radial forces that result from tension in the pull wires. The angle of the spiraling and/or spacing there between may be altered or engineered for specific purposes, wherein tighter spiraling exhibits lesser shaft compression under load forces, while lower amounts of spiraling results in greater shaft compression under load forces, but also exhibits limits bending. On the other end of the spectrum, the pull lumens may be directed parallel to the longitudinal axis of the elongated shaft **1104** to allow for controlled articulation in the desired bending or articulable sections.

In endoscopy, the elongated shaft **1104** houses a number of components to assist with the robotic procedure. The shaft may comprise a working channel for deploying surgical tools (or medical instruments), irrigation, and/or aspiration to the operative region at the distal end of the shaft **1104**. The shaft **1104** may also accommodate wires and/or optical fibers to transfer signals to/from an optical assembly at the distal tip, which may include of an optical camera. The shaft **1104** may also accommodate optical fibers to carry light from proximally-located light sources, such as light emitting diodes, to the distal end of the shaft.

At the distal end of the instrument **1100**, the distal tip may also comprise the opening of a working channel for delivering tools for diagnostic and/or therapy, irrigation, and aspiration to an operative site. The distal tip may also include a port for a camera, such as a fiberscope or a digital camera, to capture images of an internal anatomical space. Relatedly, the distal tip may also include ports for light sources for illuminating the anatomical space when using the camera.

In the example of FIG. **11**, the drive shaft axes, and thus the drive input axes, are orthogonal to the axis of the elongated shaft. This arrangement, however, complicates roll capabilities for the elongated shaft **1104**. Rolling the elongated shaft **1104** along its axis while keeping the drive inputs **1108** static results in undesirable tangling of the tendons as they extend off the drive inputs **1108** and enter pull lumens within the elongated shaft **1104**. The resulting entanglement of such tendons may disrupt any control algorithms intended to predict movement of the flexible elongated shaft during an endoscopic procedure.

FIG. **12** illustrates an alternative design for a circular instrument driver **1200** and corresponding instrument **1202** (alternately referred to as a "surgical tool") where the axes of the drive units are parallel to the axis of the elongated shaft **1206** of the instrument **1202**. As shown, the instrument driver **1200** comprises four drive units with corresponding drive outputs **1208** aligned in parallel at the end of a robotic arm **1210**. The drive units and their respective drive outputs **1208** are housed in a rotational assembly **1212** of the instrument driver **1200** that is driven by one of the drive units within the assembly **1212**. In response to torque provided by the rotational drive unit, the rotational assembly **1212** rotates along a circular bearing that connects the rotational assembly **1212** to a non-rotational portion **1214** of the instrument driver **1200**. Power and control signals may be communicated from the non-rotational portion **1214** of the instrument driver **1200** to the rotational assembly **1212** through electrical contacts maintained through rotation by a brushed slip ring connection (not shown). In other embodiments, the rotational assembly **1212** may be responsive to a separate drive unit that is integrated into the non-rotatable portion **1214**, and thus not in parallel with the other drive units. The rotational assembly **1212** allows the instrument driver **1200** to rotate the drive units and their respective drive outputs **1208** as a single unit around an instrument driver axis **1216**.

Like earlier disclosed embodiments, the instrument **1202** may include an elongated shaft **1206** and an instrument base **1218** (shown in phantom) including a plurality of drive inputs **1220** (such as receptacles, pulleys, and spools) that are configured to mate with the drive outputs **1208** of the instrument driver **1200**. Unlike prior disclosed embodiments, the instrument shaft **1206** extends from the center of the instrument base **1218** with an axis substantially parallel to the axes of the drive inputs **1220**, rather than orthogonal as in the design of FIG. **11**.

When coupled to the rotational assembly **1212** of the instrument driver **1200**, the medical instrument **1202**, comprising instrument base **1218** and instrument shaft **1206**, rotates in combination with the rotational assembly **1212** about the instrument driver axis **1216**. Since the instrument shaft **1206** is positioned at the center of the instrument base **1218**, the instrument shaft **1206** is coaxial with the instrument driver axis **1216** when attached. Thus, rotation of the rotational assembly **1212** causes the instrument shaft **1206** to rotate about its own longitudinal axis. Moreover, as the instrument base **1218** rotates with the instrument shaft **1206**, any tendons connected to the drive inputs **1220** in the instrument base **1218** are not tangled during rotation. Accordingly, the parallelism of the axes of the drive outputs **1208**, the drive inputs **1220**, and the instrument shaft **1206** allows for the shaft rotation without tangling any control tendons.

FIG. **13** illustrates a medical instrument **1300** having an instrument based insertion architecture in accordance with some embodiments. The instrument **1300** (alternately referred to as a "surgical tool") can be coupled to any of the instrument drivers discussed herein above and, as illustrated, can include an elongated shaft **1302**, an end effector **1304** connected to the shaft **1302**, and a handle **1306** coupled to the shaft **1302**. The elongated shaft **1302** comprises a tubular member having a proximal portion **1308***a* and a distal portion **1308***b*. The elongated shaft **1302** comprises one or more channels or grooves **1310** along its outer surface and configured to receive one or more wires or cables **1312** therethrough. One or more cables **1312** thus run along an outer surface of the elongated shaft **1302**. In other embodiments, the cables **1312** can also run through the elongated shaft **1302**. Manipulation of the cables **1312** (e.g., via an instrument driver) results in actuation of the end effector **1304**.

The instrument handle **1306**, which may also be referred to as an instrument base, may generally comprise an attachment interface **1314** having one or more mechanical inputs **1316**, e.g., receptacles, pulleys or spools, that are designed to be reciprocally mated with one or more drive outputs on an attachment surface of an instrument driver.

In some embodiments, the instrument **1300** comprises a series of pulleys or cables that enable the elongated shaft **1302** to translate relative to the handle **1306**. In other words, the instrument **1300** itself comprises an instrument-based insertion architecture that accommodates insertion of the instrument **1300**, thereby minimizing the reliance on a robot arm to provide insertion of the instrument **1300**. In other embodiments, a robotic arm can be largely responsible for instrument insertion.

E. Controller.

Any of the robotic systems described herein can include an input device or controller for manipulating an instrument attached to a robotic arm. In some embodiments, the controller can be coupled (e.g., communicatively, electronically, electrically, wirelessly and/or mechanically) with an instrument such that manipulation of the controller causes a corresponding manipulation of the instrument e.g., via master slave control.

FIG. **14** is a perspective view of an embodiment of a controller **1400**. In the present embodiment, the controller **1400** comprises a hybrid controller that can have both impedance and admittance control. In other embodiments, the controller **1400** can utilize just impedance or passive control. In other embodiments, the controller **1400** can utilize just admittance control. By being a hybrid controller, the controller **1400** advantageously can have a lower perceived inertia while in use.

In the illustrated embodiment, the controller **1400** is configured to allow manipulation of two medical instruments, and includes two handles **1402**. Each of the handles **1402** is connected to a gimbal **1404**, and each gimbal **1404** is connected to a positioning platform **1406**.

As shown in FIG. **14**, each positioning platform **1406** includes a selective compliance assembly robot arm (SCARA) **1408** coupled to a column **1410** by a prismatic joint **1412**. The prismatic joints **1412** are configured to translate along the column **1410** (e.g., along rails **1414**) to allow each of the handles **1402** to be translated in the z-direction, providing a first degree of freedom. The SCARA arm **1408** is configured to allow motion of the handle **1402** in an x-y plane, providing two additional degrees of freedom.

In some embodiments, one or more load cells are positioned in the controller **1400**. For example, in some embodiments, a load cell (not shown) is positioned in the body of each of the gimbals **1404**. By providing a load cell, portions of the controller **1400** are capable of operating under admittance control, thereby advantageously reducing the perceived inertia of the controller **1400** while in use. In some embodiments, the positioning platform **1406** is configured for admittance control, while the gimbal **1404** is configured for impedance control. In other embodiments, the gimbal **1404** is configured for admittance control, while the positioning platform **1406** is configured for impedance control. Accordingly, for some embodiments, the translational or positional degrees of freedom of the positioning platform **1406** can rely on admittance control, while the rotational degrees of freedom of the gimbal **1404** rely on impedance control.

F. Navigation and Control.

Traditional endoscopy may involve the use of fluoroscopy (e.g., as may be delivered through a C-arm) and other forms of radiation-based imaging modalities to provide endoluminal guidance to an operator physician. In contrast, the robotic systems contemplated by this disclosure can provide for non-radiation-based navigational and localization means to reduce physician exposure to radiation and reduce the amount of equipment within the operating room. As used herein, the term "localization" may refer to determining and/or monitoring the position of objects in a reference coordinate system. Technologies such as pre-operative mapping, computer vision, real-time EM tracking, and robot command data may be used individually or in combination to achieve a radiation-free operating environment. In other cases, where radiation-based imaging modalities are still used, the pre-operative mapping, computer vision, real-time EM tracking, and robot command data may be used individually or in combination to improve upon the information obtained solely through radiation-based imaging modalities.

FIG. **15** is a block diagram illustrating a localization system **1500** that estimates a location of one or more elements of the robotic system, such as the location of the instrument, in accordance to an example embodiment. The localization system **1500** may be a set of one or more computer devices configured to execute one or more instructions. The computer devices may be embodied by a processor (or processors) and computer-readable memory in one or more components discussed above. By way of example and not limitation, the computer devices may be in the tower **112** shown in FIG. **1**, the cart **102** shown in FIGS. **1**-**3**B, the beds shown in FIGS. **4**-**9**, etc.

As shown in FIG. **15**, the localization system **1500** may include a localization module **1502** that processes input data **1504***a*, **1504***b*, **1504***c*, and **1504***d* to generate location data **1506** for the distal tip of a medical instrument. The location data **1506** may be data or logic that represents a location and/or orientation of the distal end of the instrument relative to a frame of reference. The frame of reference can be a frame of reference relative to the anatomy of the patient or to a known object, such as an EM field generator (see discussion below for the EM field generator).

The various input data **1504***a*-*d* are now described in greater detail. Pre-operative mapping may be accomplished through the use of the collection of low dose CT scans. Pre-operative CT scans are reconstructed into three-dimensional images, which are visualized, e.g. as "slices" of a cutaway view of the patient's internal anatomy. When analyzed in the aggregate, image-based models for anatomical cavities, spaces and structures of the patient's anatomy, such as a patient lung network, may be generated. Techniques such as center-line geometry may be determined and approximated from the CT images to develop a three-dimensional volume of the patient's anatomy, referred to as model data **1504***a* (also referred to as "preoperative model data" when generated using only preoperative CT scans). The use of center-line geometry is discussed in U.S. patent application Ser. No. 14/523,760, the contents of which are herein incorporated in its entirety. Network topological models may also be derived from the CT-images, and are particularly appropriate for bronchoscopy.

In some embodiments, the instrument may be equipped with a camera to provide vision data **1504***b*. The localization module **1502** may process the vision data **1504***b* to enable one or more vision-based location tracking. For example, the preoperative model data may be used in conjunction with the vision data **1504***b* to enable computer vision-based tracking of the medical instrument (e.g., an endoscope or an instrument advance through a working channel of the endoscope). For example, using the preoperative model data **1504***a*, the robotic system may generate a library of expected endoscopic images from the model based on the expected path of travel of the endoscope, each image linked to a location within the model. Intra-operatively, this library may be referenced by the robotic system in order to compare real-time images captured at the camera (e.g., a camera at a distal end of the endoscope) to those in the image library to assist localization.

Other computer vision-based tracking techniques use feature tracking to determine motion of the camera, and thus the endoscope. Some features of the localization module **1502** may identify circular geometries in the preoperative model data **1504***a* that correspond to anatomical lumens and track the change of those geometries to determine which anatomical lumen was selected, as well as the relative rotational and/or translational motion of the camera. Use of a topological map may further enhance vision-based algorithms or techniques.

Optical flow, another computer vision-based technique, may analyze the displacement and translation of image pixels in a video sequence in the vision data **1504***b* to infer camera movement. Examples of optical flow techniques may include motion detection, object segmentation calculations, luminance, motion compensated encoding, stereo disparity measurement, etc. Through the comparison of multiple frames over multiple iterations, movement and location of the camera (and thus the endoscope) may be determined.

The localization module **1502** may use real-time EM tracking to generate a real-time location of the endoscope in a global coordinate system that may be registered to the patient's anatomy, represented by the preoperative model. In EM tracking, an EM sensor (or tracker) comprising of one or more sensor coils embedded in one or more locations and orientations in a medical instrument (e.g., an endoscopic tool) measures the variation in the EM field created by one or more static EM field generators positioned at a known location. The location information detected by the EM sensors is stored as EM data **1504***c*. The EM field generator (or transmitter), may be placed close to the patient to create a low intensity magnetic field that the embedded sensor may detect. The magnetic field induces small currents in the sensor coils of the EM sensor, which may be analyzed to determine the distance and angle between the EM sensor and the EM field generator. These distances and orientations may be intra-operatively "registered" to the patient anatomy (e.g., the preoperative model) in order to determine the geometric transformation that aligns a single location in the coordinate system with a position in the pre-operative model of the patient's anatomy. Once registered, an embedded EM tracker in one or more positions of the medical instrument (e.g., the distal tip of an endoscope) may provide real-time indications of the progression of the medical instrument through the patient's anatomy.

Robotic command and kinematics data **1504***d* may also be used by the localization module **1502** to provide localization data **1506** for the robotic system. Device pitch and yaw resulting from articulation commands may be determined during pre-operative calibration. Intra-operatively, these calibration measurements may be used in combination with known insertion depth information to estimate the position of the instrument. Alternatively, these calculations may be analyzed in combination with EM, vision, and/or topological modeling to estimate the position of the medical instrument within the network.

As FIG. **15** shows, a number of other input data can be used by the localization module **1502**. For example, although not shown in FIG. **15**, an instrument utilizing shape-sensing fiber can provide shape data that the localization module **1502** can use to determine the location and shape of the instrument.

The localization module **1502** may use the input data **1504***a-d* in combination(s). In some cases, such a combination may use a probabilistic approach where the localization module **1502** assigns a confidence weight to the location determined from each of the input data **1504***a-d*. Thus, where the EM data **1504***c* may not be reliable (as may be the case where there is EM interference) the confidence of the location determined by the EM data **1504***c* can be decrease and the localization module **1502** may rely more heavily on the vision data **1504***b* and/or the robotic command and kinematics data **1504***d*.

As discussed above, the robotic systems discussed herein may be designed to incorporate a combination of one or more of the technologies above. The robotic system's computer-based control system, based in the tower, bed and/or cart, may store computer program instructions, for example, within a non-transitory computer-readable storage medium such as a persistent magnetic storage drive, solid state drive, or the like, that, upon execution, cause the system to receive and analyze sensor data and user commands, generate control signals throughout the system, and display the navigational and localization data, such as the position of the instrument within the global coordinate system, anatomical map, etc.

2. Description

Insertion Coupled Inserting Surgical Instrument

FIG. **16** is a side view of an example surgical tool **1600** that may incorporate some or all of the principles of the present disclosure. The surgical tool **1600** may be similar in some respects to any of the surgical tools and medical instruments described above with reference to FIGS. **11-13** and, therefore, may be used in conjunction with a robotic surgical system, such as the robotically-enabled systems **100**, **400**, and **900** of FIGS. **1-9**C. As illustrated, the surgical tool **1600** includes an elongated shaft **1602**, an end effector **1604** arranged at the distal end of the shaft **1602**, and an articulable wrist **1606** (alternately referred to as a "wrist joint") that interposes and couples the end effector **1604** to the distal end of the shaft **1602**. In some embodiments, the wrist **1606** may be omitted, without departing from the scope of the disclosure.

The terms "proximal" and "distal" are defined herein relative to a robotic surgical system having an interface configured to mechanically and electrically couple the surgical tool **1600** to a robotic manipulator. The term "proximal" refers to the position of an element closer to the robotic manipulator and the term "distal" refers to the position of an element closer to the end effector **1604** and thus closer to the patient during operation. Moreover, the use of directional terms such as above, below, upper, lower, upward, downward, left, right, and the like are used in relation to the illustrative embodiments as they are depicted in the figures, the upward or upper direction being toward the top of the corresponding figure and the downward or lower direction being toward the bottom of the corresponding figure.

The surgical tool **1600** can have any of a variety of configurations capable of performing one or more surgical functions. In the illustrated embodiment, the end effector **1604** comprises a tissue grasper capable of grasping onto tissue or vessels. The end effector **1604** includes opposing jaws **1608**, **1610** configured to move (articulate) between open and closed positions. Alternatively, the end effector **1604** may comprise other types of instruments with opposing jaws such as, but not limited to, a surgical stapler, a vessel sealer, surgical scissors, clip appliers, needle drivers, a babcock including a pair of opposed grasping jaws, bipolar jaws (e.g., bipolar Maryland grasper, forceps, a fenestrated grasper, etc.), etc.

One or both of the jaws **1608**, **1610** may be configured to pivot to actuate the end effector **1604** between open and closed positions. In the illustrated example, both jaws **1608**, **1610** simultaneously move to pivot the jaws **1608**, **1610** between an open, unclamped position and a closed, clamped position and are thus referred to as "bifurcating" jaws. In other embodiments, however, only one of the jaws **1608**, **1610** may be rotatable (pivotable) relative to the opposing jaw to actuate the end effector **1604** between the open and closed positions.

The wrist **1606** enables the end effector **1604** to articulate (pivot) relative to the shaft **1602** and thereby position the end effector **1604** at various desired orientations and locations relative to a surgical site. In the illustrated embodiment, the wrist **1606** is designed to allow the end effector **1604** to pivot (swivel) left and right relative to a longitudinal axis A_1 of the shaft **1602**. In other embodiments, however, the wrist **1606** may be designed to provide multiple degrees of freedom, including one or more translational variables (i.e., surge, heave, and sway) and/or one or more rotational variables (i.e., Euler angles or roll, pitch, and yaw). The translational and rotational variables describe the position and orientation of a component of a surgical system (e.g., the end effector **1604**) with respect to a given reference Cartesian frame. "Surge" refers to forward and backward translational movement, "heave" refers to translational movement up and down, and "sway" refers to translational movement left and right. With regard to the rotational terms, "roll" refers to tilting side to side, "pitch" refers to tilting forward and backward, and "yaw" refers to turning left and right.

The end effector **1604** is depicted in FIG. **16** in the unarticulated position where the longitudinal axis of the end effector **1604** is substantially aligned with the longitudinal axis A_1 of the shaft **1602**, such that the end effector **1604** is at a substantially zero angle relative to the shaft **1602**. In the articulated position, the longitudinal axis of the end effector **1604** would be angularly offset from the longitudinal axis A_1 such that the end effector **1604** would be oriented at a non-zero angle relative to the shaft **1602**.

Still referring to FIG. **16**, the surgical tool **1600** may include a drive housing or "handle" **1612**, and the shaft **1602** extends longitudinally through the handle **1612**. The handle **1612** houses an actuation system designed to facilitate articulation of the wrist **1606** and actuation (operation) of the end effector **1604** (e.g., clamping, firing, rotation, articulation, energy delivery, etc.). As discussed in more detail below, the handle **1612** may include and otherwise house a plurality of drive gears that are actuatable to axially move (translate) a plurality of sliding rack gears nested within corresponding longitudinal channels defined along all or a portion of the shaft **1602**. In some embodiments, the distal end of each rack gear is attached to distal cables that extend to the end effector **1604** or the wrist **1606** at the distal end of the shaft **1602**, and the proximal end of the each rack gear is attached to proximal cables that extend to a proximal end of the shaft **1602**. In other embodiments, however, the distal end of one or more of the rack gears may be directly attached to portions of the end effector **1604** or the wrist **1606** to enable a push-pull translation action (e.g., in the case of push/pull rods).

Selective actuation of one or more of the sliding rack gears, for example, may cause the end effector **1604** to articulate (pivot) relative to the shaft **1602** at the wrist **1606**. Selective actuation of one or more additional sliding rack gears may cause the end effector **1604** to actuate (operate). Actuating the end effector **1604** depicted in FIG. **16** may entail closing and/or opening the jaws, **1608**, **1610** and thereby enabling the end effector **1604** to grasp (clamp) onto tissue. In embodiments where the end effector **1604** comprises a vessel sealer, once tissue is grasped or clamped between the opposing jaws **1608**, **1610**, actuating the end effector **1604** may further include "firing" the end effector **1604**, which may refer to causing a cutting element or knife (not visible) to advance distally within a slot or "guide track" defined in the first jaw **1610**. As it moves distally within the guide track, the knife transects tissue grasped between the opposing jaws **1608**, **1610**.

The actuation system housed within the handle **1612** may further be designed to move the shaft **1602** relative to (through) the handle **1612** and along the longitudinal axis A_1. More particularly, the actuation system may also include a drive gear actuatable to engage a rack gear defined on the shaft **1602** itself; i.e., a "shaft rack gear". When the drive gear drives against the shaft rack gear, the shaft **1602** along with the nested sliding rack gears are moved (translated) axially relative to the handle **1612**, as indicated by the arrows B. Moreover, as the shaft **1602** moves, the end effector **1604** and the wrist **1606** are simultaneously advanced or retracted, depending on the driving direction.

The handle **1612** may be operatively coupled to an instrument driver **1614** of a robotic surgical system. The instrument driver **1614** may be similar in some respects to the instrument drivers **1102**, **1200** of FIGS. **11** and **12**, respectively, and therefore may be best understood with reference thereto. Similar to the instrument drivers **1102**, **1200**, for example, the instrument driver **1614** may be mounted to or otherwise positioned at the end of a robotic arm (not shown) and is designed to provide the motive forces required to operate the surgical tool **1600**. Unlike the instrument drivers **1102**, **1200**, however, the shaft **1602** of the surgical tool **1600** extends through and penetrates the instrument driver **1614**.

The handle **1612** includes a plurality of rotatable drive inputs (not visible) that can be driven by a corresponding plurality of drive outputs (not visible) of the instrument driver **1614**. Each drive input is actuatable to independently drive (actuate) various portions of the actuation system housed within the handle **1612** and thereby operate the surgical tool **1600**, as generally described above. The number of drive outputs will generally be the same as the number of drive inputs, but the instrument driver **1614** can have additional drive outputs, without departing from the scope of the disclosure. Movement (rotation) of a given drive output correspondingly moves (rotates) an associated drive input and thereby operates the surgical tool **1600**. Actuation of the drive inputs drives the various drive gears mentioned above, which may be arranged to drive the corresponding rack gears, and moving the rack gears causes the end effector **1604** to articulate and/or actuate (operate) and the shaft **1602** to axially move (translate) relative to the handle **1612**.

In the illustrated embodiment, a decoupler subassembly or "decoupler" **1616** is arranged between and otherwise interposes the handle **1612** and the instrument driver **1614**. Among other functions described herein, the decoupler **1616** transfers torque from the drive outputs of the instrument driver **1614** to the drive inputs of the handle **1612**, and thus operates as a type of torque transfer apparatus. Once the drive outputs are operatively and indirectly coupled to corresponding drive inputs via the decoupler **1616**, rotational torque may be transferred from the drive outputs to the corresponding drive inputs through (via) the decoupler **1616**, thus being able to operate the handle **1612**. As discussed in more detail below, the decoupler **1616** may also be advantageous in transferring insertion motion (e.g., movement of the shaft **1602**) to all the drive inputs, thus allowing one robot motor to control insertion of the surgical tool **1600**, while allowing the other motors of the instrument driver **1614** to drive the sliding rack gears independent of insertion.

For procedures that require a sterile environment, an instrument sterile adapter **1618** (shown in dashed lines) connected to a sterile drape may be incorporated into the surgical tool **1600** upon mounting to the instrument driver **1614**. Depending on design or application, the decoupler **1616** can form part of the instrument driver **1614**, the sterile adaptor **1618**, the handle **1612**, or a combination of the foregoing. Since it has many complex parts, it may be advantageous for the decoupler **1616** to not be integrated with the handle **1612**, which is commonly the disposable portion of the surgical tool **1600**. This reduces the cost of the surgical tool **1600** and the quantity of decouplers **1616** needed per procedure. In some embodiments, the decoupler **1616** could be integrated into the sterile adaptor **1618**, as shown in FIG. **16**. The sterile adaptor **1618** can be designed to have a longer lifetime than the surgical tool **1600** and fewer are needed per procedure, thus, moving the decoupler **1616** can reduce the cost of the device. Moreover, this has the benefit that the instrument driver **1614** remains unchanged, which is important for driving non-inserting tools, such as endoscopy tools.

In other embodiments, however, the decoupler **1616** may be integrated into and otherwise form part of the instrument driver **1614**. In such embodiments, the decoupler **1616** is never disposed of and thus entails a one-time cost for the user. However, this may create an issue when trying to drive non-inserting instruments. In such scenarios, the decoupler **1616** may be configured such that each motor of the instrument driver **1614** has two outputs; one output would be the insertion-decoupled motion while the other output is not. The instrument driver **1614** would then be designed to selectively engage the appropriate outputs. This may be helpful for instruments where both coupled and uncoupled motions are desired. For example, a suction irrigator with valves driven by the inputs could operate with coupled motions for the wrist **1606** and uncoupled motion for the valves that are not inserting with the tool shaft **1602**.

In yet other embodiments, the decoupler **1616** could be a stand-alone separable assembly that can attach to the instrument driver **1614** as desired. In such embodiments, the decoupler **1616** could be designed to be mounted below the sterile barrier **1618**, or outside of it. The stand-alone version of the decoupler **1616** may be designed and otherwise capable of being sterilized for multiple procedures (e.g., **100** uses), and multiple different tools of single or multiple use design could be attached on top of it.

Lastly, in some embodiments, the surgical tool **1600** may include a tailpiece **1620** arranged at the proximal end of the shaft **1602**. The tailpiece **1620**, its operation, and various embodiments will be described in more detail below. Briefly, however, the tailpiece **1620** may comprise a mechanical device that provides a means for manually controlling the end effector **1604** and/or the wrist **1606**. The tailpiece **1620** can be designed to hold a mechanism referred to herein as a "pantograph" or a "pantograph button". The pantograph essentially acts as a mirror to the wrist **1606** ensuring that the system maintains tension in the surgical tool **1600** when disconnected from the instrument driver **1614** (e.g., the robot). As described herein, however, the tailpiece **1620** can be provided in various forms and still perform essentially the same function, without departing from the scope of the present disclosure. In at least one embodiment, as described herein, the pantograph can receive a separate input for manual activation, such as a slider that allows the user to manually actuate one of the degrees of freedom of the wrist **1606**, such as jaw opening.

FIGS. **17**A and **17**B are isometric and bottom views, respectively, of an example actuation system **1700**, according to one or more embodiments. The actuation system **1700** may be housed within the handle **1612** (FIG. **16**) and operable to actuate (operate) the end effector **1604** (FIG. **16**), articulate the wrist **1606** (FIG. **16**), and axially move (translate) the shaft **1602** relative to (i.e., through) the handle **1612**. Several parts and structural elements of the handle **1612**, such as the outer housing, are omitted from FIGS. **17**A-**17**B to enable ease of viewing of the actuation system **1700** for purposes of discussion.

As illustrated, the actuation system **1700** may include a plurality of rotatable drive inputs **1702**. As discussed above, the drive inputs **1702** can be driven by a corresponding plurality of drive outputs of the instrument driver **1614**. In embodiments that include the decoupler **1616**, however, a transmission differential or differential assembly provided by the decoupler **1616** will axially interpose corresponding drive inputs and drive outputs, such that any rotational torque provided by a given drive output will be transferred to the corresponding drive input via the corresponding transmission differential.

Rotating a given drive input **1702** will cause a corresponding drive gear **1704** to rotate (operate), and each drive gear **1704** may be arranged to drive against an adjacent sliding rack gear **1706**. Each sliding rack gear **1706** is movably nested within a corresponding longitudinal channel **1708** defined along all or a portion of the shaft **1602**. In the illustrated embodiment, the drive gears **1704** are depicted as spur gears with teeth matable with corresponding teeth defined on the opposing sliding rack gear **1706**. Accordingly, the drive gears **1704** may alternatively be referred to herein as "spur" gears, and operation of the spur gears **1704** and corresponding rack gears **1706** may be similar to rack-and-pinion operation. Driving a given sliding rack gear **1706** will urge the sliding rack gear **1706** to move (slide) within the corresponding longitudinal channel **1708**, and moving the rack gears **1706** within the channels **1708** may actuate (operate) the end effector **1604** (FIG. **16**) and/or articulate the wrist **1606** (FIG. **16**).

The rack gears **1706** may prove advantageous over cable-based systems since they have a much larger cross-sectional area than cables, so their stiffness is much higher than cables. Consequently, the performance of the tool can be more robust and predictable. Moreover, rack gears **1706** enable the driving of instrument end effectors that do not use cables, such as push/pull rods that are often used in certain designs, such as vessel sealers or staplers.

One of the drive inputs, shown as drive input **1702**_a_, may be configured to cause a corresponding shaft drive gear **1704**_a_ to rotate (operate), and the shaft drive gear **1704**_a_ may be arranged to drive against an adjacent shaft rack gear **1710**. Accordingly, the drive input **1702**_a_ may be referred to herein as the "shaft" drive input **1702**_a_. As illustrated, the shaft rack gear **1710** may form part of and may otherwise be defined along all or a portion of the outer surface of the shaft **1602**. Driving against the shaft rack gear **1710** will cause the shaft **1602** to move (translate) axially relative to (i.e., through) the handle **1612** (FIG. **16**).

Movement of the shaft **1602** via actuation of the shaft drive input **1702**_a_ is one reason why the decoupler **1616** (FIG. **16**) may be advantageous or even needed in the surgical tool **1600** (FIG. **16**). As the shaft drive gear **1704**_a_ is actuated (driven) to move the shaft **1602**, the remaining drive gears **1704** must also be driven or the sliding rack gears **1706** will be inadvertently moved, thus affecting articulation, end effector operation, etc. This would require all motors in the instrument driver **1614** (FIG. **16**) to operate concurrently whenever the shaft **1602** is axially translated. Moreover, if the shaft drive gear **1704***a* is actuated (driven) without driving any of the remaining drive gears **1704**, the shaft **1602** would bind against opposing forces or would inadvertently move the wrist **1606** (FIG. **16**) or actuate the end effector **1604** (FIG. **16**). As described in more detail below, the differential assemblies included in the decoupler **1616** may be configured to transfer insertion motion (e.g., movement of the shaft **1602**) to all the drive inputs **1702**, thus allowing one robot motor to control insertion of the surgical tool **1600** (FIG. **16**), while allowing the other motors of the instrument driver **1614** to drive the sliding rack gears **1706** independent of insertion. In addition to applying insertion motion to all inputs, the decoupler **1616** may be designed to cancel out reaction loads, such that tensions applied to wrist actuators are not realized as reaction torques on the insertion driver.

In some embodiments, a gear train including one or more intermediate gears may interpose each drive input **1702** and the corresponding drive gear **1704**, such that rotating the drive input **1702** will correspondingly rotate the corresponding drive gear **1704** via the interposing gear train. A similar type of gear train may interpose the shaft drive input **1702***a* and the shaft drive gear **1704***a*. Those skilled in the art will readily appreciate that this gear train can assume a variety of configurations. In the illustrated embodiment, for example, the gear train includes mating helical gears that transition the rotational axis of the drive inputs **1702**, **1702***a* 90° to enable the drive gears **1704** and the shaft drive gear **1704***a* to properly engage the rack gears **1706** and the shaft rack gear **1710**, respectively. In at least one embodiment, however, the gear train may be omitted and rotating the drive inputs **1702**, **1702***a* may directly drive the adjacent rack gear **1706**, **1710**, without departing from the scope of the disclosure.

FIG. **17**C is another example of a gear train that may be used to transfer rotational torque from the drive inputs **1702**, **1702***a* to the rack gears **1706** or the shaft rack gear **1710**, respectively. In the illustrated embodiment, the drive input **1702**, **1702***a* may include a bevel drive gear **1712** arranged to drive a bevel driven gear **1714**, and the bevel driven gear **1714** may further include a spur gear **1716** arranged to drive the drive gear **1704**, **1704***a*. The intermeshed bevel gears **1712**, **1714** facilitates the directional change required in the handle **1612** (FIG. **16**). Through the depicted gear train arrangement, rotation of the drive input **1702**, **1702***a* will correspondingly move the rack gears **1706** or the shaft rack gear **1710**. In other embodiments, other known gearing mechanisms may be utilized or combined in any number of configurations and dimensioned for optimal torque and/or speed outputs. In at least one embodiment, for example, the gear train may incorporate worm gears or a combination of bevel and spur gears.

FIGS. **18**A-**18**D are schematic diagrams of example operation of a portion of the actuation system **1700**, according to one or more embodiments. As mentioned above, the actuation system **1700** is housed within the handle **1612** and includes the drive gears **1704** rotatable (operable) to drive against adjacent sliding rack gears **1706**. As also mentioned above, the rack gears **1706** are nested within corresponding longitudinal channels **1708** defined along all or a portion of the shaft **1602**. As depicted, the drive and rack gears **1704**, **1706** provide or define meshing gear teeth that allows the drive gears **1704** to drive the rack gears **1706** longitudinally along the length of the shaft **1602**. A distal structure **1802***a* (shown in dashed lines) is provided at the distal end of the shaft **1602** and is representative of the end effector **1604**, the wrist **1606** (FIG. **16**), or another mechanism that may be driven or operated through operation of the actuation system **1700**. Similarly, a proximal structure **1802***b* (shown in dashed lines) is positioned at the proximal end of the shaft **1602** and is representative of the tailpiece **1620** (FIG. **16**) or another mechanism that may be driven or operated through operation of the actuation system **1700**.

In some embodiments, a distal cable **1804***a* may be attached to the distal end of each rack gear **1706**, and a proximal cable **1804***b* may be attached to the proximal end of each rack gear **1706**. In the illustrated embodiment, the distal cable **1804***a* extends from one of the rack gears **1706**, wraps around a distal pulley **1806***a*, and is attached to an opposing rack gear **1706**. Similarly, the proximal cable **1804***b* extends from one of the rack gears **1706**, wraps around a proximal pulley **1806***b*, and is attached to the opposing rack gear **1706**. The cables **1804***a,b* can be made from a variety of materials including, but not limited to, a metal (e.g., tungsten, stainless steel, nitinol, etc.) a polymer (e.g., ultra-high molecular weight polyethylene), a synthetic fiber (e.g., KEVLAR®, VECTRAN®, etc.), an elastomer, or any combination thereof.

The coupled assembly of the rack gears **1706**, the distal and proximal cables **1804***a,b*, and the distal and proximal pulleys **1806***a,b* completes or provides a cable loop, which allows the rack gears **1706** to operate in an antagonistic relationship where movement of one rack gear **1706** in one longitudinal direction can cause the other rack gear to move in the opposite direction and thereby manipulate the angular position of the distal structure **1802***a* (e.g., the end effector **1604** or the wrist **1806**). In this example, selective actuation of the drive gears **1704** can cause the end effector **1604** (FIG. **16**) to open or close, or may alternatively cause the wrist **1606** (FIG. **16**) to articulate.

In FIG. **18**B, for example, actuation (articulation) of the wrist **1606** may be accomplished by rotating the drive gears **1704** in the same direction, as indicated by the arrows C. This allows the rack gears **1706** to antagonistically operate and cause the distal structure **1802***a* to move (rotate) in the direction D. Alternatively, and depending on how the distal pulley **1806***a* is configured, rotating the drive gears **1704** in the same direction C may also cause one of the jaws **1608**, **1610** (FIG. **16**) of the end effector **1604** to open or close.

In FIG. **18**C, axial movement of the shaft **1602** (e.g., insertion of the instrument) may be accomplished by rotating the drive gears **1704** in opposite directions, as shown by the arrows C and E. In this scenario, the shaft **1602** and the rack gears **1706** will be moved (translated) along its axis through the handle **1612** in the direction F. As will be appreciated, the configuration of the actuation system **1700** may be altered and otherwise modified to facilitate pitch, yaw, and jaw actuation of the distal structure **1802***a*.

This concept extends to more complicated wrists (e.g., the wrist **1606** of FIG. **16**) that have more than one degree of freedom and follows N+1 rules where there are N+1 cables **1804***a,b* for N degrees of freedom in the wrist **1606**. The handle **1612** would contain N+1 drive gears **1704** that each drive a rack gear **1706**. The proximal structure **1802***b* at the proximal end of the shaft **1602** would also change to accommodate a wrist with more degrees of freedom. For instance, an example needle driver wrist may be driven by four cables **1804***a,b*, so the instrument would have four drive gears **1704** and four rack gears **1706**. Additionally, this design could support more wrist concepts, such as a **2**N wrist, and the proximal structure **1802***b* would have to change to appropriately mirror the wrist configuration.

In FIG. **18**D, the actuation system **1700** is shown with the shaft drive gear **1704***a* arranged to drive against the adjacent shaft rack gear **1710**, where the teeth of the shaft rack gear **1710** are defined along all or a portion of the shaft **1602**. In some embodiments, as discussed above, driving against the shaft rack gear **1710** will cause the shaft **1602** to move (translate) axially relative to (i.e., through) the handle **1612**. In other embodiments, however, driving against the shaft rack gear **1710** may help adjust tension in the cables (e.g., the distal cable **1804***a*). More specifically, in order to facilitate on-robot tensioning, each of the drive gears **1704** (only one shown) may be rotated in the direction G, which places the distal cables **1804***a* (only one shown) in tension. The generated tension may then be resolved by actuating the shaft drive gear **1704***a* in the direction E, which urges the shaft **1602** in the direction F. Consequently, the insertion degree of freedom may also be used to place tension on the robot, and, theoretically, all backlash in the system is now taken up when the robot tensions the tool.

In this scenario, portions of the shaft **1602** and the shaft rack gear **1710** located distal to the handle **1612** (i.e., to the left of the handle **1612** in FIG. **18**D) will be under load when the robot puts tension in the tool. More specifically, portions of the shaft **1602** distal to the handle **1612** will be in compression and portions of the rack gear **1706** distal to the handle **1612** will be in tension. The remaining portions of the shaft **1602** and the rack gear **1706** proximal to the handle **1612**, however, will not be loaded. This is in contrast to cable-based surgical tool designs, where the loaded regions extend the entire length of the tool shaft with the cable in tension and the tool shaft in compression. Here, the actuation system **1700** results in a shorter loading path, which may be advantageous in generating smaller amounts of deflection at the wrist **1606** (FIG. **16**) because the potential "spring" length is shorter. This may also result in the deflection length being dependent on the insertion length, but the input motion may be software adjusted based on the insertion length.

This architecture may further prove advantageous in removing backlash from insertion of the surgical tool **1600** (FIG. **16**) and the sterile adaptor **1618** (FIG. **16**). In this architecture, tension in the cables extending through the wrist **1606** (FIG. **16**) may be able to react against the compressive load through the shaft **1602**. This means that the gear trains located in the handle **1612** and the decoupler **1616** (FIG. **16**) are all preloaded and all backlash in the decoupler **1616** and the surgical tool **1600** are removed. If the decoupler **1616** is located in the instrument driver **1614** (FIG. **16**), however, the driver motors can be attached directly to the drive inputs provided on the decoupler **1616**, all components between the wrist **1606** and the motors of the instrument driver **1614** are preloaded, and all backlash is theoretically eliminated.

Additionally, this architecture allows for more complicated components to be moved or designed into the instrument driver **1614** (FIG. **16**). If the decoupler **1616** (FIG. **16**) is integrated into the instrument driver **1614** or the sterile adaptor **1618** (FIG. **16**), the surgical tool **1600** (FIG. **16**) would contain fewer parts than a cable-differential design. As will be appreciated, this will help drive down the cost of the disposable component of the system, reduce manufacturing time, and lower the number of failure points in the instrument.

FIG. **19** is an isometric view of one example of the tailpiece **1620**, according to one or more embodiments. As mentioned above, the tailpiece **1620** may be alternately referred to as a "pantograph" or "pantograph button," and may provide a means for maintaining tension in the surgical tool **1600** (FIG. **16**) when the instrument is detached from the instrument driver **1614** (FIG. **16**). The pantograph **1620** may additionally provide a way to manually control the end effector **1604** (FIG. **16**) and/or the wrist **1606** (FIG. **16**).

In the illustrated embodiment, the tailpiece **1620** includes a housing **1902** arranged at the distal end of the shaft **1602** (shown in dashed lines). A manual actuation device may be mounted to the housing **1902**. In this embodiment, the manual actuation device includes first and second buttons **1904***a* and **1904***b* pivotably coupled to the housing **1902** and laterally offset from each other. Each button **1904***a,b* may be coupled to a corresponding one of the proximal cables **1804***b*. In the illustrated configuration, manipulation of the buttons **1904***a,b* may cause the jaws **1608**, **1610** (FIG. **16**) to open and close. More specifically, when the first button **1904***a* is depressed, the jaws **1608**, **1610** open, and when the second button **1904***b* is depressed, the jaws **1608**, **1610** close. The architecture of the pantograph **1620** could be altered, however, such that manipulation of the buttons **1904***a,b* may cause the wrist **1606** (FIG. **16**) to articulate, without departing from the scope of the disclosure.

FIGS. **20**A and **20**B depict example operation of the tailpiece (pantograph) **1620** of FIG. **19**, according to one or more embodiments. Each of FIGS. **20**A-**20**B include two images of the pantograph **1620**, the left image being a partial, cross-sectional view, and the right image including portions in phantom (dashed lines) to enable viewing of various internal components. As illustrated, the first and second buttons **1904***a,b* may be coupled to a toggle or "rocker" **2002** pivotably coupled to the housing **1902** such that pressing down on one button **1904***a,b* simultaneously causes the other button **1904***a,b* to pivot upward.

First and second proximal pulleys **2004***a* and **2004***b* may be rotatably mounted to the first and second buttons **1904***a,b* and are axially movable therewith during actuation of the pantograph **1620** and within the housing **1902**. The proximal pulleys **2004***a,b* may be similar to the proximal pulley **1806***b* of FIGS. **18**A-**18**C and thus have corresponding proximal cables **2006***a* and **2006***b* extending (wrapped) thereabout, where the proximal cables **2006***a,b* are similar to the proximal cable **1804***b* of FIGS. **18**A-**18**C.

As mentioned above, the purpose of the pantograph **1620** is to maintain tension in the surgical tool **1600** (FIG. **16**) when disconnected from the instrument driver **1614** (FIG. **16**), but additionally, to provide a way to manually control the end effector **1604** (FIG. **16**) and/or the wrist **1606** (FIG. **16**). The pantograph **1620** ensures that cable length is conserved within the surgical tool **1600**, which prevents the cables **2006***a,b* from derailing off the pulleys **2004***a,b* (also prevents the distal cables **1804***a* of FIGS. **18**A-**18**C from derailing off the distal pulleys **1806***a* of FIGS. **18**A-**18**C). The pantograph **1620** maintains tension in the surgical tool **1600** by completing the cable loops and conserving cable length.

In the illustrated embodiment, manually depressing the first button **1904***a* may cause the jaws **1608**, **1610** (FIG. **16**) to open, and manually depressing the second button **1904***b* may cause the jaws **1608**, **1610** to close. The buttons **1904***a,b* are pivotably constrained together by the rocker **2002** such that if one button **1904***a,b* is pressed down, the opposite button **1904***a,b* correspondingly moves up with the same axial displacement. Moreover, since the pulleys **2004***a,b* are coupled to the buttons **1904***a,b*, as one button **1904***a,b* is pressed down, the corresponding pulley **2004***a,b* also moves down, and the opposing button **1904***a,b* and its corresponding pulley **2004***a,b* moves up with the same displacement. Consequently, the net cable length of the cables **2006**_a,b_ remains the same because the two pulleys **2004**_a,b_ have the same displacement, but the change in length of each pair changes, which causes movement of the jaws **1608**, **1610**.

FIG. **21** is an enlarged side view of the tailpiece (pantograph) **1620** of FIG. **19**, according to one or more embodiments. The pantograph **1620** can also simplify the process of tensioning the surgical tool **1600** (FIG. **16**). In the illustrated embodiment, for example, the housing **1902** is movably mounted to the shaft **1602** adjacent a tensioning nut **2102** threaded to the proximal end of the shaft **1602**. Rotating the tensioning nut **2102** may apply an axial load on the bottom of the housing **1902**, which may correspondingly extend the cable paths and thus tension the cables **2006**_a,b_ (FIGS. **20**A-**20**B) in the system. Accordingly, pushing against the housing **1902** with the tensioning nut **2102** applies tension equally to all cables **1804**_a,b_ (FIGS. **18**A-**18**C) in the system.

FIG. **22** is a side view of the surgical tool **1600**, according to one or more additional embodiments. The tailpiece (pantograph) **1620** arranged at the proximal end of the shaft **1602** may further prove advantageous in converting the surgical tool **1600** into a type of manual laparoscopic surgical tool. More specifically, a manual accessory **2202** may be mounted to or otherwise secured to the tailpiece **1620**. In the illustrated embodiment, for instance, the manual accessory may include ergonomic features, such as opposing handles **2204** and finger holes **2206**, that allow a user to operate the manual accessory **2202** and thereby manually operate at least one of the buttons **1904**_a,b_ to control the end effector **1604** (FIG. **16**) or the wrist **1606** (FIG. **16**). In at least one embodiment, the manual accessory **2202** may be used to lock the wrist **1606** so manual actuation of the pantograph **1620** only articulates the jaws **1608**, **1610** (FIG. **16**) open and closed.

FIGS. **23**A and **23**B are isometric and bottom views, respectively, of one example of the decoupler **1616** of FIG. **16**, according to one or more embodiments. As discussed above, the decoupler **1616** may interpose the handle **1612** (FIG. **16**) and the instrument driver **1614** (FIG. **16**), and may otherwise operate to transfer torque from the drive outputs of the instrument driver **1614** to the drive inputs of the handle **1612**. The architecture of the decoupler **1616** further allows for the transfer of insertion motion (e.g., movement of the shaft **1602**) to all the drive inputs of the handle **1612**, thus allowing one robot motor from the instrument driver **1614** to control insertion of the surgical tool **1600**, while allowing the other driver motors to drive the sliding rack gears independent of insertion.

As best seen in FIG. **23**A, the decoupler **1616** may include a first or "upper" flange **2302**_a_ and a second or "lower" flange **2302**_b_ axially offset from the upper flange **2302**_a_. Concentrically aligned central apertures **2303** are defined in each flange **2302**_a,b_ and through which the shaft **1602** (FIG. **16**) can extend. The flanges **2302**_a,b_ may be operatively coupled with one or more columns **2304** that extend between the flanges **2302**_a,b_. In FIG. **23**B, the lower flange **2302**_b_ and the columns **2304** are omitted to enable viewing of the internal components of the decoupler **1616** from a bottom perspective.

The decoupler **1616** includes a plurality of differential assemblies **2306** rotatably mounted between the upper and lower flanges **2302**_a,b_. While five differential assemblies **2306** are depicted in FIG. **23**A-**23**B, more or less than five may be included in the decoupler **1616**, without departing from the scope of the disclosure. As best seen in FIG. **23**B, each differential assembly **2306** includes a differential input **2308**, which is matable with a corresponding one of the drive outputs of the instrument driver **1614** (FIG. **16**); each motor in the instrument driver **1614** drives one of the differential assemblies **2306**. As illustrated, each differential input **2308** may define a receptacle that defines splines, protrusions, or other structural features designed to mate with corresponding features of the drive outputs of the instrument driver **1614**, or vice versa. Once properly mated, the differential inputs **2308** will share axes of rotation with the corresponding drive outputs of the instrument driver **1614** to allow the transfer of rotational torque from the drive output to the corresponding differential input **2308**.

As best seen in FIG. **23**A, each differential assembly **2306** may also include a differential output **2310**, which is matable with a corresponding one of the drive inputs **1702** (FIGS. **17**A-**17**B) of the actuation system **1700** (FIGS. **17**A-**17**B). As illustrated, each differential output **2310** may define splines, protrusions, or other structural features designed to mate with corresponding receptacles of the drive inputs **1702**, or vice versa. Once properly mated, the drive inputs **1702** will share axes of rotation with a corresponding differential output **2310** to allow rotational torque from the differential output **2310** to be transferred to the corresponding drive inputs **1702**. Accordingly, once the decoupler **1616** is properly installed between the handle **1612** (FIG. **16**) and the instrument driver **1614** (FIG. **16**), the drive inputs **1702** will share axes of rotation with the corresponding drive outputs of the instrument driver **1614** (FIG. **16**) via the decoupler **1616**, which allows the transfer of rotational torque from the drive outputs to the corresponding drive inputs **1720**.

The decoupler **1616** further includes an insertion assembly **2312** also rotatably mounted between the upper and lower flanges **2302**_a,b_. As best seen in FIG. **23**B, the insertion assembly **2312** includes an insertion input **2314**, which is matable with a corresponding one of the drive outputs of the instrument driver **1614** (FIG. **16**); referred to herein as the "shaft drive output". The insertion input **2314** may define a receptacle that defines splines, protrusions, or other structural features designed to mate with corresponding features of the corresponding drive output of the instrument driver **1614**, or vice versa. Once properly mated, the insertion input **2314** will share an axis of rotation with the corresponding drive output of the instrument driver **1614** to allow the transfer of rotational torque from the drive output to the insertion input **2314**.

As seen in FIG. **23**A, the insertion assembly **2312** further includes an insertion output **2316**, which is matable with a corresponding one of the drive inputs **1702** (FIGS. **17**A-**17**B) of the actuation system **1700** (FIGS. **17**A-**17**B); referred to herein as the "shaft drive input". As illustrated, the insertion output **2316** may define splines, protrusions, or other structural features designed to mate with a receptacle of a corresponding drive input **1702**, or vice versa. Once properly mated, the insertion output **2316** will share an axis of rotation with the corresponding drive input **1702** to allow the transfer of rotational torque from the insertion output **2316** to the corresponding drive input **1702**. Accordingly, once the decoupler **1616** is properly installed between the handle **1612** (FIG. **16**) and the instrument driver **1614** (FIG. **16**), the drive input **1702** mated to the insertion output **2316** will share an axis of rotation with the drive output of the instrument driver **1614** (FIG. **16**) mated with the insertion input **2314** via the decoupler **1616**, which allows the transfer of rotational torque from the drive output to the corresponding drive input **1720**.

In the case of an insertion-coupled instrument, such as the surgical tool **1600** (FIG. **16**), when the shaft **1602** (FIG. **16**) is inserted or retracted, all the sliding rack gears **1706** (FIGS. **17**A-**17**B and **18**A-**18**D) need to move at the same rate to maintain the position of the wrist **1606** (FIG. **16**). One solution to accomplish this may be to have the motors of the instrument driver **1614** (FIG. **16**) jointly perform the coupled motion. In this solution, however, the power requirements for the motors increases because the performance of the surgical tool **1600** is based on maintaining a grip force and a tip velocity. If the motors were to drive in a coupled fashion, then the motors would have to move faster and still maintain the same force output. This is particularly difficult because the required insertion velocity is much higher than the velocity to drive the sliding rack gears **1706**.

In contrast, the decoupler **1616** allows the surgical tool **1600** (FIG. **1**) with coupled motions to be driven by uncoupled inputs. More specifically, the decoupler **1616** allows one motor from the instrument driver **1614** (FIG. **16**) to control insertion of the surgical tool **1600** (i.e., axial movement of the shaft **1602** of FIG. **16**) while simultaneously allowing the other motors of the instrument driver **1614** to drive the sliding rack gears **1706** (FIGS. **17**A-**17**B and **18**A-**18**D) independent of insertion. To accomplish this, the decoupler **1616** includes a differential gear train **2318**, which can include a system of mechanically-linked differential sub-assemblies that allow the insertion input **2314** to simultaneously drive each differential output **2310** of the decoupler **1616**, while also allowing each differential input **2308** to independently drive the corresponding differential output **2310**.

As best seen in FIG. **23**B, the differential gear train **2318** includes an insertion transmission gear **2320** that may be driven by an insertion input gear **2322** mounted to and otherwise forming part of the insertion assembly **2312**. As the insertion assembly **2312** is driven (rotated), the insertion input gear **2322** drives against and causes the insertion transmission gear **2320** to rotate, and the insertion transmission gear **2320** is arranged to interface with a differential insertion input gear **2324** mounted to and otherwise forming part of each differential assembly **2306**. As the insertion transmission gear **2320** drives against the differential insertion input gears **2324** simultaneously, each differential assembly **2306** correspondingly rotates. Accordingly, the insertion assembly **2312** is coupled to all the differential assemblies **2306** in the decoupler **1616** by a single gear; i.e., the insertion transmission gear **2320**. Thus, when insertion is driven by operation (rotation) of the insertion assembly **2312**, each of the differential assemblies **2306** is simultaneously rotated, which means that by driving the insertion input **2314**, all the differential outputs **2310** simultaneously rotate. Additionally, if a motor input to any of the differential assemblies **2306** is rotated, then the corresponding differential output **2310** is simultaneously rotated. As will be appreciated, the result of this is the separation of the insertion motion from the motions (articulation) of the wrist **1606** (FIG. **16**).

FIG. **24** is an isometric view of one example of the insertion assembly **2312**, according to one or more embodiments. As illustrated, the insertion assembly **2312** includes a drive shaft **2402**, and the insertion input **2314** is located at a first end of the drive shaft **2402** while the insertion output **2316** is located at a second (opposite) end of the drive shaft **2402**. The insertion input gear **2322** is mounted to the drive shaft **2402** at a location between the insertion input and output **2314**, **2316**. In some embodiments, as illustrated, the insertion input and output **2314**, **2316** and the insertion input gear **2322** may form an integral part of the drive shaft **2402**, thus making the insertion assembly **2312** a monolithic part. In other embodiments, however, one or more of the insertion input and output **2314**, **2316** and the insertion input gear **2322** may be coupled (fixed) to the drive shaft **2402**, without departing from the scope of the disclosure.

FIG. **25** is an isometric view of an example differential assembly **2306**, according to one or more embodiments. As illustrated, the differential assembly **2306** includes a drive shaft **2502**, and the differential input **2308** is located at a first end of the drive shaft **2502** while the differential output **2310** is located at a second (opposite) end of the drive shaft **2502**. The differential insertion input gear **2324** is mounted to or otherwise provided on the drive shaft **2502** at a location between the differential input **2308** and the differential output **2310**.

The differential assembly **2306** may further include a differential **2504** also mounted to the drive shaft **2502** at a location between the differential input **2308** and the differential output **2310**. The differential **2504** allows the differential output **2310** to be driven by the difference of two inputs; i.e., one from the differential input **2308** and another from the differential insertion input gear **2324** as driven by operation of the insertion assembly **2312** (FIGS. **23**A-**23**B and **24**).

FIGS. **26**A-**26**C are side views of the differential assembly **2306** of FIG. **25** in various stages of deconstruction, according to one or more embodiments. In FIG. **26**A, various parts of the differential assembly **2306** are shown in phantom (dashed lines) to enable viewing of various internal parts of the differential **2504**. As illustrated, the differential **2504** may include a differential gear box or "carrier" **2602**, a first or "upper" bevel gear **2604***a*, a second or "lower" bevel gear **2604***b*, and a pair of opposing side bevel gears or "carrier gears" **2606** extending between the upper and lower bevel gears **2604***a,b*.

The lower bevel gear **2604***b* operates as an input gear and may be secured to the drive shaft **2502** such that rotation of the drive shaft **2502** rotates the lower bevel gear **2604***b* and the differential output **2310**. In some embodiments, the lower bevel gear **2604***b* may form part of the differential insertion input gear **2324**, but may alternatively be nested within a portion of the differential insertion input gear **2324**. The differential insertion input gear **2324**, however, may nonetheless be able to drive rotation of the lower bevel gear **2604***b*, which drives rotation of the drive shaft **2502** and the differential output **2310** via interaction with the carrier gears **2606** and the upper bevel gear **2604***a*. The upper bevel gear **2604***a* operates as an output gear and may rotatably mounted to the drive shaft **2502** (i.e., free floating). While rotation of the lower bevel gear **2604***b* creates rotation input to the carrier **2602**, the upper bevel gear **2604***a* rotates as a combination of rotation of the lower bevel gear **2604***b* and the carrier **2602**. As the upper bevel gear **2604***a* rotates, the differential output **2310** correspondingly rotates.

An axle **2608** may be mounted to the carrier **2602**, and the carrier gears **2606** may be rotatably mounted to the axle **2608**. When the differential input **2308** is actuated, as discussed above, the drive shaft **2502** will rotate and correspondingly rotate the lower bevel gear **2604***b* and the differential output **2310**. Rotation of the lower bevel gear **2604***b* will also drive against and cause the carrier gears **2606** to rotate about (on) the upper bevel gear **2604***a*, which results in rotation of the carrier **2602** while the upper bevel gear **2604***a* remains stationary. In contrast, however, when the differential insertion input gear **2324** is rotated via actuation of the insertion assembly **2312**, the upper bevel gear **2604***a* will rotate and thereby cause the carrier gears **2606** to drive against the lower bevel gear **2604***b*, which correspondingly rotates the drive shaft **2502** and the differential output **2310**. In this scenario, the carrier **2602** remains stationary. Accordingly, the differential **2504** may allow two inputs to create rotation of the differential output **2310**. As will be appreciated, the insertion motion generated by the insertion assembly **2312** is transferred to all differential assemblies **2306** of the decoupler **1616**.

While this design uses bevel gear differentials, those skilled in the art will readily appreciate that this same concept may be realized with any type of differential, such as a planetary or spur differential, which are described in more detail herein. Moreover, as mentioned above, the decoupler **1616** (FIGS. **23**A-**23**B) could be integrated into the instrument driver **1614 1614** (FIG. **16**). In such embodiments, the decoupler **1616** may be integrated into the gearbox of the motors of the instrument driver **1614** because the differentials can provide a gear reduction. This may require a redesign of the decoupler **1616** such that each motor of the instrument driver **1614** has two outputs. One would be the insertion-decoupled motion while the other is not, and the instrument driver **1614** would then be designed to selectively engage the appropriate outputs. One way to accomplish this is graphically depicted in FIGS. **27**A and **27**B.

FIGS. **27**A and **27**B are isometric and cross-sectional side views, respectively, of another example differential assembly **2306**, according to one or more additional embodiments. The differential assembly **2306** of FIGS. **27**A-**27**B may be similar in some respects to the differential assembly **2306** of FIGS. **25** and **26**A-**26**B, and therefore may be best understood with reference thereto, where like numerals will represent like components not described again in detail. As illustrated, for example, the differential assembly **2306** of FIGS. **27**A-**27**B includes the drive shaft **2502**, the differential input **2308** located at the first end of the drive shaft **2502**, the differential insertion input gear **2324**, and the differential **2504**.

Unlike the differential assembly **2306** of FIGS. **25** and **26**A-**26**C, however, the differential assembly **2306** of FIGS. **27**A-**27**B may include first and second differential outputs **2702***a* and **2702***b* located at the second (opposite) end of the drive shaft **2502**. The first and second differential outputs **2702***a,b* are coaxially aligned with each other and able to rotate independent of the other. More specifically, the first differential output **2702***a* is coupled to the drive shaft **2502** such that actuating the differential input **2308** drives the drive shaft **2502** and rotates the first differential output **2702***a*. In contrast, when the differential insertion input gear **2324** is rotated via actuation of the insertion assembly **2312** (FIGS. **23**A-**23**B and **24**), the differential **2504** operates to drive against the upper bevel gear **2604***a*, which correspondingly rotates the second differential output **2702***b*. In such embodiments, a corresponding drive input of the handle **1612** (FIG. **16**) will be configured to engage with one of the differential outputs **2702***a,b*, while the other differential output **2702***a,b* is able to freely spin. This allows the instrument input design to determine which differential output **2702***a,b* is used.

Another solution could be a mechanism that uncouples the insertion assembly **2312** (FIGS. **23**A-**23**B and **24**) from the differential insertion input gears **2324** on each differential assembly **2306** then keeps the differential insertion input gears **2324** on all the differential assemblies **2306** stationary. With this setup, the differential assembly **2306** only has one input driving the differential output **2310**, so they drive the differential output **2310** as normal. One design to execute this concept may be to have the insertion transmission gear **2320** (FIG. **23**) on a shifter such that it could be selectively engaged or disengaged with the differential insertion input gears **2324** on each differential assembly **2306**, and then lock the insertion transmission gear **2320**. This design could be actuated by a single solenoid in the instrument driver **1614** (FIG. **16**), for example.

FIG. **28** is a top, schematic view of another example decoupler **2802**, according to one or more additional embodiments. The decoupler **2802** may be similar in some respects to the decoupler **1616** of FIGS. **23**A-**23**B, and therefore may be best understood with reference thereto. Similar to the decoupler **1616**, for example, the decoupler **2802** may be incorporated into the surgical tool **1600** (FIG. **16**) and may be configured to interpose the instrument driver **1614** (FIG. **16**) and the handle **1612** (FIG. **16**). The decoupler **2802** may be operable to transfer torque from the drive outputs of the instrument driver **1614** to the drive inputs of the handle **1612**. Moreover, the architecture of the decoupler **2802** further allows for the transfer of insertion motion (e.g., movement of the shaft **1602**) to all the drive inputs of the handle **1612**, thus allowing one robot motor from the instrument driver **1614** to control insertion of the surgical tool **1600**, while allowing the other driver motors to drive the sliding rack gears independent of insertion. The decoupler **2802** defines a central aperture **2803** through which the shaft **1602** is able to extend and translate.

Unlike the decoupler **1616** of FIGS. **23**A-**23**B, however, which incorporated a bevel gear differential design, the decoupler **2802** incorporates a planetary or epicyclic gearbox as the differential and primary axle driver. Those skilled in the art will appreciate that the specific design of the decoupler **2802** shown herein can allow for additional options to vary gear ratios and thereby augment load output for the cable drivers that may require higher loads. The decoupler **2802** may also prove beneficial in facilitating smaller packaging, which allows for a reduced overall height for the tool assembly and thereby improves internal reach for a common shaft.

As illustrated, the decoupler **2802** includes a housing **2804** and a plurality of differential assemblies **2806** are mounted to the housing **2804**. While five differential assemblies **2806** are depicted in FIG. **28**, more or less than five may be included in the decoupler **2802**, without departing from the scope of the disclosure. On the bottom of the decoupler **2802**, each differential assembly **2806** includes a differential input **2808** (see FIGS. **29**, **31**, and **32**) matable with a corresponding one of the drive outputs of the instrument driver **1614** (FIG. **16**); each motor in the instrument driver **1614** drives one of the differential assemblies **2806** via a corresponding one of the differential inputs **2808**. Once properly mated, the differential input **2808** will share an axis of rotation with the corresponding drive output of the instrument driver **1614** to allow the transfer of rotational torque from the drive output to the corresponding differential input **2808**.

Each differential assembly **2806** may also include a differential output **2810** (see FIGS. **29**, **31**, and **32**), which is matable with a corresponding one of the drive inputs **1702** (FIGS. **17**A-**17**B) of the actuation system **1700** (FIGS. **17**A-**17**B). Once properly mated, the drive inputs **1702** will share axes of rotation with corresponding differential outputs **2810** to allow rotational torque from the differential output **2810** to be transferred to the corresponding drive input **1702**. Accordingly, once the decoupler **2802** is properly installed between the handle **1612** (FIG. **16**) and the instrument driver **1614** (FIG. **16**), the drive inputs **1702** will share axes of rotation with the corresponding drive outputs of the instrument driver **1614** (FIG. **16**) via the decoupler **2802**, which allows the transfer of rotational torque from the drive outputs to the corresponding drive inputs **1720**.

The decoupler **2802** further includes an insertion assembly **2812** also mounted to the housing **2804**. The insertion assembly **2812** includes an insertion input **2814** (see FIGS. **33-34**), which is matable with a corresponding one of the drive outputs of the instrument driver **1614** (FIG. **16**); referred to herein as a "shaft drive output". Once properly mated, the insertion input **2814** will share an axis of rotation with the shaft drive output of the instrument driver **1614** to allow the transfer of rotational torque from the drive output to the insertion input **2814**.

In the illustrated embodiment, the insertion assembly **2812** is provided in the form of a planetary gear box, which includes a sun gear **2816** (see FIGS. **33-34**), a plurality of planetary gears **2818** surrounding and intermeshed with the sun gear **2816**, and a planet carrier **2820** (see FIGS. **33-34**) coupled to each planetary gear **2818**. As best seen in FIGS. **33-34**, and in some embodiments, the planet carrier **2820** may form part of an insertion output **2824** matable with a corresponding one of the drive inputs **1702** (FIGS. **17A-17B**) of the actuation system **1700** (FIGS. **17A-17B**); referred to herein as the "shaft drive input". Once properly mated, the insertion output **2824** will share an axis of rotation with the corresponding shaft drive input **1702** to allow the transfer of rotational torque from the insertion output **2824** to the corresponding drive input **1702**. Accordingly, once the decoupler **2802** is properly installed between the handle **1612** (FIG. **16**) and the instrument driver **1614** (FIG. **16**), the shaft drive input **1702** mated to the insertion output **2824** will share an axis of rotation with the shaft drive output of the instrument driver **1614** (FIG. **16**) mated with the insertion input **2814** via the decoupler **2802**. This allows the transfer of rotational torque from the shaft drive output of the instrument driver **1614** to the corresponding shaft drive input **1720**.

Referring again to FIG. **28**, each differential assembly **2806** may further include a differential **2826** that allows the differential output **2810** (FIGS. **29**, **31**, and **32**) to be driven by the difference of two inputs; i.e., one from the differential input **2808** (FIGS. **29**, **31**, and **32**) and another from the insertion assembly **2812**. Similar to the insertion assembly **2812**, each differential **2826** is provided in the form of a planetary gearbox, which includes a sun gear **2828**, a plurality of planetary gears **2830** surrounding the sun gear **2828**, and a planet carrier **2832** (see FIGS. **29-31**) coupled to each planetary gear **2816**. In some embodiments, as seen in FIGS. **31** and **32**, the planet carrier **2832** may form part of the differential output **2810**. Each differential **2826** may further include a differential ring gear **2834** surrounding and intermeshed with the planetary gears **2830**. As described below, the differential ring gear **2834** may be driven by operation of the insertion assembly **2812**, and thereby take into account insertion movement during operation.

Similar to the decoupler **1616** of FIGS. **23A-23B**, the decoupler **2802** allows the surgical tool **1600** (FIG. **1**) with coupled motions to be driven by uncoupled inputs. More specifically, the decoupler **2802** allows one motor from the instrument driver **1614** (FIG. **16**) to control insertion of the surgical tool **1600** (i.e., axial movement of the shaft **1602** of FIG. **16**) while simultaneously allowing the other motors of the instrument driver **1614** to drive the sliding rack gears **1706** (FIGS. **17A-17B** and **18A-18D**) independent of insertion. To accomplish this, the decoupler **2802** includes a differential gear train **2836**, which can include a system of mechanically-linked differential sub-assemblies that allows the insertion input **2814** (see FIGS. **33-34**) to simultaneously drive each differential output **2810** (see FIGS. **29**, **31**, and **32**) of each differential assembly **2806**, while also allowing each differential input **2808** (see FIGS. **29**, **31**, and **32**) of each differential assembly **2806** to independently drive the corresponding differential output **2810**.

In the illustrated embodiment, the differential gear train **2836** includes an insertion transmission gear **2838** and an insertion input gear **2840** arranged to drive the insertion transmission gear **2838**. As illustrated, the insertion input gear **2840** surrounds and is intermeshed with the planetary gears **2818**. As the insertion assembly **2812** is driven (rotated) to move the shaft **1602** (FIG. **16**), the insertion input gear **2840** is simultaneously driven against and causes the insertion transmission gear **2838** to rotate. The insertion transmission gear **2838** is arranged to interface with (drive) the differential ring gear **2834** of each differential assembly **2806** such that each differential assembly **2806** correspondingly rotates.

Accordingly, the insertion assembly **2812** is coupled to the all the differential assemblies **2806** in the decoupler **2802** by a single gear; i.e., the insertion transmission gear **2838**. Thus, when insertion is driven by operation (rotation) of the insertion assembly **2812**, each of the differential assemblies **2806** is simultaneously rotated, which means that by driving the insertion input **2814** (FIGS. **33-34**), all the differential outputs **2810** (FIGS. **29**, **31**, and **32**) simultaneously rotate. Additionally, if a motor input to any of the differential assemblies **2806** is rotated, then the corresponding differential output **2810** is simultaneously rotated. As will be appreciated, the result of this is the separation of the insertion motion from the motions (articulation) of the wrist **1606** (FIG. **16**).

In some embodiments, the differential gear train **2836** may further include a second insertion transmission gear **2842**. In such embodiments, the first insertion transmission gear **2838** may be characterized as a central spur gear and the second insertion transmission gear **2842** may be characterized as an outer ring gear. The second insertion transmission gear **2842** may operate similar to the first differential gear **2838**, in that the second insertion transmission gear **2842** may intermesh with and be driven via rotation of the insertion input gear **2840**. Moreover, the second insertion transmission gear **2842** may be arranged to interface with the differential ring gear **2834** of each differential assembly **2806**, and rotation of the second insertion transmission gear **2842** simultaneously drives against each differential ring gear **2834**. In at least one embodiment, the first insertion transmission gear **2838** may be omitted and the differential gear train **2836** may only include the second insertion transmission gear **2842** to drive the differential ring gears **2834**.

FIG. **29** is an isometric view of an example differential assembly **2806**, FIG. **30** is a cross-sectional top view of the differential assembly **2806** taken along the lines shown in FIG. **29**, and FIG. **31** is a schematic cross-sectional side view of the differential assembly **2806** of FIG. **29**, according to one or more embodiments. As best seen in FIGS. **29** and **31**, the differential assembly **2806** includes opposing first and second ends **2902***a* and **2902***b*. The differential input **2808** is located at the first end **2902***a* and is matable with a corresponding one of the drive outputs of the instrument driver **1614** (FIG. **16**). As best seen in FIG. **29**, the differential input **2808** may define a receptacle that defines splines, protrusions, or other structural features designed to mate with corresponding features of the drive outputs of the instrument driver **1614**, or vice versa. The differential output **2810** is located at the second end **2902***b* and is matable with a corresponding one of the drive inputs **1702** (FIGS. **17**A-**17**B) of the actuation system **1700** (FIGS. **17**A-**17**B). As best seen in FIG. **29**, the differential output **2810** may define splines, protrusions, or other structural features designed to mate with a corresponding receptacle of the drive input **1702**, or vice versa.

The differential assembly **2806** also includes the differential **2826**, which allows the differential output **2810** to be driven by both the differential input **2808** and the insertion assembly **2812** (FIG. **28**). As best seen in FIGS. **30-31**, the differential **2826** includes the sun gear **2828**, the plurality of planetary gears **2830** surrounding the sun gear **2828**, and the planet carrier **2832** coupled to each planetary gear **2830**. In some embodiments, as shown in FIG. **31**, at least a portion of the planet carrier **2832** may form part of the differential output **2810**. The differential **2826** further includes the differential ring gear **2834**, which surrounds and intermeshes with the planetary gears **2830** and is driven by the insertion transmission gear **2838** or **2842** (FIG. **28**).

FIG. **32** is a schematic, cross-sectional side view of another example of the differential assembly **2806** of FIG. **28**, according to one or more additional embodiments. In the illustrated embodiment, the differential assembly **2812** includes a drive shaft **3202** having opposing first and second ends **3204***a* and **3204***b*. The differential input **2808** is located at the first end **3404***a* and the differential output **2810** is located at the second end **3404***b*. The sun gear **2828** either forms part of the drive shaft **3202** or is fixed thereto such that rotation of the drive shaft **3202** correspondingly rotates the sun gear **2828**. Moreover, the planet carrier **2832** may be coupled to the drive shaft **3202** such that rotation of the drive shaft **3202** correspondingly rotates the planet carrier **2832**. Accordingly, the illustrated embodiment provides a non-coupled direct drive motion through the center of the differential assembly **2806**. Those skilled in the art will readily appreciate that this may be done as an opportunity to drive a non-coupled actuator on a different instrument architecture.

FIG. **33** is a cross-sectional side view of one example of the insertion assembly **2812** of FIG. **28**, according to one or more embodiments. As illustrated, the insertion assembly **2812** has opposing first and second ends **3202***a* and **3202***b*. The insertion input **2814** is provided at the first end **3202***a*, and the insertion output **2824** is provided at the second end **3202***b*. In some embodiments, as illustrated, the insertion input **2814** may define a receptacle that defines splines, protrusions, or other structural features designed to mate with corresponding features of a corresponding drive output of the instrument driver **1614** (FIG. **16**), or vice versa. Similarly, in some embodiments, the insertion output **2824** define splines, protrusions, or other structural features designed to mate with a corresponding receptacle of a drive input **1702** (FIG. **17**), or vice versa.

The insertion assembly **2812** further includes the sun gear **2816**, the planetary gears **2818** surrounding and intermeshed with the sun gear **2816**, and the planet carrier **2820** coupled to each planetary gear **2818**. In at least one embodiment, the planet carrier **2820** may extend into and otherwise form part of the insertion output **2824**. The insertion assembly **2812** also includes the insertion input gear **2840** operable to drive the insertion transmission gear **2838** (FIG. **28**).

FIG. **34** is a schematic, cross-sectional side view of another example of the insertion assembly **2812** of FIG. **28**, according to one or more additional embodiments. In the illustrated embodiment, the sun gear **2816** may include a distally extending extension **3402** that is keyed (fixed) to the housing **2804** of the decoupler **2802** (FIG. **28**) at or near the insertion input **2814**. Moreover, the insertion drive for the insertion assembly **2812** may be linked directly to the bottom of the planet carrier **2820**. More specifically, the planet carrier **2820** may be mounted to a drive shaft **3404** that extends along the axial length of the insertion assembly **2812**. The insertion input **2814** may be provided at one end of the drive shaft **3404**, and the insertion output **2824** may be provided at the opposing end of the drive shaft **3404**. Accordingly, instead of the insertion axis just having a gear on it, in the illustrated embodiment, the insertion axis directly drives the insertion output **2824** via rotation of the drive shaft **3404** and the planet carrier **2820**; i.e., insertion directly drives the output.

Actuation of the insertion input **2814** simultaneously drives the planet carrier **2820**, which drives the planetary gears **2818** against the insertion input gear **2840**. This ensures that the rotation of the insertion axis is scaled to the correct output that occurs at each individual axis of the differential assemblies **2806** (FIGS. **28-31**), without having to pair uneven gear ratios. Moreover, each rotation of the planet carrier **2820** drives the shaft rack gear **1710** (FIG. **17**A) on the shaft **1602** (FIGS. **16** and **17**A), while simultaneously rotating the insertion input gear **2840**. As the insertion input gear **2840** rotates, it drives rotation of the insertion transmission gear **2838** (FIG. **28**) and/or the second insertion transmission gear **2842** (FIG. **28**). This motion then acts on the differential **2826** (FIG. **28**) of each differential assembly **2806** (FIG. **28**), which rotation is summed with the sun drive motion of each differential assembly **2806** to obtain a total output planet carrier motion at the individual differential assemblies **2806**.

FIGS. **35**A and **35**B are isometric and cross-sectional side views of another example of the differential assembly **2806** of FIG. **28**, according to one or more additional embodiments. Similar to the differential assembly **2806** shown in FIGS. **29-31**, the differential assembly **2806** in FIGS. **35**A-**35**B includes opposing first and second ends **2902***a* and **2902***b*, where the differential input **2808** is located at the first end **2902***a* and the differential output **2810** is located at the second end **2902***b*. Moreover, the differential assembly **2806** further includes the differential ring gear **2834**, which is driven by the insertion transmission gear **2838** or **2842** (FIG. **28**).

Unlike the differential assembly **2806** of FIGS. **29-31**, however, where the differential **2826** was provided in the form of a planetary gearbox, the differential assembly **2806** of FIGS. **35**A-**35**B includes a differential **3502** in the form of an offset axle gearbox. At least one advantage to the offset axle gearbox is that it can achieve a more ideal gear ratio (closer to 1:1) while limiting the height of the overall differential mechanism.

As illustrated, the differential **3502** includes an input shaft **3504***a* and an output shaft **3504***b*, where the input and output shafts **3504***a,b* are axially aligned and extend between the first and second ends **2902***a,b*. The differential input **2808** either forms part of or is coupled to the input shaft **3504***a*, and the differential output **2810** either forms part of or is coupled to the output shaft **3504***b*.

The differential **3502** further includes a housing **3506**, and an offset axle **3508** (FIG. **35**B) extends between the housing **3506** and the differential ring gear **2834**. The offset axle **3508** extends parallel to but eccentric from the input and output shafts **3504***a,b*. A first offset gear **3510***a* is coupled to the offset axle **3508** and arranged to engage an input shaft gear **3512***a* mounted to the input shaft **3504***a*, and a second offset gear **3510***b* is coupled to the offset axle **3508** and arranged to engage an output shaft gear **3512***b* mounted to the output shaft **3504***a*.

The differential **3502** allows the differential output **2810** to be driven by both the differential input **2808** and the insertion assembly **2812** (FIG. **28**). More specifically, rotating the differential input **2808** will cause the input shaft **3504***a* and the input shaft gear **3512***a* to rotate, which will drive against the first offset gear **3510***a* and thereby cause the offset axle **3508** and the second offset gear **3510***b* to drive against the output shaft gear **3512***b*, thus resulting in rotation of the output shaft **3504***b* and the differential output **2810**. In contrast, rotating the differential ring gear **2834**, as driven by the insertion transmission gear **2838** or **2842** (FIG. **28**), will cause the offset axle **3508** and the housing **3506** to rotate about the input and output shafts **3504***a,b*, and thus driving the second offset gear **3510***b* against the output shaft gear **3512***b* and resulting in rotation of the output shaft **3504***b* and the differential output **2810**. In such a scenario, the motor driving the differential input **2808** and the input shaft **3504***a* may be static or operating.

The differential **3502** shown in FIGS. **35**A-**35**B is closer to 1.2:1 ratio. Utilizing a true 1:1 ratio through this gearbox would have the first and second offset gears **3510***a,b* of equal size, which for this configuration of differential **3502** would create a unique singularity wherein the motion of the differential **3502** would translate only to rotation of the offset axle **3508**, and not the intended motion of the output shaft **3504***b* and the differential output **2810**.

FIGS. **36**A and **36**B are isometric and cross-sectional side views, respectively, of another example of the insertion assembly **2812** of FIG. **28**, according to one or more additional embodiments. The insertion assembly **2812** of FIGS. **36**A-**36**B may be similar in some respects to the insertion assembly **2812** of FIGS. **33**-**34**, and thus may be best understood with reference thereto, where like numerals will refer to similar components. As illustrated, the insertion assembly **2812** includes a drive shaft **3602** that has opposing first and second ends **3604***a* and **3604***b*. The insertion input **2814** is provided at the first end **3604***a*, and the insertion output **2824** is provided at the second end **3604***b*. Moreover, the insertion assembly also includes the insertion input gear **2840**, which is arranged to drive the insertion transmission gear **2838** (FIG. **28**) to enable simultaneous driving of each differential ring gear **2834** (FIG. **28**) of each differential assembly **2806** (FIG. **28**), as discussed above.

Unlike the insertion assembly **2812** of FIGS. **23**-**34**, however, which included a planetary gearbox, the insertion assembly **2812** of FIGS. **36**A-**36**B includes an offset axle gearbox. More specifically, the insertion assembly **2812** includes a housing **3606**, and an offset axle **3608** (FIG. **36**B) extends between the housing **3606** and the insertion input gear **2840**. The offset axle **3608** extends parallel to but eccentric from the drive shaft **3602**. A first offset gear **3610***a* is coupled to the offset axle **3608** and arranged to engage a stationary gear **3612***a* forming part of a stationary structure **3614** through which the drive shaft **3602** extends. The stationary structure **3614** may be keyed into the housing **3606**, such as through a hex head mating engagement or the like. A second offset gear **3610***b* is coupled to the offset axle **3608** and arranged to engage a drive shaft gear **3612***b* mounted to the drive shaft **3602**.

In example operation, rotating the insertion input **2814** will cause the drive shaft **3602** to rotate, which will cause insertion of the tool. Rotating the drive shaft **3602**, however, will also cause the offset axle **3608** and the housing **3606** to rotate about the stationary structure **3614**, which drives the insertion input gear **2840** in rotation. As discussed herein, rotating the insertion input gear **2840** drives the insertion transmission gear **2838** (FIG. **28**) and thereby enables simultaneous driving of each differential ring gear **2834** (FIG. **28**) of each differential assembly **2806** (FIG. **28**). Accordingly, the insertion assembly **2812** of FIGS. **36**A-**36**B ensures that all rotation of the insertion axis output (i.e., the drive shaft **3602**) is simultaneously transferred to the differential assemblies **2806** at the inverted rate of the other gearboxes. Thus, when the motion is converted from a given differential assembly **2806** to its output **2810**, the output rotation is equal to that of insertion. In some embodiments, to accomplish this, the same size offset gears **3510***a,b* (FIGS. **35**A-**35**B) and **3610**A,B may be used.

FIG. **37** is an isometric view of another example surgical tool **3700** that may incorporate some or all of the principles of the present disclosure. The surgical tool **3700** may be similar in some respects to the surgical tool **1600** of FIG. **16** and therefore may be best understood with reference thereto, where like numerals correspond to similar components or structures not described again in detail. Similar to the surgical tool **1600**, for example, the surgical tool **3700** includes the elongated shaft **1602**, the end effector **1604** arranged at the distal end of the shaft **1602**, and the articulable wrist **1606** that interposes and couples the end effector **1604** to the distal end of the shaft **1602**. Moreover, a tailpiece **3702** may be arranged at a proximal end of the shaft **1602**.

The surgical tool **3700** may include a drive housing or "handle" **3704** similar in some respects to the handle **1612** of FIG. **16**. The shaft **1602** extends longitudinally through the handle **3704**, and the handle **3704** houses an actuation system designed to facilitate articulation of the wrist **1606**, actuation (operation) of the end effector **1604** (e.g., clamping, firing, rotation, articulation, energy delivery, etc.), and movement of the shaft **1602** relative to (through) the handle **3704** and along the longitudinal axis A_1. The actuation system may be the same as or similar to the actuation system **1700** of FIGS. **17**A-**17**B, but could alternatively be another type of actuation system.

The handle **3704** may be operatively coupled to an instrument driver **3706** (shown in dashed lines) of a robotic surgical system. The instrument driver **3706** may be the same as or similar to the instrument driver **1614** of FIG. **16**, and therefore may be best understood with reference thereto. Similar to the instrument driver **1614**, for example, the instrument driver **3706** may be mounted to or otherwise positioned at the end of a robotic arm (not shown) and is designed to provide the motive forces required to operate the surgical tool **3700**.

The handle **3704** includes a plurality of rotatable drive inputs (not visible) that can be driven by a corresponding plurality of drive outputs (not visible) of the instrument driver **3706**. Each drive input is actuatable to independently drive (actuate) various portions of the actuation system housed within the handle **3704** and thereby operate the surgical tool **3700**. Movement (rotation) of a given drive output correspondingly moves (rotates) the associated drive input and thereby operates the surgical tool **3700**. Actuation of the drive inputs operates the actuation system, which can cause the end effector **1604** to articulate and/or actuate (operate) and the shaft **1602** to axially move (translate) relative to the handle **3704**.

In the illustrated embodiment, a decoupler subassembly or "decoupler" **3708** is arranged between and otherwise interposes the handle **3704** and the instrument driver **3706**. The decoupler **3708** may be the same as or similar in some respects to the decouplers **1616**, **2802** of FIGS. **16** and **28**, respectively. Similar to the decouplers **1616**, **2802**, for example, the decoupler **3708** transfers torque from the drive outputs of the instrument driver **3706** to the drive inputs of the handle **3704**. Once the drive outputs are operatively and indirectly coupled to corresponding drive inputs via the decoupler **3708**, the drive inputs will share axes of rotation with the corresponding drive outputs to allow the transfer of rotational torque from the drive outputs to the corresponding drive inputs, thus being able to operate the handle **3704**. The decoupler **3708** may also be advantageous in transferring insertion motion (e.g., movement of the shaft **1602**) to all the drive inputs, thus allowing one robot motor to control insertion of the surgical tool **3700**, while allowing the other motors of the instrument driver **3706** to drive the sliding rack gears independent of insertion.

FIG. **38** depicts separated isometric end views of the instrument driver **3706** and the surgical tool **3700** of FIG. **37**. With the jaws **1608**, **1610** closed, the shaft **1602** and the end effector **1604** can penetrate the instrument driver **3706** by extending through a central aperture **3802** defined longitudinally through the instrument driver **3706** between first and second ends **3804***a,b*. A drive interface **3806** is provided at the first end **3804***a* of the instrument driver **3706** and is matable with a driven interface **3808** provided on the distal end of the handle **3704** and, more particularly, the distal end (bottom) of the decoupler **3708**. The drive and driven interfaces **3806**, **3808** may be configured to mechanically, magnetically, and/or electrically couple the handle **3704** (e.g., the decoupler **3708**) to the instrument driver **3706**.

The instrument driver **3706** includes a plurality of drive outputs **3810** that extend through the drive interface **3806**. In embodiments where the surgical tool **3700** includes the decoupler **3708**, the drive outputs **3810** are configured to mate with corresponding differential inputs **3812** provided at the distal end of the decoupler **3708**. At least one of the differential inputs **3812** may be an insertion input **3814** operable to facilitate axial translation of the shaft **1602**. The number of drive outputs **3810** will generally be the same as the number of differential and insertion inputs **3812**, **3814**, but it is contemplated herein that the instrument driver **3706** can have additional drive outputs, without departing from the scope of the disclosure.

The drive outputs **3810** may define splines, protrusions, or other mechanical features designed to mate with corresponding receptacles of the differential and insertion inputs **3812**, **3814**, or vice versa. One of the drive outputs **3810** may be configured to mate with the insertion input **3814**, this drive output **3810** is referred to herein as a "shaft drive output." Once properly mated, the differential and insertion inputs **3812**, **3814** will share axes of rotation with the corresponding drive outputs **3810** to allow the transfer of rotational torque from the drive outputs **3810** to the corresponding differential inputs **3812**, **3814**. In some embodiments, each drive output **3810** may be spring loaded and otherwise biased to spring outwards away from the drive interface **3806**. Each drive output **3810** may be capable of partially or fully retracting into the drive interface **3806**.

FIGS. **39**A and **39**B are isometric open (disengaged) and closed (engaged) views, respectively, of another example actuation system **3900**, according to one or more embodiments. The actuation system **3900**, also referred to as an axle redirect assembly, may be similar in some respects to the actuation system **1700** of FIGS. **17**A-**17**B, and may thus be best understood with reference thereto. The actuation **3900** may be housed within the handle **3704** and operable to actuate (operate) the end effector **1604** (FIG. **16**), articulate the wrist **1606** (FIG. **16**), and axially move (translate) the shaft **1602** relative to (i.e., through) the handle **3704**. Several parts and structural elements of the handle **3704**, such as the outer housing, are omitted from FIGS. **39**A-**39**B to enable ease of viewing of the actuation system **3900** for purposes of discussion.

As illustrated, the actuation system **3900** may include a first or "upper" mounting assembly **3901***a* and a second or "bottom" mounting assembly **3901***b* Briefly, the upper mounting assembly **3901***a* is a translating ring that moves to allow and enable the assembly of the instrument shaft **1602** to the actuation system **3900** and the decoupler **3708**, and the bottom mounting assembly **3901***b* is the base of the axle redirect assembly or actuation system **3900**. The mounting assemblies **3901***a,b* may be vertically offset from each other and concentrically arranged about the shaft **1602**. A plurality of spur linkage subassemblies **3902** may be pivotably mounted to the mounting assemblies **3901***a,b* and configured to pivot between a first or "disengaged" position, as shown in FIG. **39**A, and a second or "engaged" position, as shown in FIG. **39**B.

Each spur linkage subassembly **3902** includes a corresponding drive gear **3904** arranged to drive against an adjacent sliding rack gear **3906** (two visible in FIGS. **39**A-**39**B). Each sliding rack gear **3906** is movably nested within a corresponding longitudinal channel **3908** defined along all or a portion of the shaft **1602**. In the illustrated embodiment, the drive gears **3904** are depicted as spur gears with teeth matable with corresponding teeth defined on the opposing sliding rack gear **3906**. Accordingly, the drive gears **3904** may alternatively be referred to herein as "spur" gears, and operation of the spur gears **3904** and corresponding rack gears **3906** may conform to known rack-and-pinion operation. Driving a given sliding rack gear **3906** will urge the sliding rack gear **3906** to move (slide) within its corresponding longitudinal channel **3908**, and moving the sliding rack gear **3906** within the channel **3908** may actuate (operate) the end effector **1604** (FIG. **16**) and/or articulate the wrist **1606** (FIG. **16**).

One of the drive gears is indicated in FIGS. **39**A-**39**B as a shaft drive gear **3904***a*, which may be arranged to drive against an adjacent shaft rack gear **3910**. The shaft rack gear **3910** may form part of and may otherwise be defined along all or a portion of the outer surface of the shaft **1602**. Driving against the shaft rack gear **3910** will cause the shaft **1602** to move (translate) axially relative to (i.e., through) the handle **3704** (FIG. **16**).

Referring briefly to FIG. **40**, illustrated is an isometric view of an example spur linkage subassembly **3902**, according to one or more embodiments. As illustrated, the spur linkage subassembly **3902** includes a rotatable drive input **4002**, which, in some embodiments, can be driven by one of the drive outputs **3810** (FIG. **38**) of the instrument driver **3706** (FIGS. **37-38**). In embodiments that include the decoupler **1616** (FIG. **37**), however, a transmission differential or differential assembly provided by the decoupler **1616** will axially interpose the drive input **4002** and a corresponding drive output **3810**, as generally described herein. In such embodiments, any rotational torque provided by a given drive output **3810** will be transferred to the corresponding drive input **4002** via a corresponding transmission differential of the decoupler **1616**.

A gear train including one or more intermediate gears may interpose the drive input **4002** and the corresponding drive gear **3904**, such that rotating the drive input **4002** will cause the corresponding drive gear **3904** to rotate. Those skilled in the art will readily appreciate that this gear train can assume a variety of configurations. In the illustrated embodiment, for example, the gear train includes mating bevel gears, shown as a bevel drive gear **4004***a* arranged to drive a bevel driven gear **4004***b*. The bevel drive gear **4004***a* may be coupled to or otherwise form part of the drive input **4002** such that rotation of the drive input **4002** correspondingly rotates the bevel drive gear **4004***a*. In some embodiments, the bevel driven gear **4004***b* may be mounted to an axle **4006** configured to be rotatably mounted to the lower mounting assembly **3901***b* (FIGS. **39**A-**39**B). A spur gear **4008** may also be mounted to the axle **4006** and axially offset from the bevel driven gear **4004***b*. In at least one embodiment, however, the spur gear **4008** may be coupled to or otherwise form part of the bevel driven gear **4004***b*. In either scenario, rotation of the bevel driven gear **4004***b* will cause the spur gear **4008** to correspondingly rotate, and the spur gear **4008** may be arranged to drive the drive gear **3904**.

The intermeshed bevel gears **4004***a,b* facilitate the directional change required in the handle **3704** (FIGS. **39**A-**39**B). More specifically, the bevel gears **4004***a,b* redirect motor rotation of the drive input **4002** to be perpendicular to the shaft **1602** (FIGS. **39**A-**39**B). Through the depicted gear train arrangement, rotation of the drive input **4002** will correspondingly move the rack gears **3906** (FIGS. **39**A-**39**B). In other embodiments, other known gearing mechanisms may be utilized or combined in any number of configurations and dimensioned for optimal torque and/or speed outputs. In at least one embodiment, for example, the gear train may incorporate worm gears or a combination of bevel and spur gears. Moreover, in at least one embodiment, the gear train may be omitted and rotating the drive input **4002** may directly drive an adjacent rack gear **3906** without departing from the scope of the disclosure.

While the spur linkage assembly **3902** shown in FIG. **40** is described with reference to interfacing with a sliding rack gear **3906** (FIGS. **39**A-**39**B), the foregoing description is equally applicable to a spur linkage assembly **3902** configured to interface with the shaft rack gear **3910**. In such embodiments, the drive input **4002** may be referred to as a "shaft drive input," which may be configured to cause the shaft drive gear **3904***a* (FIGS. **39**A-**39**B) to rotate (operate) and drive against the shaft rack gear **3910**. Driving against the shaft rack gear **3910**, as mentioned above, will cause the shaft **1602** (FIGS. **39**A-**39**B) to move (translate) axially relative to (i.e., through) the handle **3704** (FIGS. **39**A-**39**B).

Still referring to FIG. **40**, the spur linkage subassembly **3902** may further include a first or "upper" linkage **4010***a* and a second or "lower" linkage **4010***b*. As illustrated, one end of the upper linkage **4010***a* may provide or otherwise define a pair of pins **4012** configured to help pivotably couple the upper linkage **4010***a* to the upper mounting assembly **3901***a* (FIGS. **39**A-**39**B). The pins **4012**, however, could be replaced with any other type of pivotable coupling engagement mechanism or structure, without departing from the scope of the disclosure. The opposing end of the upper linkage **4010***a* may be pivotably coupled to one end of the lower linkage **4010***b*, and the opposing end of the lower linkage **4010***b* may be rotatably mounted to the axle **4006**, which, as mentioned above, can be rotatably mounted to the lower mounting assembly **3901***b* (FIGS. **39**A-**39**B).

Referring again to FIGS. **39**A-**39**B, with continued reference to FIG. **40**, in some embodiments, the spur linkage subassemblies **3902** may be spring biased to the disengaged position, shown in FIG. **39**A. In the disengaged position, the drive gears **3904** are disengaged from the sliding rack gears **3906** and the shaft drive gear **3904***a* is disengaged from the shaft rack gear **3910**. The spur linkage subassemblies **3902** are transitioned to the engaged position by collapsing the axial distance between the upper and lower mounting assemblies **3901***a,b*. As the upper mounting assembly **3901***a* is lowered toward the lower mounting assembly **3901***b*, the spur linkage subassemblies **3902** will pivot in tandem at the pivotably coupled linkages **4010***a,b* toward the engaged (closed) position, as shown in FIG. **39**B. In the engaged position, each drive gear **3904**, **3904***a* engages and mates with the adjacent sliding rack gear **3906** or shaft rack gear **3910** simultaneously. Accordingly, the upper linkage **4010***a* may be configured to move linearly up and down to move the drive gears **3904**, **3904***a* away from and toward the axis of the shaft **1602** as the actuation system **3900** transitions between the open and closed positions.

Referring now to FIG. **41**, in some embodiments, the actuation system **3900** may further include a clocking wheel linkage subassembly **4102** configured to help properly align (e.g., angularly, rotationally, etc.) the actuation system **3900** with the shaft **1602**. FIG. **42** is an enlarged, isometric view of one example of the clocking wheel linkage subassembly **4102**, according to one or more embodiments. As illustrated, the clocking wheel linkage subassembly **4102** may include a first or "upper" linkage **4202***a* and a second or "lower" linkage **4202***b*. As illustrated, one end of the upper linkage **4202***a* may provide or otherwise define a pair of pins **4204** configured to help pivotably couple the upper linkage **4202***a* to the upper mounting assembly **3901***a* (FIG. **41**). Similarly, one end of the lower linkage **4202***b* may also provide or otherwise define a pair of pins **4206** configured to help pivotably couple the lower linkage **4202***a* to the lower mounting assembly **3901***b*. The pins **4204**, **4206**, however, could be replaced with any other type of pivotable coupling engagement mechanism or structure, without departing from the scope of the disclosure. The opposing ends of the linkages **4202***a,b* may be pivotably attached to each other at a pivot axis **4208**.

The clocking wheel linkage subassembly **4102** may also include a clocking wheel **4210** rotatably mounted at the pivot axis **4208**. In some embodiments, one or more thrust bearings and/or washers **4212** (e.g., belleville washers) may help maintain the pivotably mounted linkages **4202***a,b* and clocking wheel **4210** axially tight and rotationally free at the pivot axis **4208**.

Referring again to FIG. **41**, with continued reference to FIG. **42**, similar to the spur linkage subassemblies **3902**, the clocking wheel linkage subassembly **4102** may be pivotably mounted to the mounting assemblies **3901***a,b* and configured to pivot between a first or "disengaged" position, as shown in FIG. **39**A, and a second or "engaged" position, as shown in FIGS. **39**B and **41**. Upon transitioning to the engaged position, the clocking wheel **4210** may be configured to be received within and otherwise mate with a longitudinal groove **4104** defined along all or a portion of the shaft **1602**. Receiving the clocking wheel **4210** within the groove **4104** will help properly align all the spur linkage subassemblies **3902** rotationally (angularly) with the proper sliding rack gears **3906** or shaft rack gear **3910** (FIGS. **39**A-**39**B).

FIG. **43** is an enlarged isometric view of the tailpiece **3702**, according to one or more embodiments. The tailpiece **3702** may be similar in respects to the tailpiece **1620** of FIG. **16**, and may thus be best understood with reference thereto. For example, similar to the tailpiece **1620**, the tailpiece **3702** may be arranged at the proximal end of the shaft **1602**. Moreover, the tailpiece **3702** may comprise a mechanical device that provides a means for manually controlling the end effector **1604** (FIG. **37**) and/or the wrist **1606** (FIG. **37**). The tailpiece **3702** may also be used to maintain tension in the surgical tool **3700** (FIG. **37**) when disconnected from the instrument driver **3706** (FIG. **37**). As described herein, however, the tailpiece **3702** can be provided in various forms and still perform essentially the same function, without departing from the scope of the present disclosure.

In the illustrated embodiment, the tailpiece **3702** includes a housing **4302** that may be attached to the proximal end of the shaft **1602**. The housing **4302** may include first and second housing portions **4304***a* and **4304***b* that are matable and coupled together using one or more mechanical fasteners **4306** or the like. The tailpiece **3702** may further include a manual actuation device, which, in this embodiment, comprises a slider **4308** that extends out of the housing **4302** and provides a means for manually actuating the tailpiece **3702**. More specifically, the slider **4308** extends past an outer circumferential periphery of the housing **4302**, and as the slider **4308** is manually moved (rotated) about the outer circumference, the end effector **1604** (FIG. **37**) may be actuated or the wrist **1606** (FIG. **37**) may be articulated.

FIG. **44** is an isometric view of the interior of the tailpiece **3702**, according to one or more embodiments. The second or "upper" housing portion **4304***b* is omitted to enable viewing of the internal components and mechanics of the tailpiece **3702**. As illustrated, the tailpiece **3702** includes first and second pulley arms **4402***a* and **4402***b* that can be secured to the slider **4308** such that manually rotating the slider **4308** about the axis of the shaft **1602** correspondingly rotates the pulley arms **4402***a,b* in the same angular direction. First and second proximal pulleys **4404***a* and **4404***b* may also be rotatably mounted to the first and second pulley arms **4402***a,b* and move with the pulley arms **4402***a,b* within the housing **4302** as the slider **4308** is manually moved. The proximal pulleys **4404***a,b* may be similar to the proximal pulley **1806***b* discussed above with reference to FIGS. **18**A-**18**C, and thus have corresponding proximal cables **4406***a* and **4406***b* extending (wrapped) thereabout, where the proximal cables **4406***a,b* are similar to the proximal cable **1804***b* of FIGS. **18**A-**18**C.

As illustrated, the proximal cables **4406***a,b* may be routed to and from the shaft **1602** using one or more rerouting pulleys **4408**. Some of the rerouting pulleys **4408** may be located within the shaft **1602** and may exhibit horizontal axes (e.g., perpendicular to shaft **1602**), while other rerouting pulleys **4408** may be located along the outer diameter of the housing **4302** and exhibit vertical axes (e.g., parallel to the shaft **1602**). Each proximal cable **4406***a,b* is distributed through corresponding rerouting pulleys **4408** and wrapped around the corresponding proximal pulley **4404***a,b*, respectively.

When the slider **4308** is manually moved in either angular direction relative to the outer circumference of the housing **4302**, the pulley arms **4402***a,b* move in the same angular direction, which causes one of the proximal pulleys **4404***a,b* to draw in its proximal cable **4406***a,b* from the shaft **1602** while simultaneously causing the other proximal pulley **4404***a,b* to pay out its proximal cable **4406***a,b* to the shaft **1602**. More specifically, as the slider **4308** moves counterclockwise, for example, as indicated by the arrow C, the first proximal pulley **4404***a* moves away from its corresponding rerouting pulleys **4408** and thereby draws a length of the first proximal cable **4406***a* into the tailpiece **3702** from the shaft **1602**. At the same time, the second proximal pulley **4404***b* simultaneously moves toward its corresponding rerouting pulleys **4408** and thereby pays out a length of the second proximal cable **4406***b* into the shaft **1602**. Consequently, the net cable length of the cables **4406***a,b* remains the same because the two pulleys **4404***a,b* have the same displacement, but the change in length of each pair changes, which causes movement (actuation) of the jaws **1608**, **1610** (FIG. **37**). Moving the slider **4308** clockwise, as indicated by arrow D, will act on the first and second proximal cables **4406***a,b* in the opposite manner, and actuate the jaws **1608**, **1610** in the opposite direction. In alternative embodiments, this cable configuration may alternatively allow pitch and yaw articulations at the wrist **1606** (FIG. **37**) to create motion where each cable loop rolls around its respective pulley system.

The tailpiece **3702** may also be useful in facilitating assembly pretension in the cable system. More specifically, during assembly of the tool, the pulley arms **4402***a,b* may be able to move relative to the slider **4308**. When the full system is assembled with cable routing, the jaws **1608**, **1610** (FIG. **37**) are held still and the pulley arms **4402***a,b* are rotated (drawn) towards each other and the center of the slider **4308**. This rotation may be done with a set torque load to create a desired pretension in the system, and once the predetermined tension is achieved, one or more mechanical fasteners **4410** may be used to rigidly secure the pulley arms **4402***a,b* to the slider **4308**. Consequently, by setting the relative position of the two pulley arms **4402***a,b* to the slider **4308**, the pretension of the cable system may be set and held.

FIG. **45** is an isometric view of another example tailpiece **4502**, according to one or more additional embodiments. The tailpiece **4502** may be similar in some respects to the tailpiece **1620** of FIG. **16** or the tailpiece **3702** of FIG. **37**, and thus may comprise a mechanical device that provides a means for manually controlling the end effector **1604** (FIG. **37**) and/or the wrist **1606** (FIG. **37**). The tailpiece **4502** may also be used to maintain tension in the surgical tool **3700** (FIG. **37**) when disconnected from the instrument driver **3706** (FIG. **37**).

As illustrated, the tailpiece **4502** includes a housing **4504** that may be attached to the proximal end of the shaft **1602**. The tailpiece **4502** may further include a manual actuation device, which, in this embodiment, comprises a slider **4506** that extends out of the housing **4504** and provides a means for manually actuating the tailpiece **4502**. In some embodiments, as illustrated, the slider **4506** may be manually moved side to side relative to the housing **4504** to actuate the tailpiece **4502**. In other embodiments, however, the slider **4506** may be configured to slide (move) in other directions, without departing from the scope of the disclosure. As the slider **4506** is manually moved, the end effector **1604** (FIG. **37**) may be actuated or the wrist **1606** (FIG. **37**) may be articulated.

FIGS. **46**A and **46**B are isometric views of the interior of the tailpiece **4502**, according to one or more embodiments. A top portion of the housing **4504** is omitted in FIGS. **46**A-**46**B to enable viewing of the internal components and mechanisms of the tailpiece **4502**. As illustrated, the tailpiece **4502** includes first and second camming plates **4602***a* and **4602***b* that are vertically offset from each other within the housing **4504**. In FIG. **46**B, only the second or "lower" camming plate **4602***b* is shown to facilitate better viewing of various component parts of the tailpiece **4502**. The camming plates **4602***a,b* may be secured together and mounted within the housing **4504** such that they are able to move (slide) in tandem relative to housing **4504**. As illustrated, the first camming plate **4602***a* may define or otherwise provide the slider **4506**.

The tailpiece **4502** may further include first and second proximal pulleys **4604***a* and **4604***b* rotatably mounted between the first and second camming plates **4602***a,b*. Each pulley **4604***a,b* may be rotatably mounted to a corresponding pin **4606** extending between the camming plates **4602***a, b*, and the pins **4606** may allow the pulleys **4604***a,b* to move laterally within the housing **4504** as the slider **4506** is manually moved. More specifically, each camming plate **4602***a,b* defines and otherwise provides distal and proximal slots **4608***a* and **4608***b* configured to receive opposing ends of each pin **4606**. The pin **4606** of the first pulley **4604***a* may be arranged to extend between the camming plates **4602***a,b* and into the distal slots **4608***a*, and the pin **4606** of the second pulley **4604***b* may be arranged to extend between the camming plates **4602***a,b* and into the proximal slots **4608***b*. As illustrated, the distal and proximal slots **4608***a,b* of each camming plate **4602***a,b* are angled and extend in the same direction such that the distal slots **4608***a* align and the proximal slots **4608***b* align. Moreover, the slots **4608***a,b* converge toward or away from each other in a lateral direction, which allows the pulleys **4604***a,b* to progressively converge or diverge as the pins **4606** traverse the slots **4608***a,b*.

The proximal pulleys **4604***a,b* may be similar to the proximal pulley **1806***b* discussed above with reference to FIGS. **18**A-**18**C, and may thus have a corresponding proximal cable **4610***a* and **4610***b* extending (wrapped) thereabout, where the proximal cables **4610***a,b* are similar to the proximal cable **1804***b* of FIGS. **18**A-**18**C. As the slider **4506** is moved laterally, the camming plates **4602***a,b* correspondingly move laterally and force the pulleys **4604***a,b* (i.e., the pins **4606**) to traverse the slots **4608***a,b* defined in the camming plates **4602***a,b*. As they traverse the slots **4608***a,b*, the pulleys **4604***a,b* converge toward each other or diverge away from each other, depending on the direction of the slider **4506**, which correspondingly changes the length of the cables **4610***a,b* within the system. For example, moving the slider **4506** to the left in FIGS. **46**A-**46**B will tend make the pulleys converge toward each other, and moving the slider **4506** to the right in FIGS. **46**A-**46**B will tend make the pulleys diverge away from each other. The net cable length of the cables **4610***a,b*, however, remains the same because the two pulleys **4604***a,b* have the same displacement, but the change in length of each pair changes, which causes movement (actuation) of the jaws **1608**, **1610** (FIG. **37**). In alternative embodiments, this cable configuration may be configured to allow pitch and yaw articulations of the wrist **1606** (FIG. **37**) to create motion where each cable loop rolls around its respective pulley system.

As best seen in FIG. **46**B, the pulleys **4604***a,b* may be configured as spools rotatably mounted to their corresponding pins **4606**, and each spool has two parts that are matable at a corresponding engagement feature **4612**. When the two parts are properly mated, the engagement feature **4612** prevents the two parts of each pulley **4604***a,b* from rotating relative to the other. When separated, however, the two parts may be able to rotate relative to one another. In the illustrated embodiment, the engagement features **4612** comprise castellated features, but could alternatively comprise other types of structural features that prevent relative rotation of the opposing parts when engaged, but allow relative rotation when separated. Assembly pretension in the cable system can be achieved by rotating the two parts of each pulley **4604***a,b* in opposite directions in order to apply a set torque load on the associated cables **4610***a,b*, and thus creating the desired pretension in the system. Once the desired (predetermined) tension is reached, the two parts may be mated once again at the engagement feature **4612** to hold the pretension of the system.

FIG. **47** is an enlarged isometric view of another example tailpiece **4702**, according to one or more additional embodiments. The tailpiece **4702** may be similar in respects to the tailpiece **3702** of FIGS. **43-44**, and may thus be best understood with reference thereto. For example, similar to the tailpiece **3702**, the tailpiece **4702** may be arranged at the proximal end of the shaft **1602** and may comprise a mechanical device that provides a means for manually controlling the end effector **1604** (FIG. **37**) and/or the wrist **1606** (FIG. **37**). The tailpiece **4702** may also be used to maintain tension in the surgical tool **3700** (FIG. **37**) when disconnected from the instrument driver **3706** (FIG. **37**).

The tailpiece **4702** may include a housing **4704** that may be attached to the proximal end of the shaft **1602**. In FIG. **47**, an upper portion of the housing **4704** is omitted to enable viewing of the internal components and mechanics of the tailpiece **4702**. The tailpiece **4702** may further include a manual actuation device, which, in this embodiment, comprises a slider **4706** that extends out of the housing **4704** and provides a means for manually actuating the tailpiece **4702**. Similar to the slider **4308** of FIGS. **43-44**, the slider **4706** extends past an outer circumferential periphery of the housing **4704**. As the slider **4706** is manually moved (rotated) about a portion of the outer circumference, the end effector **1604** (FIG. **37**) may be actuated or the wrist **1606** (FIG. **37**) may be articulated.

Unlike the tailpiece **3702** of FIGS. **43-44**, however, the tailpiece **4702** includes an internal linear slider **4708** movably mounted within the housing **4704**. A first end **4710***a* of the slider **4706** extends out of the housing **4704** to be manually manipulated by the user, but the opposing second end **4710***b* of the slider **4706** is configured to interact with the linear slider **4708** such that manually sliding (rotating) the slider **4706** causes the linear slider **4708** to move laterally within the housing **4704**. In some embodiments, for example, the linear slider **4708** may define or otherwise provide a rack gear **4712**, and the second end **4710***b* of the slider **4706** may define or otherwise provide a pinion gear **4714** (mostly occluded) arranged to engage and mate with the rack gear **4712**. As the slider **4706** is moved (rotated), the pinion gear **4714** drives against the rack gear **4712** and thereby causes the linear slider **4708** to move laterally within the housing **4704**, depending on the driving direction of the pinion gear **4714**.

The tailpiece **4702** may further include first and second proximal pulleys **4714***a* and **4714***b* rotatably mounted to opposing ends of the linear slider **4708**. The proximal pulleys **4714***a,b* may be similar to the proximal pulley **1806***b* discussed above with reference to FIGS. **18**A-**18**C, and thus have corresponding proximal cables **4716***a* and **4716***b* extending (wrapped) thereabout, where the proximal cables **4716***a,b* are similar to the proximal cable **1804***b* of FIGS. **18**A-**18**C. The proximal cables **4716***a,b* may be routed to and from the shaft **1602** using one or more rerouting pulleys (not shown).

When the slider **4706** is manually moved in either angular direction relative to the outer circumference of the housing **4704**, the linear slider **4708** moves linearly within the housing **4704**. As the linear slider **4708** moves, the axis of each proximal pulley **4714***a,b* is moved relative to the axis of the shaft **1602**. As a result, and depending on the sliding direction of the linear slider **4708**, one of the proximal pulleys **4714***a,b* will draw in its proximal cable **4716***a,b* from the shaft **1602**, and the other proximal pulley **4714***a,b* will simultaneously pay out its proximal cable **4716***a,b* to the shaft **1602**. Consequently, the net cable length of the cables **4716***a,b* remains the same because the two pulleys **4714***a,b* will have the same displacement, but the change in length of each pair changes, which causes movement (actuation) of the jaws **1608**, **1610** (FIG. **37**). In alternative embodiments, this cable configuration may alternatively allow pitch and yaw articulations at the wrist **1606** (FIG. **37**) to create motion where each cable loop rolls around its respective pulley system.

The tailpiece **4702** may also be useful in facilitating assembly pretension in the cable system. More specifically, in some embodiments, the pulleys **4714***a,b* may be rotatably mounted to the linear slider **4708** using corresponding pulley brackets **4718***a,b*. During assembly of the tool, the pulley brackets **4718***a,b* can be adjusted relative to the linear slider **4708** so that a set torque load (tension) on the cables **4716***a,b* is created; e.g., the axis of the pulleys **4714***a,b* may be pulled outward from the device or shaft **1602** centerline. Once the predetermined tension is achieved, the pulley brackets **4718***a,b* may be secured to the linear slider **4708** in that position using one or more mechanical fasteners (not shown) accessible to the pulley brackets **4718***a,b* via one or more apertures **4720** (one shown) defined in the linear slider **4708**.

Embodiments disclosed herein include:

A. A robotic surgical tool includes a handle providing a plurality of drive inputs and a shaft drive input, an instrument driver providing a plurality of drive outputs and a shaft drive output, an elongate shaft extendable through the handle and the instrument driver, an end effector arranged at a distal end of the shaft and an articulable wrist interposing the end effector and the distal end, and a decoupler interposing the handle and the instrument driver and including a plurality of differential assemblies mounted to a decoupler housing, each differential assembly including a differential input matable with a corresponding one of the plurality of drive outputs, and a differential output matable with a corresponding one of the plurality of drive inputs, wherein rotation of a given drive output will actuate a corresponding differential assembly and thereby rotate a corresponding one of the plurality of drive inputs to operate the end effector or articulate the wrist, an insertion assembly mounted to the decoupler housing and including an insertion input matable with the shaft drive output, and an insertion output matable with the shaft drive input such that rotation of the shaft drive output will actuate the insertion assembly and thereby rotate the shaft drive input to cause the shaft to move axially relative to the handle and the instrument driver, and a differential gear train extending between the insertion assembly and each differential assembly such that actuation of the insertion assembly correspondingly actuates each differential assembly as the shaft moves.

B. A method of operating a robotic surgical tool includes arranging a robotic surgical tool adjacent a patient, the robotic surgical tool including, a handle providing a plurality of drive inputs and a shaft drive input, an instrument driver providing a plurality of drive outputs and a shaft drive output, an elongate shaft extendable through the handle and the instrument driver, an end effector arranged at a distal end of the shaft and an articulable wrist interposing the end effector and the distal end, and a decoupler interposing the handle and the instrument driver and including a plurality of differential assemblies, an insertion assembly, and a differential gear train extending between the insertion assembly and each differential assembly such that actuation of the insertion assembly correspondingly actuates each differential assembly. The method further includes actuating the shaft drive input and thereby rotating the insertion assembly and the shaft drive input to cause the shaft to move axially relative to the handle and the instrument driver, and actuating each differential assembly via the differential gear train as the shaft moves.

Each of embodiments A and B may have one or more of the following additional elements in any combination: Element 1: further comprising a sterile barrier arranged between the handle and the decoupler, wherein the decoupler forms part of the instrument driver. Element 2: wherein the decoupler forms part of the handle. Element 3: further comprising an actuation system housed within the handle and operatively coupled to the plurality of drive inputs and the shaft drive input such that actuation of the plurality of the drive inputs causes operation of the end effector or the wrist and actuation of the shaft drive input causes the shaft to move axially relative to the handle and the instrument driver. Element 4: wherein the actuation system includes a plurality of sliding rack gears movably nested within a corresponding plurality of longitudinal channels defined along a portion of the shaft, and a gear train extending between each drive input and each sliding rack gear such that actuation of a given drive input drives a corresponding one of the plurality of sliding rack gears to move within a corresponding one of the plurality of longitudinal channels. Element 5: wherein the plurality of sliding rack gears includes a first rack gear nested within a first longitudinal channel, and a second rack gear nested within a second longitudinal channel, and wherein the actuation system further includes a distal pulley positioned at a distal end of the shaft and operatively coupled to the end effector or the wrist, and a distal cable wrapped around the distal pulley and having first and second ends attached to distal ends of the first and second rack gears, respectively, wherein antagonistically moving the first and second rack gears causes the end effector or the wrist to operate. Element 6: wherein the actuation system further includes a shaft rack gear defined on the shaft, and a gear train extending between the shaft drive input and the shaft rack gear such that actuation of the shaft drive input drives the shaft to move axially relative to the handle and the instrument driver. Element 7: wherein the differential gear train includes an insertion input gear mounted to the insertion assembly, and an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential insertion input gear of each differential assembly, wherein as the insertion assembly actuates, the insertion transmission gear drives against the differential insertion input gear of each differential assembly to correspondingly operate each differential assembly. Element 8: wherein each differential assembly further includes a drive shaft having opposing first and second ends, the differential input being located at the first end, the differential output being located at the second end, and the differential insertion input gear being arranged at a location between the first and second ends, and a differential mounted to the drive shaft and including a lower bevel gear secured to the drive shaft, an upper bevel gear driven by rotation of the differential insertion input gear, an axle mounted to a carrier, and a pair of opposing carrier gears rotatably mounted to the axle and extending between the upper and lower bevel gears, wherein rotation of the differential output is independently driven by both the differential input and the differential insertion input gear. Element 9: wherein the differential output comprises a first differential output coupled to the drive shaft such that actuating the differential input drives the drive shaft and simultaneously rotates the first differential output, a second differential output coaxially aligned with the first differential output and operatively coupled to the lower bevel gear such that actuating the differential insertion input gear causes the differential to drive the lower bevel gear and simultaneously rotate the second differential output. Element 10: wherein the insertion assembly comprises a planetary gear box that includes a sun gear, a plurality of planetary gears surrounding and intermeshed with the sun gear, and a planet carrier coupled to each planetary gear, the differential gear train further including an insertion input gear surrounding and intermeshing with the plurality of planetary gears, and an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential ring gear of each differential assembly, wherein as the insertion assembly actuates, the insertion transmission gear drives against the differential ring gear of each differential assembly to correspondingly actuate each differential assembly. Element 11: wherein each differential assembly further includes opposing first and second ends, the differential input being located at the first end, the differential output being located at the second end, and the differential ring gear being arranged at a location between the first and second ends, and a differential including a sun gear, a plurality of planetary gears surrounding the sun gear of the differential, and a planet carrier coupled to each planetary gear of the differential, wherein the differential ring gear of each differential assembly surrounds and intermeshes with the plurality of planetary gears of the differential, and wherein rotation of the differential output is independently driven by both the differential input and the differential ring gear. Element 12: wherein the differential assembly further includes a drive shaft, and the sun gear and the planet carrier of the differential are mounted to the drive shaft such that rotation of the drive shaft correspondingly rotates the sun gear and the planet carrier of the differential. Element 13: wherein the sun gear of the differential is keyed to the decoupler housing at or near the insertion input. Element 14: wherein each differential assembly further includes an input shaft axially aligned with an output shaft, the differential input being located on the input shaft, the differential output being located on the output shaft, and the differential ring gear being mounted to the output shaft, a housing and an offset axle that extends between the housing and the differential ring gear, the offset axle extending parallel to but eccentric from the input and output shafts, and a first offset gear provided on the offset axle and arranged to engage an input shaft gear mounted to the input shaft, a second offset gear provided on the offset axle and arranged to engage an output shaft gear mounted to the output shaft, wherein the differential output is driven by the differential input through the offset axle, and wherein the differential output is driven by the insertion assembly acting on the differential ring gear. Element 15: wherein the insertion assembly further includes a drive shaft with opposing first and second ends, the insertion input being located at the first end, and the insertion output being located at the second end, an insertion input gear mounted to the drive shaft at a location between the first and second ends, an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential ring gear of each differential assembly, a housing and an offset axle that extends between the housing and the insertion input gear, the offset axle extending parallel to but eccentric from the drive shaft, a first offset gear provided on the offset axle and arranged to engage a stationary gear, and a second offset gear provided on the offset axle and arranged to engage drive shaft gear mounted to the drive shaft, wherein as the insertion assembly actuates, the insertion transmission gear drives against the differential ring gear of each differential assembly to correspondingly actuate each differential assembly.

Element 16: wherein each differential assembly includes a differential input matable with a corresponding one of the plurality of drive outputs, and a differential output matable with a corresponding one of the plurality of drive inputs, wherein rotation of a given drive output will actuate a corresponding differential assembly and thereby rotate a corresponding one of the plurality of drive inputs to operate the end effector or articulate the wrist, and the insertion assembly includes an insertion input matable with the shaft drive output, and an insertion output matable with the shaft drive input such that rotation of the shaft drive output will actuate the insertion assembly and thereby rotate the shaft drive input to cause the shaft to move axially relative to the handle and the instrument driver. Element 17: further comprising actuating one of the plurality of drive outputs and thereby transferring torque to a corresponding one of the plurality of drive inputs via the decoupler, and rotating the corresponding one of the plurality of drive inputs and thereby operating the end effector or articulating the wrist independent of operation of the insertion assembly. Element 18: wherein the differential gear train includes an insertion input gear mounted to the insertion assembly, and an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential insertion input gear of each differential assembly, the method further comprising actuating the insertion assembly and thereby driving the insertion transmission gear against the differential insertion input gear of each differential assembly to correspondingly actuate each differential assembly.

By way of non-limiting example, exemplary combinations applicable to A and B include: Element 3 with Element 4; Element 4 with Element 5; Element 3 with Element 6; Element 7 with Element 8; Element 8 with Element 9; Element 10 with Element 11; Element 11 with Element 12; and Element 12 with Element 13.

3. Implementing Systems and Terminology

Implementations disclosed herein provide systems, methods and apparatus for instruments for use with robotic systems. It should be noted that the terms "couple," "coupling," "coupled" or other variations of the word couple as used herein may indicate either an indirect connection or a direct connection. For example, if a first component is "coupled" to a second component, the first component may be either indirectly connected to the second component via another component or directly connected to the second component.

The methods disclosed herein comprise one or more steps or actions for achieving the described method. The method steps and/or actions may be interchanged with one another without departing from the scope of the claims. In other words, unless a specific order of steps or actions is required for proper operation of the method that is being described, the order and/or use of specific steps and/or actions may be modified without departing from the scope of the claims.

As used herein, the term "plurality" denotes two or more. For example, a plurality of components indicates two or more components. The term "determining" encompasses a wide variety of actions and, therefore, "determining" can include calculating, computing, processing, deriving, investigating, looking up (e.g., looking up in a table, a database or another data structure), ascertaining and the like. Also, "determining" can include receiving (e.g., receiving information), accessing (e.g., accessing data in a memory) and the like. Also, "determining" can include resolving, selecting, choosing, establishing and the like.

The phrase "based on" does not mean "based only on," unless expressly specified otherwise. In other words, the phrase "based on" describes both "based only on" and "based at least on."

As used herein, the terms "generally" and "substantially" are intended to encompass structural or numeral modification, which do not significantly affect the purpose of the element or number modified by such term.

To aid the Patent Office and any readers of this application and any resulting patent in interpreting the claims appended herein, applicants do not intend any of the appended claims or claim elements to invoke 35 U.S.C. 112(f) unless the words "means for" or "step for" are explicitly used in the particular claim.

The foregoing previous description of the disclosed implementations is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these implementations will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other implementations without departing from the scope of the invention. For example, it will be appreciated that one of ordinary skill in the art will be able to employ a number corresponding alternative and equivalent structural details, such as equivalent ways of fastening, mounting, coupling, or engaging tool components, equivalent mechanisms for producing particular actuation motions, and equivalent mechanisms for delivering electrical energy. Thus, the present invention is not intended to be limited to the implementations shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

What is claimed is:

1. A robotic surgical tool, comprising:
- a handle providing a plurality of drive inputs and a shaft drive input;
- an instrument driver providing a plurality of drive outputs and a shaft drive output;
- an elongate shaft extendable through the handle and the instrument driver;
- an end effector arranged at a distal end of the shaft and an articulable wrist interposing the end effector and the distal end; and
- a decoupler interposing the handle and the instrument driver and including:
  - a plurality of differential assemblies mounted to a decoupler housing, each differential assembly including a differential input matable with a corresponding one of the plurality of drive outputs, and a differential output matable with a corresponding one of the plurality of drive inputs, wherein rotation of a given drive output will actuate a corresponding differential assembly and thereby rotate a corresponding one of the plurality of drive inputs to operate the end effector or articulate the wrist;
  - an insertion assembly mounted to the decoupler housing and including an insertion input matable with the shaft drive output, and an insertion output matable with the shaft drive input such that rotation of the shaft drive output will actuate the insertion assembly and thereby rotate the shaft drive input to cause the shaft to move axially relative to the handle and the instrument driver; and
  - a differential gear train extending between the insertion assembly and each differential assembly such that actuation of the insertion assembly correspondingly actuates each differential assembly as the shaft moves.

2. The robotic surgical tool of claim **1**, further comprising a sterile barrier arranged between the handle and the decoupler, wherein the decoupler forms part of the instrument driver.

3. The robotic surgical tool of claim **1**, wherein the decoupler forms part of the handle.

4. The robotic surgical tool of claim **1**, further comprising an actuation system housed within the handle and operatively coupled to the plurality of drive inputs and the shaft drive input such that actuation of the plurality of the drive inputs causes operation of the end effector or the wrist and actuation of the shaft drive input causes the shaft to move axially relative to the handle and the instrument driver.

5. The robotic surgical tool of claim **4**, wherein the actuation system includes:
- a plurality of sliding rack gears movably nested within a corresponding plurality of longitudinal channels defined along a portion of the shaft; and
- a gear train extending between each drive input and each sliding rack gear such that actuation of a given drive input drives a corresponding one of the plurality of sliding rack gears to move within a corresponding one of the plurality of longitudinal channels.

6. The robotic surgical tool of claim **5**, wherein the plurality of sliding rack gears includes a first rack gear nested within a first longitudinal channel, and a second rack gear nested within a second longitudinal channel, and wherein the actuation system further includes:
- a distal pulley positioned at a distal end of the shaft and operatively coupled to the end effector or the wrist; and
- a distal cable wrapped around the distal pulley and having first and second ends attached to distal ends of the first and second rack gears, respectively, wherein antagonistically moving the first and second rack gears causes the end effector or the wrist to operate.

7. The robotic surgical tool of claim **4**, wherein the actuation system further includes:
- a shaft rack gear defined on the shaft; and
- a gear train extending between the shaft drive input and the shaft rack gear such that actuation of the shaft drive input drives the shaft to move axially relative to the handle and the instrument driver.

8. The robotic surgical tool of claim **1**, wherein the differential gear train includes:
- an insertion input gear mounted to the insertion assembly; and
- an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential insertion input gear of each differential assembly,
- wherein as the insertion assembly actuates, the insertion transmission gear drives against the differential insertion input gear of each differential assembly to correspondingly operate each differential assembly.

9. The robotic surgical tool of claim **8**, wherein each differential assembly further includes:
- a drive shaft having opposing first and second ends, the differential input being located at the first end, the differential output being located at the second end, and the differential insertion input gear being arranged at a location between the first and second ends; and
- a differential mounted to the drive shaft and including:
  - a lower bevel gear secured to the drive shaft;
  - an upper bevel gear driven by rotation of the differential insertion input gear;

an axle mounted to a carrier; and

a pair of opposing carrier gears rotatably mounted to the axle and extending between the upper and lower bevel gears,

wherein rotation of the differential output is independently driven by both the differential input and the differential insertion input gear.

10. The robotic surgical tool of claim **9**, wherein the differential output comprises:

a first differential output coupled to the drive shaft such that actuating the differential input drives the drive shaft and simultaneously rotates the first differential output; and

a second differential output coaxially aligned with the first differential output and operatively coupled to the lower bevel gear such that actuating the differential insertion input gear causes the differential to drive the lower bevel gear and simultaneously rotate the second differential output.

11. The robotic surgical tool of claim **1**, wherein the insertion assembly comprises a planetary gear box that includes a sun gear, a plurality of planetary gears surrounding and intermeshed with the sun gear, and a planet carrier coupled to each planetary gear, the differential gear train further including:

an insertion input gear surrounding and intermeshing with the plurality of planetary gears; and

an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential ring gear of each differential assembly,

wherein as the insertion assembly actuates, the insertion transmission gear drives against the differential ring gear of each differential assembly to correspondingly actuate each differential assembly.

12. The robotic surgical tool of claim **11**, wherein each differential assembly further includes:

opposing first and second ends, the differential input being located at the first end, the differential output being located at the second end, and the differential ring gear being arranged at a location between the first and second ends; and

a differential including a sun gear, a plurality of planetary gears surrounding the sun gear of the differential, and a planet carrier coupled to each planetary gear of the differential,

wherein the differential ring gear of each differential assembly surrounds and intermeshes with the plurality of planetary gears of the differential, and

wherein rotation of the differential output is independently driven by both the differential input and the differential ring gear.

13. The robotic surgical tool of claim **12**, wherein the differential assembly further includes a drive shaft, and the sun gear and the planet carrier of the differential are mounted to the drive shaft such that rotation of the drive shaft correspondingly rotates the sun gear and the planet carrier of the differential.

14. The robotic surgical tool of claim **13**, wherein the sun gear of the differential is keyed to the decoupler housing at or near the insertion input.

15. The robotic surgical tool of claim **1**, wherein each differential assembly further includes:

an input shaft axially aligned with an output shaft, the differential input being located on the input shaft, the differential output being located on the output shaft, and the differential ring gear being mounted to the output shaft;

a housing and an offset axle that extends between the housing and the differential ring gear, the offset axle extending parallel to but eccentric from the input and output shafts;

a first offset gear provided on the offset axle and arranged to engage an input shaft gear mounted to the input shaft; and

a second offset gear provided on the offset axle and arranged to engage an output shaft gear mounted to the output shaft,

wherein the differential output is driven by the differential input through the offset axle, and

wherein the differential output is driven by the insertion assembly acting on the differential ring gear.

16. The robotic surgical tool of claim **1**, wherein the insertion assembly further includes:

a drive shaft with opposing first and second ends, the insertion input being located at the first end, and the insertion output being located at the second end;

an insertion input gear mounted to the drive shaft at a location between the first and second ends;

an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential ring gear of each differential assembly;

a housing and an offset axle that extends between the housing and the insertion input gear, the offset axle extending parallel to but eccentric from the drive shaft;

a first offset gear provided on the offset axle and arranged to engage a stationary gear; and

a second offset gear provided on the offset axle and arranged to engage drive shaft gear mounted to the drive shaft,

wherein as the insertion assembly actuates, the insertion transmission gear drives against the differential ring gear of each differential assembly to correspondingly actuate each differential assembly.

17. A method of operating a robotic surgical tool, comprising:

arranging a robotic surgical tool adjacent a patient, the robotic surgical tool including:

a handle providing a plurality of drive inputs and a shaft drive input;

an instrument driver providing a plurality of drive outputs and a shaft drive output;

an elongate shaft extendable through the handle and the instrument driver;

an end effector arranged at a distal end of the shaft and an articulable wrist interposing the end effector and the distal end; and

a decoupler interposing the handle and the instrument driver and including a plurality of differential assemblies, an insertion assembly, and a differential gear train extending between the insertion assembly and each differential assembly such that actuation of the insertion assembly correspondingly actuates each differential assembly;

actuating the shaft drive input and thereby:

rotating the insertion assembly and the shaft drive input to cause the shaft to move axially relative to the handle and the instrument driver; and

actuating each differential assembly via the differential gear train as the shaft moves.

18. The method of claim **17**, wherein:

each differential assembly includes a differential input matable with a corresponding one of the plurality of drive outputs, and a differential output matable with a corresponding one of the plurality of drive inputs, wherein rotation of a given drive output will actuate a corresponding differential assembly and thereby rotate a corresponding one of the plurality of drive inputs to operate the end effector or articulate the wrist; and

the insertion assembly includes an insertion input matable with the shaft drive output, and an insertion output matable with the shaft drive input such that rotation of the shaft drive output will actuate the insertion assembly and thereby rotate the shaft drive input to cause the shaft to move axially relative to the handle and the instrument driver.

19. The method of claim **17**, further comprising:

actuating one of the plurality of drive outputs and thereby transferring torque to a corresponding one of the plurality of drive inputs via the decoupler; and

rotating the corresponding one of the plurality of drive inputs and thereby operating the end effector or articulating the wrist independent of operation of the insertion assembly.

20. The method of claim **17**, wherein the differential gear train includes an insertion input gear mounted to the insertion assembly, and an insertion transmission gear driven by the insertion input gear and arranged to interface with a differential insertion input gear of each differential assembly, the method further comprising:

actuating the insertion assembly and thereby driving the insertion transmission gear against the differential insertion input gear of each differential assembly to correspondingly actuate each differential assembly.

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