

**(12) STANDARD PATENT**  
**(19) AUSTRALIAN PATENT OFFICE**

(11) Application No. **AU 2018384820 B2**

(54) Title  
**System and method for estimating instrument location**

(51) International Patent Classification(s)  
**B25J 9/16** (2006.01)                      **B25J 13/08** (2006.01)  
**A61B 5/06** (2006.01)

(21) Application No: **2018384820**                      (22) Date of Filing: **2018.12.13**

(87) WIPO No: **WO19/118767**

(30) Priority Data

(31) Number	(32) Date	(33) Country
<b>62/598,934</b>	<b>2017.12.14</b>	<b>US</b>

(43) Publication Date: **2019.06.20**

(44) Accepted Journal Date: **2024.07.04**

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(56) Related Art  
**US 2007/0265527 A1**  
**US 2017/0084027 A1**



(51) International Patent Classification:

B25J 9/16 (2006.01) A61B 5/06 (2006.01)  
B25J 13/08 (2006.01)

(21) International Application Number:

PCT/US2018/065530

(22) International Filing Date:

13 December 2018 (13.12.2018)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/598,934 14 December 2017 (14.12.2017) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available):

AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

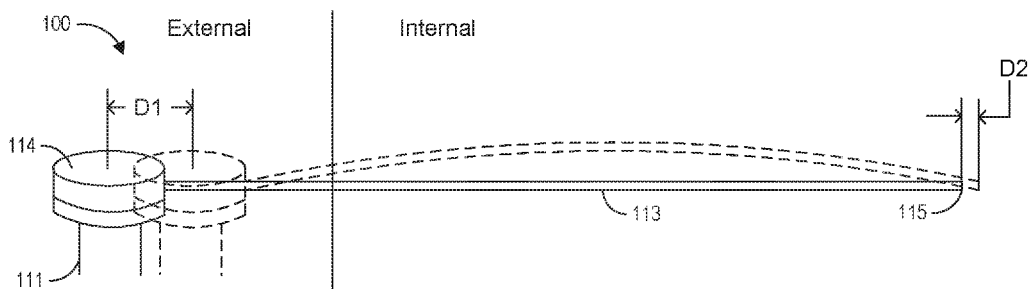
(84) Designated States (unless otherwise indicated, for every kind of regional protection available):

ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: SYSTEM AND METHOD FOR ESTIMATING INSTRUMENT LOCATION



**FIG. 17A**

(57) Abstract: Systems and methods for estimating instrument location are described. The methods and systems can obtain a first motion estimate based on robotic data and a second motion estimate based on position sensor data. The methods and systems can determine a motion estimate disparity based on a comparison of the first and second motion estimates. Based on the motion estimate disparity, the methods and systems can update a weighting factor for a location derivable from the robotic data or a weighting factor for a location derivable from the position sensor data. Based on the updated weighting factor, the methods and systems can determine a location/position estimate for the instrument. The methods and systems can provide increased accuracy for a position estimate in cases where the instrument experiences buckling or hysteresis.



# SYSTEM AND METHOD FOR ESTIMATING INSTRUMENT LOCATION

## TECHNICAL FIELD

[0001] This application relates generally to estimating a location of an instrument, and more particularly to systems and methods for estimating a location of a robotically-enabled medical instrument based on a comparison of location input data.

## BACKGROUND

[0002] Medical procedures such as endoscopy may involve accessing and visualizing the inside of a patient's luminal network for diagnostic and/or therapeutic purposes. For example, bronchoscopy is a medical procedure that allows a physician to examine airways, such as bronchi and bronchioles, in a patient's lungs. During the procedure, a thin, flexible instrument, known as a bronchoscope, may be inserted into the patient's mouth and passed down the patient's throat into the lung. The instrument is navigated through the lung's airways towards a tissue site identified for subsequent diagnosis and/or treatment.

[0003] In certain procedures, a robotically-enabled medical system may be used to control the insertion and/or manipulation of the instrument. The robotically-enabled medical system may include a robotic arm, or other instrument positioning device, having a manipulator assembly used to control the positioning of the instrument during the procedure.

## SUMMARY

[0003a] In an aspect of the present invention, there is provided a non-transitory computer readable storage medium having stored thereon instructions that, when executed, cause one or more processors to at least:

obtain a first position estimate for an instrument based on robotic data indicating movement of a robotic positioning device configured to mechanically manipulate the instrument;

obtain a second position estimate for the instrument based on position sensor data received from at least one position sensor associated with the instrument;

determine a position estimate disparity between the first position estimate and the second position estimate based on a comparison of the first position estimate and the second position estimate;

update one or more confidence weights indicating a confidence of the first position estimate relative to the second position estimate based at least in part on the determined position estimate disparity, said updating comprising:

decreasing a confidence weight associated with the robotic data,  
increasing a confidence weight associated with the position sensor data, or  
decreasing a confidence weight associated with an image-based position determination; and

determine a third position estimate for the instrument based on the updated one or more confidence weights.

**[0003b]** In another aspect of the present invention, there is provided a robotic system comprising:

an instrument having an elongate body and at least one position sensor disposed on the elongate body;

an instrument positioning device attached to the instrument and configured to move the instrument;

at least one computer-readable memory having stored thereon executable instructions;  
and

one or more processors in communication with the at least one computer-readable memory and configured to execute the instructions to cause the system to at least:

obtain a first position estimate for the instrument based on robotic data indicating movement of a robotic positioning device configured to mechanically manipulate the instrument;

obtain a second position estimate for the instrument based on position sensor data received from the at least one position sensor;

determine a position estimate disparity between the first position estimate and the second position estimate based on a comparison of the first position estimate and the second position estimate;

update one or more confidence weights indicating a confidence of the first position estimate relative to the second position estimate based at least in part on the determined position estimate disparity, said updating comprising:

the position sensor data; and determine a location/position estimate for the instrument based on the updated weighting factor.

[0005] The non-transitory computer readable storage medium can include one or more of the following features, in any combination: (a) wherein the instructions, when executed, cause the processor to: decrease the weighting factor for a location derivable from the robotic data, or increase the weighting factor for a location derivable from the position sensor data, when the motion estimate disparity indicates that the second motion estimate exceeds the first motion estimate; (b) wherein the instructions, when executed, cause the processor to determine that the instrument has experienced a hysteresis condition when the motion estimate disparity indicates that the second motion estimate exceeds the first motion estimate; (c) wherein the instructions, when executed, cause the processor to: decrease the weighting factor for a location derivable from the robotic data, or increase the weighting factor for a location derivable from the position sensor data, when the motion estimate disparity indicates that the first motion estimate exceeds the second motion estimate; (d) wherein the instructions, when executed, cause the processor to determine that the instrument has experienced a buckling condition when the motion estimate disparity indicates that the first motion estimate exceeds the second estimate; (e) wherein the instructions, when executed, cause the processor to update the weighting factor for a location derivable from the robotic data to zero; (f) wherein the instructions, when executed, cause the processor to determine the motion estimate disparity by determining a difference between the first motion estimate and the second motion estimate; (g) wherein the instructions, when executed, cause the processor to update: the weighting factor for a location derivable from the robotic data, or the weighting factor for a location derivable from the position sensor data, when the difference exceeds a disparity threshold value; (h) wherein the instructions, when executed, cause the processor to: obtain the first motion estimate by determining a change in position of the instrument based on the robotic data during an interval, and obtain the second motion estimate by determining a change in position of the instrument based on the position sensor data during the interval; (i) wherein the interval is a time interval; (j) wherein the interval is a distance interval; (k) wherein the position estimate is determined based on the updated weighting factor, the location derivable from the robotic data, and the location derivable from the position sensor data; (l) wherein the position sensor is positioned on the instrument; (m) wherein the position sensor comprises an EM sensor; (n) wherein the position sensor comprises an imaging device

positioned on the instrument, and wherein the processor is further configured to determine positional information from images captured by the imaging device; (o) wherein the at least one position sensor comprises at least one of: a shape-sensing fiber, an accelerometer, a gyroscope, an electromagnetic sensor, an imaging device, and an ultrasonic sensor; (p) wherein the instruction, when executed, are cause the processor to: obtain a third motion estimate for the instrument based on vision data received from an imaging device positioned on the instrument, determine the motion estimate disparity based on a comparison of the second motion estimate and the third motion estimate, and based on the motion estimate disparity, update a weighting factor for a location derivable from the vision data; (q) wherein the instructions, when executed, cause the processor to: increase the weighting factor for a location derivable from the position sensor data, or decrease the weighting factor for a location derivable from the vision, when the motion estimate disparity indicates that the second motion estimate exceeds the third motion estimate; (r) wherein the instructions, when executed, cause the processor to determine that the instrument has experienced a hysteresis condition when the motion estimate disparity indicates that the second motion estimate exceeds the third motion estimate; (s) wherein the instructions, when executed, cause the processor to: increase the weighting factor for a location derivable from the position sensor data, or decrease the weighting factor for a location derivable from the vision data, when the motion estimate disparity indicates that the third motion estimate exceeds the second motion estimate; and/or (t) wherein the instructions, when executed, cause the processor to determine that the instrument has experienced a buckling condition when the motion estimate disparity indicates that the third motion estimate exceeds the second estimate.

[0006] In another aspect, a robotic system is described. The robotic system includes an instrument having an elongate body and at least one position sensor disposed on the elongate body; an instrument positioning device attached to the instrument and configured to move the instrument; at least one computer-readable memory having stored thereon executable instructions; and one or more processors in communication with the at least one computer-readable memory and configured to execute the instructions to cause the system to at least: obtain a first motion estimate for the instrument based on robotic data regarding physical manipulation of the instrument with the instrument positioning device; obtain a second motion estimate for the instrument based on position sensor data received from at least one position sensor; determine a motion estimate disparity based on a comparison of the first motion estimate

and the second motion estimate; based on the motion estimate disparity, update: a weighting factor for a location derivable from the robotic data, or a weighting factor for a location derivable from the position sensor data; and determine a location/position estimate for the instrument based on the updated weighting factor.

[0007] The system may include one or more of the following features in any combination: (a) wherein the instrument comprises an endoscope; (b) wherein the instrument positioning device comprises a robotic arm; (c) wherein the at least one position sensor comprises an EM sensor; (d) wherein the at least one position sensor comprises an imaging device positioned on the instrument, and wherein the instructions further cause the one or more processors to determine positional information from images captured by the imaging device; (e) wherein the at least one position sensor comprises a shape-sensing fiber, an accelerometer, a gyroscope, an electromagnetic sensor, an imaging device, or an ultrasonic sensor; (f) wherein the instructions, when executed cause the one or more processors to: decrease the weighting factor for the location derivable from the robotic data, or increase the weighting factor for the location derivable from the position sensor data, when the motion estimate disparity indicates that the second motion estimate exceeds the first motion estimate; (g) wherein the instructions, when executed cause the one or more processors to: decrease the weighting factor for the location derivable from the robotic data, or increase the weighting factor for the location derivable from the position sensor data, when the motion estimate disparity indicates that the first motion estimate exceeds the second motion estimate; (h) wherein the instructions, when executed cause the one or more processors to determine that the instrument has experienced a buckling condition when the motion estimate disparity indicates that the first motion estimate exceeds the second motion estimate; (i) wherein the instructions, when executed cause the one or more processors to update the weighting factor for the location derivable from the robotic data to zero when the motion estimate disparity indicates that the second motion estimate exceeds the first motion estimate; (j) wherein the instructions, when executed cause the one or more processors to update the weighting factor for the location derivable from the position sensor data to zero when the motion estimate disparity indicates that the first motion estimate exceeds the second motion estimate; (k) when executed

cause the one or more processors to determine the motion estimate disparity by determining a difference between the first motion estimate and the second motion estimate; (l) wherein the instructions, when executed cause the one or more processors to update: the weighting factor for the location derivable from the robotic data, or the weighting factor for the location derivable from the position sensor data, when the difference exceeds a disparity threshold value; (m) wherein the instructions, when executed cause the one or more processors to: obtain the first motion estimate by determining a change in position of the instrument based on the robotic data during an interval, and obtain the second motion estimate by determining a change in position of the instrument based on the position sensor data during the interval; (n) wherein the interval is a time interval; and/or (o) wherein the interval is a distance interval.

[0008] In another aspect, a method for navigating an instrument within an interior region of a body is described. The method includes: obtaining a first motion estimate for an instrument based on robotic data regarding physical manipulation of the instrument; obtaining a second motion estimate for the instrument based on position sensor data received from at least one position sensor; determining a motion estimate disparity based on a comparison of the first motion estimate and the second motion estimate; based on the motion estimate disparity, updating: a weighting factor for a location derivable from the robotic data, or a weighting factor for a location derivable from the position sensor data; and determining a location/position estimate for the instrument based on the updated weighting factor.

[0009] The method may include one or more of the following features, in any combination: (a) wherein updating the weighting factor comprises decreasing the weighting factor for the location derivable from the robotic data, or increasing the weighting factor for the location derivable from the position sensor data, when the motion estimate disparity indicates that the second motion estimate exceeds the first motion estimate; (b) determining that the instrument has experienced a hysteresis condition when the motion estimate disparity indicates that the second motion estimate exceeds the first motion estimate; (c) wherein updating the weighting factor comprises decreasing the weighting factor for the location derivable from the robotic data, or increasing the weighting factor for the location derivable from the position sensor data, when the motion estimate disparity indicates that the first motion estimate exceeds the second motion estimate; (d) determining that the instrument has experienced a buckling condition when the motion estimate disparity indicates that the first motion estimate exceeds the

second motion estimate; (e) updating the weighting factor for the location derivable from the robotic data to zero when the motion estimate disparity indicates that the second motion estimate exceeds the first motion estimate; (f) updating the weighting factor for the location derivable from the position sensor data to zero when the motion estimate disparity indicates that the first motion estimate exceeds the second motion estimate; (g) determining the motion estimate disparity comprises determining a difference between the first motion estimate and the second motion estimate; (h) determining the difference comprises determining a magnitude of the difference; (i) updating the weighting factor for the location derivable from the robotic data, or the weighting factor for the location derivable from the position sensor data, when the difference exceeds a disparity threshold value; (j) obtaining the first motion estimate comprises determining a change in position of the instrument based on the robotic data during an interval, and obtaining the second motion estimate comprises determining a change in position of the instrument based on the position sensor data during the interval; (k) wherein the interval is a time interval; (l) wherein the interval is a distance interval; (m) wherein the position sensor is positioned on the instrument; (n) wherein the position sensor comprises an EM sensor; (o) wherein the position sensor comprises an imaging device positioned on the instrument, and wherein the method further comprises determining positional information from images captured by the imaging device; and/or (p) wherein the position sensor comprises a shape-sensing fiber, an accelerometer, a gyroscope, an electromagnetic sensor, an imaging device, or an ultrasonic sensor.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

[0010] 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.

[0011] FIG. 1 illustrates an embodiment of a cart-based robotic system arranged for diagnostic and/or therapeutic bronchoscopy procedure(s).

[0012] FIG. 2 depicts further aspects of the robotic system of FIG. 1.

[0013] FIG. 3 illustrates an embodiment of the robotic system of FIG. 1 arranged for ureteroscopy.

[0014] FIG. 4 illustrates an embodiment of the robotic system of FIG. 1 arranged for a vascular procedure.

[0015] FIG. 5 illustrates an embodiment of a table-based robotic system arranged for a bronchoscopy procedure.

[0016] FIG. 6 provides an alternative view of the robotic system of FIG. 5.

[0017] FIG. 7 illustrates an example system configured to stow robotic arm(s).

[0018] FIG. 8 illustrates an embodiment of a table-based robotic system configured for a ureteroscopy procedure.

[0019] FIG. 9 illustrates an embodiment of a table-based robotic system configured for a laparoscopic procedure.

[0020] FIG. 10 illustrates an embodiment of the table-based robotic system of FIGs. 5-9 with pitch or tilt adjustment.

[0021] FIG. 11 provides a detailed illustration of the interface between the table and the column of the table-based robotic system of FIGs. 5-10.

[0022] FIG. 12 illustrates an exemplary instrument driver.

[0023] FIG. 13 illustrates an exemplary medical instrument with a paired instrument driver.

[0024] FIG. 14 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.

[0025] 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. 1-10, such as the location of the instrument of FIGs. 13-14, in accordance to an example embodiment.

[0026] FIG. 16 depicts another block diagram illustrating the localization system of FIG. 15 in greater detail.

[0027] FIG. 17A illustrates an example of a medical instrument experiencing a buckling condition.

[0028] FIG. 17B illustrates an example of a medical instrument experiencing a hysteresis condition.

[0029] FIG. 18A is a flowchart illustrating an example method for determining a location/position estimate for a medical instrument based on a comparison of robotic data and position sensor data.

[0030] FIG. 18B is a flowchart illustrating an example method for determining a location/position estimate for a medical instrument based on a comparison of vision data and position sensor data.

[0031] FIG. 19 is a block diagram illustrating an embodiment of a robotically-enabled medical system configured to provide an estimate of instrument location with comparison of location input data.

## DETAILED DESCRIPTION

### 1. Overview.

[0032] 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, such as laparoscopy, and non-invasive, such as endoscopy, procedures. Among endoscopy procedures, the system may be capable of performing bronchoscopy, ureteroscopy, gastroscopy, etc.

[0033] 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.

[0034] 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. Such concepts may have applicability throughout the entire specification.

### A. Robotic System – Cart.

[0035] 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 10 arranged for a diagnostic and/or therapeutic bronchoscopy procedure. During a bronchoscopy, the system 10 may comprise a cart 11 having one or more

robotic arms 12 to deliver a medical instrument, such as a steerable endoscope 13, which may be a procedure-specific bronchoscope for bronchoscopy, to a natural orifice access point (i.e., the mouth of the patient positioned on a table in the present example) to deliver diagnostic and/or therapeutic tools. As shown, the cart 11 may be positioned proximate to the patient's upper torso in order to provide access to the access point. Similarly, the robotic arms 12 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. FIG. 2 depicts an example embodiment of the cart in greater detail.

[0036] With continued reference to FIG. 1, once the cart 11 is properly positioned, the robotic arms 12 may insert the steerable endoscope 13 into the patient robotically, manually, or a combination thereof. As shown, the steerable endoscope 13 may comprise at least two telescoping parts, such as an inner leader portion and an outer sheath portion, each portion coupled to a separate instrument driver from the set of instrument drivers 28, each instrument driver coupled to the distal end of an individual robotic arm. This linear arrangement of the instrument drivers 28, which facilitates coaxially aligning the leader portion with the sheath portion, creates a "virtual rail" 29 that may be repositioned in space by manipulating the one or more robotic arms 12 into different angles and/or positions. The virtual rails described herein are depicted in the Figures using dashed lines, and accordingly the dashed lines do not depict any physical structure of the system. Translation of the instrument drivers 28 along the virtual rail 29 telescopes the inner leader portion relative to the outer sheath portion or advances or retracts the endoscope 13 from the patient. The angle of the virtual rail 29 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 29 as shown represents a compromise between providing physician access to the endoscope 13 while minimizing friction that results from bending the endoscope 13 into the patient's mouth.

[0037] The endoscope 13 may be directed down the patient's trachea and lungs after insertion using precise commands from the robotic system until reaching the target destination or operative site. In order to enhance navigation through the patient's lung network and/or reach the desired target, the endoscope 13 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 28 also allows the leader portion and sheath portion to be driven independent of each other.

[0038] For example, the endoscope 13 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 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 nodule to be malignant, the endoscope 13 may endoscopically deliver tools to resect the potentially cancerous tissue. In some instances, diagnostic and therapeutic treatments may need to be delivered in separate procedures. In those circumstances, the endoscope 13 may also be used to deliver a fiducial to “mark” the location of the target nodule as well. In other instances, diagnostic and therapeutic treatments may be delivered during the same procedure.

[0039] The system 10 may also include a movable tower 30, which may be connected via support cables to the cart 11 to provide support for controls, electronics, fluidics, optics, sensors, and/or power to the cart 11. Placing such functionality in the tower 30 allows for a smaller form factor cart 11 that may be more easily adjusted and/or re-positioned by an operating physician and his/her staff. Additionally, the division of functionality between the cart / table and the support tower 30 reduces operating room clutter and facilitates improving clinical workflow. While the cart 11 may be positioned close to the patient, the tower 30 may be stowed in a remote location to stay out of the way during a procedure.

[0040] In support of the robotic systems described above, the tower 30 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 30 or the cart 11, 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, the motors in the joints of the robotics arms may position the arms into a certain posture.

[0041] The tower 30 may also include a pump, flow meter, valve control, and/or fluid access in order to provide controlled irrigation and aspiration capabilities to system that may be deployed through the endoscope 13. These components may also be controlled using the computer system of tower 30. In some embodiments, irrigation and aspiration capabilities may be delivered directly to the endoscope 13 through separate cable(s).

[0042] The tower 30 may include a voltage and surge protector designed to provide filtered and protected electrical power to the cart 11, thereby avoiding placement of a power transformer and other auxiliary power components in the cart 11, resulting in a smaller, more moveable cart 11.

[0043] The tower 30 may also include support equipment for the sensors deployed throughout the robotic system 10. For example, the tower 30 may include opto-electronics equipment for detecting, receiving, and processing data received from the optical sensors or cameras throughout the robotic system 10. 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 30. Similarly, the tower 30 may also include an electronic subsystem for receiving and processing signals received from deployed electromagnetic (EM) sensors. The tower 30 may also be used to house and position an EM field generator for detection by EM sensors in or on the medical instrument.

[0044] The tower 30 may also include a console 31 in addition to other consoles available in the rest of the system, e.g., console mounted on top of the cart. The console 31 may include a user interface and a display screen, such as a touchscreen, for the physician operator. Consoles in system 10 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 13. When the console 31 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.

[0045] The tower 30 may be coupled to the cart 11 and endoscope 13 through one or more cables or connections (not shown). In some embodiments, the support functionality from the tower 30 may be provided through a single cable to the cart 11, 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, the support for controls, optics, fluidics, and/or navigation may be provided through a separate cable.

[0046] FIG. 2 provides a detailed illustration of an embodiment of the cart from the cart-based robotically-enabled system shown in FIG. 1. The cart 11 generally includes an elongated support structure 14 (often referred to as a “column”), a cart base 15, and a console 16 at the top of the column 14. The column 14 may include one or more carriages, such as a carriage 17 (alternatively “arm support”) for supporting the deployment of one or more robotic arms 12 (three shown in FIG. 2). The carriage 17 may include individually configurable arm mounts that rotate along a perpendicular axis to adjust the base of the robotic arms 12 for better positioning relative to the patient. The carriage 17 also includes a carriage interface 19 that allows the carriage 17 to vertically translate along the column 14.

[0047] The carriage interface 19 is connected to the column 14 through slots, such as slot 20, that are positioned on opposite sides of the column 14 to guide the vertical translation of the carriage 17. The slot 20 contains a vertical translation interface to position and hold the carriage at various vertical heights relative to the cart base 15. Vertical translation of the carriage 17 allows the cart 11 to adjust the reach of the robotic arms 12 to meet a variety of table heights, patient sizes, and physician preferences. Similarly, the individually configurable arm mounts on the carriage 17 allow the robotic arm base 21 of robotic arms 12 to be angled in a variety of configurations.

[0048] In some embodiments, the slot 20 may be supplemented with slot covers that are flush and parallel to the slot surface to prevent dirt and fluid ingress into the internal chambers of the column 14 and the vertical translation interface as the carriage 17 vertically translates. The slot covers may be deployed through pairs of spring spools positioned near the vertical top and bottom of the slot 20. The covers are coiled within the spools until deployed to extend and retract from their coiled state as the carriage 17 vertically translates up and down. The spring-loading of the spools provides force to retract the cover into a spool when carriage 17 translates towards the spool, while also maintaining a tight seal when the carriage 17 translates away from the spool. The covers may be connected to the carriage 17 using, for example, brackets in the carriage interface 19 to ensure proper extension and retraction of the cover as the carriage 17 translates.

[0049] The column 14 may internally comprise mechanisms, such as gears and motors, that are designed to use a vertically aligned lead screw to translate the carriage 17 in a mechanized fashion in response to control signals generated in response to user inputs, e.g., inputs from the console 16.

[0050] The robotic arms 12 may generally comprise robotic arm bases 21 and end effectors 22, separated by a series of linkages 23 that are connected by a series of joints 24, each joint comprising an independent actuator, each actuator comprising an independently controllable motor. Each independently controllable joint represents an independent degree of freedom available to the robotic arm. Each of the arms 12 have seven joints, and thus provide seven degrees of freedom. A multitude of joints result in a multitude of degrees of freedom, allowing for “redundant” degrees of freedom. Redundant degrees of freedom allow the robotic arms 12 to position their respective end effectors 22 at a specific position, orientation, and trajectory in space using different linkage positions and joint angles. This allows for the system to position and direct a medical instrument from a desired point in space while allowing the physician to move the arm joints into a clinically advantageous position away from the patient to create greater access, while avoiding arm collisions.

[0051] The cart base 15 balances the weight of the column 14, carriage 17, and arms 12 over the floor. Accordingly, the cart base 15 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 15 includes rollable wheel-shaped casters 25 that allow for the cart to easily move around the room prior to a procedure. After reaching the appropriate position, the casters 25 may be immobilized using wheel locks to hold the cart 11 in place during the procedure.

[0052] Positioned at the vertical end of column 14, the console 16 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 26) to provide the physician user with both pre-operative and intra-operative data. Potential pre-operative data on the touchscreen 26 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 display 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 16 may be positioned and tilted to allow a physician to access the console from the side of the column 14 opposite carriage 17. From this position the physician may view the console 16, robotic arms 12, and patient while operating the console 16 from behind the cart 11. As shown, the console 16 also includes a handle 27 to assist with maneuvering and stabilizing cart 11.

[0053] FIG. 3 illustrates an embodiment of a robotically-enabled system 10 arranged for ureteroscopy. In a ureteroscopic procedure, the cart 11 may be positioned to deliver a ureteroscope 32, 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 32 to be directly aligned with the patient's urethra to reduce friction and forces on the sensitive anatomy in the area. As shown, the cart 11 may be aligned at the foot of the table to allow the robotic arms 12 to position the ureteroscope 32 for direct linear access to the patient's urethra. From the foot of the table, the robotic arms 12 may insert the ureteroscope 32 along the virtual rail 33 directly into the patient's lower abdomen through the urethra.

[0054] After insertion into the urethra, using similar control techniques as in bronchoscopy, the ureteroscope 32 may be navigated into the bladder, ureters, and/or kidneys for diagnostic and/or therapeutic applications. For example, the ureteroscope 32 may be directed into the ureter and kidneys to break up kidney stone build up using laser or ultrasonic lithotripsy device deployed down the working channel of the ureteroscope 32. After lithotripsy is complete, the resulting stone fragments may be removed using baskets deployed down the ureteroscope 32.

[0055] FIG. 4 illustrates an embodiment of a robotically-enabled system similarly arranged for a vascular procedure. In a vascular procedure, the system 10 may be configured such the cart 11 may deliver a medical instrument 34, 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 relatively less circuitous and tortuous path to the patient's heart, which simplifies navigation. As in a ureteroscopic procedure, the cart 11 may be positioned towards the patient's legs and lower abdomen to allow the robotic arms 12 to provide a virtual rail 35 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 34 may be directed and inserted by translating the instrument drivers 28. Alternatively, the cart 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 shoulder and wrist.

### **B. Robotic System -- Table.**

[0056] 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. 5 illustrates an embodiment of such a robotically-enabled system arranged for a bronchoscopy procedure. System 36 includes a support structure or column 37 for supporting platform 38 (shown as a "table" or "bed") over the floor. Much like in the cart-based systems, the end effectors of the robotic arms 39 of the system 36 comprise instrument drivers 42 that are designed to manipulate an elongated medical instrument, such as a bronchoscope 40 in FIG. 5, through or along a virtual rail 41 formed from the linear alignment of the instrument drivers 42. 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 table 38.

[0057] FIG. 6 provides an alternative view of the system 36 without the patient and medical instrument for discussion purposes. As shown, the column 37 may include one or more carriages 43 shown as ring-shaped in the system 36, from which the one or more robotic arms 39 may be based. The carriages 43 may translate along a vertical column interface 44 that runs the length of the column 37 to provide different vantage points from which the robotic arms 39 may be positioned to reach the patient. The carriage(s) 43 may rotate around the column 37 using a mechanical motor positioned within the column 37 to allow the robotic arms 39 to have access to multiples sides of the table 38, such as, for example, both sides of the patient. In embodiments with multiple carriages, the carriages may be individually positioned on the column and may translate and/or rotate independent of the other carriages. While carriages 43 need not surround the column 37 or even be circular, the ring-shape as shown facilitates rotation of the carriages 43 around the column 37 while maintaining structural balance. Rotation and translation of the carriages 43 allows the system to align the medical instruments, such as endoscopes and laparoscopes, into different access points on the patient.

[0058] The arms 39 may be mounted on the carriages through a set of arm mounts 45 comprising a series of joints that may individually rotate and/or telescopically extend to provide additional configurability to the robotic arms 39. Additionally, the arm mounts 45 may be

positioned on the carriages 43 such that, when the carriages 43 are appropriately rotated, the arm mounts 45 may be positioned on either the same side of table 38 (as shown in FIG. 6), on opposite sides of table 38 (as shown in FIG. 9), or on adjacent sides of the table 38 (not shown).

[0059] The column 37 structurally provides support for the table 38, and a path for vertical translation of the carriages. Internally, the column 37 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 37 may also convey power and control signals to the carriage 43 and robotic arms 39 mounted thereon.

[0060] The table base 46 serves a similar function as the cart base 15 in cart 11 shown in FIG. 2, housing heavier components to balance the table/bed 38, the column 37, the carriages 43, and the robotic arms 39. The table base 46 may also incorporate rigid casters to provide stability during procedures. Deployed from the bottom of the table base 46, the casters may extend in opposite directions on both sides of the base 46 and retract when the system 36 needs to be moved.

[0061] Continuing with FIG. 6, the system 36 may also include a tower (not shown) that divides the functionality of system 36 between table and tower to reduce the form factor and bulk of the table. As in earlier disclosed embodiments, the tower may provide a variety of support functionalities to table, 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 for potential stowage of the robotic arms. The tower may also include a 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.

[0062] In some embodiments, a table base may stow and store the robotic arms when not in use. FIG. 7 illustrates a system 47 that stows robotic arms in an embodiment of the table-based system. In system 47, carriages 48 may be vertically translated into base 49 to stow robotic arms 50, arm mounts 51, and the carriages 48 within the base 49. Base covers 52 may be translated and retracted open to deploy the carriages 48, arm mounts 51, and arms 50 around column 53, and closed to stow to protect them when not in use. The base covers 52 may be

sealed with a membrane 54 along the edges of its opening to prevent dirt and fluid ingress when closed.

[0063] FIG. 8 illustrates an embodiment of a robotically-enabled table-based system configured for a ureteroscopy procedure. In ureteroscopy, the table 38 may include a swivel portion 55 for positioning a patient off-angle from the column 37 and table base 46. The swivel portion 55 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 55 away from the column 37. For example, the pivoting of the swivel portion 55 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 38. By rotating the carriage 35 (not shown) around the column 37, the robotic arms 39 may directly insert a ureteroscope 56 along a virtual rail 57 into the patient's groin area to reach the urethra. In ureteroscopy, stirrups 58 may also be fixed to the swivel portion 55 of the table 38 to support the position of the patient's legs during the procedure and allow clear access to the patient's groin area.

[0064] In a laparoscopic procedure, through small incision(s) in the patient's abdominal wall, minimally invasive instruments (elongated in shape to accommodate the size of the one or more incisions) may be inserted into the patient's anatomy. After inflation of the patient's abdominal cavity, the instruments, often referred to as laparoscopes, may be directed to perform surgical or medical tasks, such as grasping, cutting, ablating, suturing, etc. FIG. 9 illustrates an embodiment of a robotically-enabled table-based system configured for a laparoscopic procedure. As shown in FIG. 9, the carriages 43 of the system 36 may be rotated and vertically adjusted to position pairs of the robotic arms 39 on opposite sides of the table 38, such that laparoscopes 59 may be positioned using the arm mounts 45 to be passed through minimal incisions on both sides of the patient to reach his/her abdominal cavity.

[0065] To accommodate laparoscopic procedures, the robotically-enabled table system may also tilt the platform to a desired angle. FIG. 10 illustrates an embodiment of the robotically-enabled medical system with pitch or tilt adjustment. As shown in FIG. 10, the system 36 may accommodate tilt of the table 38 to position one portion of the table at a greater distance from the floor than the other. Additionally, the arm mounts 45 may rotate to match the tilt such that the arms 39 maintain the same planar relationship with table 38. To accommodate

steeper angles, the column 37 may also include telescoping portions 60 that allow vertical extension of column 37 to keep the table 38 from touching the floor or colliding with base 46.

[0066] FIG. 11 provides a detailed illustration of the interface between the table 38 and the column 37. Pitch rotation mechanism 61 may be configured to alter the pitch angle of the table 38 relative to the column 37 in multiple degrees of freedom. The pitch rotation mechanism 61 may be enabled by the positioning of orthogonal axes 1, 2 at the column-table interface, each axis actuated by a separate motor 3, 4 responsive to an electrical pitch angle command. Rotation along one screw 5 would enable tilt adjustments in one axis 1, while rotation along the other screw 6 would enable tilt adjustments along the other axis 2.

[0067] 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.

### **C. Instrument Driver & Interface.**

[0068] The end effectors of the system's robotic arms comprise (i) an instrument driver (alternatively referred to as "instrument drive mechanism" or "instrument device manipulator") 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.

[0069] FIG. 12 illustrates an example instrument driver. Positioned at the distal end of a robotic arm, instrument driver 62 comprises of one or more drive units 63 arranged with parallel axes to provide controlled torque to a medical instrument via drive shafts 64. Each drive

unit 63 comprises an individual drive shaft 64 for interacting with the instrument, a gear head 65 for converting the motor shaft rotation to a desired torque, a motor 66 for generating the drive torque, an encoder 67 to measure the speed of the motor shaft and provide feedback to the control circuitry, and control circuitry 68 for receiving control signals and actuating the drive unit. Each drive unit 63 being independent controlled and motorized, the instrument driver 62 may provide multiple (four as shown in FIG. 12) independent drive outputs to the medical instrument. In operation, the control circuitry 68 would receive a control signal, transmit a motor signal to the motor 66, compare the resulting motor speed as measured by the encoder 67 with the desired speed, and modulate the motor signal to generate the desired torque.

[0070] 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 of 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.**

[0071] FIG. 13 illustrates an example medical instrument with a paired instrument driver. Like other instruments designed for use with a robotic system, medical instrument 70 comprises an elongated shaft 71 (or elongate body) and an instrument base 72. The instrument base 72, also referred to as an “instrument handle” due to its intended design for manual interaction by the physician, may generally comprise rotatable drive inputs 73, e.g., receptacles, pulleys or spools, that are designed to be mated with drive outputs 74 that extend through a drive interface on instrument driver 75 at the distal end of robotic arm 76. When physically connected,

latched, and/or coupled, the mated drive inputs 73 of instrument base 72 may share axes of rotation with the drive outputs 74 in the instrument driver 75 to allow the transfer of torque from drive outputs 74 to drive inputs 73. In some embodiments, the drive outputs 74 may comprise splines that are designed to mate with receptacles on the drive inputs 73.

[0072] The elongated shaft 71 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 66 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 a rigid elongated shaft may be connected to an end effector comprising a jointed wrist formed from a clevis with an axis of rotation 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 rotate in response to torque received from the drive outputs 74 of the instrument driver 75. When designed for endoscopy, the distal end of a flexible elongated shaft may include a steerable or controllable bending section that may be articulated and bent based on torque received from the drive outputs 74 of the instrument driver 75.

[0073] Torque from the instrument driver 75 is transmitted down the elongated shaft 71 using tendons within the shaft 71. These individual tendons, such as pull wires, may be individually anchored to individual drive inputs 73 within the instrument handle 72. From the handle 72, the tendons are directed down one or more pull lumens within the elongated shaft 71 and anchored at the distal portion of the elongated shaft 71. In laparoscopy, these tendons may be coupled to a distally mounted end effector, such as a wrist, grasper, or scissor. Under such an arrangement, torque exerted on drive inputs 73 would transfer tension to the tendon, thereby causing the end effector to actuate in some way. In laparoscopy, 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 71, where tension from the tendon cause the grasper to close.

[0074] In endoscopy, the tendons may be coupled to a bending or articulating section positioned along the elongated shaft 71 (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 73 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 71 to allow for controlled articulation in the desired bending or articulable sections.

[0075] In endoscopy, the elongated shaft 71 houses a number of components to assist with the robotic procedure. The shaft may comprise of 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 71. The shaft 71 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 71 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.

[0076] At the distal end of the instrument 70, 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.

[0077] In the example of FIG. 13, 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 71. Rolling the elongated shaft 71 along its axis while keeping the drive inputs 73 static results in undesirable tangling of the tendons as they extend off the drive inputs 73 and enter pull lumens within the elongate shaft 71. The resulting entanglement of such tendons may disrupt any control algorithms intended to predict movement of the flexible elongate shaft during an endoscopic procedure.

[0078] FIG. 14 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. As shown, a circular instrument driver 80 comprises four drive units with their drive outputs 81 aligned in parallel at the end of a robotic arm 82. The drive units, and their respective drive outputs 81, are housed in a rotational assembly 83 of the instrument driver 80 that is driven by one of the drive units within the assembly 83. In response to torque provided by the rotational drive unit, the rotational assembly 83 rotates along a circular bearing that connects the rotational assembly 83 to the non-rotational portion 84 of the instrument driver. Power and controls signals may be communicated from the non-rotational portion 84 of the instrument driver 80 to the rotational assembly 83 through electrical contacts may be maintained through rotation by a brushed slip ring connection (not shown). In other embodiments, the rotational assembly 83 may be responsive to a separate drive unit that is integrated into the non-rotatable portion 84, and thus not in parallel to the other drive units. The rotational mechanism 83 allows the instrument driver 80 to rotate the drive units, and their respective drive outputs 81, as a single unit around an instrument driver axis 85.

[0079] Like earlier disclosed embodiments, an instrument 86 may comprise an elongated shaft portion 88 and an instrument base 87 (shown with a transparent external skin for discussion purposes) comprising a plurality of drive inputs 89 (such as receptacles, pulleys, and spools) that are configured to receive the drive outputs 81 in the instrument driver 80. Unlike prior disclosed embodiments, instrument shaft 88 extends from the center of instrument base 87 with an axis substantially parallel to the axes of the drive inputs 89, rather than orthogonal as in the design of FIG. 13.

[0080] When coupled to the rotational assembly 83 of the instrument driver 80, the medical instrument 86, comprising instrument base 87 and instrument shaft 88, rotates in combination with the rotational assembly 83 about the instrument driver axis 85. Since the instrument shaft 88 is positioned at the center of instrument base 87, the instrument shaft 88 is coaxial with instrument driver axis 85 when attached. Thus, rotation of the rotational assembly 83 causes the instrument shaft 88 to rotate about its own longitudinal axis. Moreover, as the instrument base 87 rotates with the instrument shaft 88, any tendons connected to the drive inputs 89 in the instrument base 87 are not tangled during rotation. Accordingly, the parallelism of the axes of the drive outputs 81, drive inputs 89, and instrument shaft 88 allows for the shaft rotation without tangling any control tendons.

### E. Navigation and Control.

[0081] 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.

[0082] FIG. 15 is a block diagram illustrating a localization system 90 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 90 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 30 shown in FIG. 1, the cart shown in FIGs. 1-4, the beds shown in FIGs. 5-10, etc.

[0083] As shown in FIG. 15, the localization system 90 may include a localization module 95 that processes input data 91-94 to generate location data 96 for the distal tip of a medical instrument. The location data 96 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).

[0084] The various input data 91-94 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 91 (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. Pat. App. 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.

[0085] In some embodiments, the instrument may be equipped with a camera to provide vision data 92. The localization module 95 may process the vision data to enable one or more vision-based location tracking. For example, the preoperative model data may be used in conjunction with the vision data 92 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 91, 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.

[0086] 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 95 may identify circular geometries in the preoperative model data 91 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.

[0087] Optical flow, another computer vision-based technique, may analyze the displacement and translation of image pixels in a video sequence in the vision data 92 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.

[0088] The localization module 95 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 93. 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.

[0089] Robotic command and kinematics data 94 may also be used by the localization module 95 to provide location data 96 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.

[0090] As FIG. 15 shows, a number of other input data can be used by the localization module 95. For example, although not shown in FIG. 15, an instrument utilizing shape-sensing fiber can provide shape data that the localization module 95 can use to determine the location and shape of the instrument.

[0091] The localization module 95 may use the input data 91-94 in combination(s). In some cases, such a combination may use a probabilistic approach where the localization module 95 assigns a confidence weight to the location determined from each of the input data

91-94. Thus, where the EM data may not be reliable (as may be the case where there is EM interference) the confidence of the location determined by the EM data 93 can be decrease and the localization module 95 may rely more heavily on the vision data 92 and/or the robotic command and kinematics data 94.

[0092] 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. Estimating Instrument Location with Comparison of Location Input Data.**

[0093] Robotically-enabled medical systems, such as those described above with reference to FIGs. 1-15, may be configured to provide an estimate of instrument position or location during a medical or surgical procedure, such as an endoscopic or laparoscopic procedure. During the procedure, a physician can guide or direct the instrument through an internal region (e.g., a lumen, a luminal network, a cavity, etc.) of a patient. To assist the physician, a location/position estimate for the instrument may be determined and displayed to the user, for example, with the localization system 90 (FIG. 15).

[0094] FIG. 16 depicts a block diagram illustrating an embodiment of localization system 90 in greater detail. In the illustrated example, the localization system 90 is configured to receive and process vision data 92, position sensor data 93 (e.g., EM data), and robotic data 94 (e.g., robotic command and kinematics data) and thereby provide location data 96 as an output. The location data 96 can include, for example, a position estimate for the instrument.

[0095] Although, the vision data 92, the position sensor data 93, and the robotic data 94 are illustrated as input data in FIG. 16, the localization system 90 may also receive and process additional types of input data as described above. As one example, the localization system 90 may also receive and process preoperative model data 91 as previously described.

[0096] As illustrated, the localization module 95 can include vision-based module 101, a position sensor-based module 103, and a robotic-based module 105. Each of the

modules 101, 103, 105 can include software and/or hardware for receiving and processing the various input data. In some embodiments, one or more of the modules 101, 103, 105 may be combined with each other and/or with other modules (such as a location/position estimator module 108). Example modules are described in detail in U.S. Application No. 15/268,238, filed September 16, 2016, which issued as U.S. Patent No. 9,727,963 on August 8, 2017, and which is incorporated herein by reference.

[0097] The vision-based module 101 may be configured to receive and process the vision data 92. The vision data 92 may be received from an imaging device (e.g., fiberscope or camera). The imaging device may be positioned on the instrument. The vision data 92 can include one or more images or videos. The vision-based module 101 may be configured to determine a vision-based location/position estimate 102 from the vision data 92. For example, the vision-based module 101 can process images received from the instrument device positioned on the instrument to determine the position of the instrument relative to a preoperative model (e.g., the preoperative model data 91) as described above.

[0098] The position sensor-based module 103 may be configured to receive and process the position sensor data 93. The position sensor data 93 may be received from one or more position sensors. The position sensors may be positioned on the instrument. The position sensors may be, for example, EM sensors, shape-sensing fibers, accelerometers, gyroscopes, imaging devices, ultrasonic sensors, etc. The position sensor-based module 103 may be configured to determine a position sensor-based location/position estimate 104 from the position sensor data 93. For example, the position sensor-based module 103 can process data received from an EM sensor on the instrument to determine the position of the instrument relative to a coordinate frame of the preoperative model.

[0099] The robotic-based module 105 may be configured to receive and process the robotic data 94. The robotic data 94 include can insertion and/or articulation commands for controlling the shape and movement of the instrument. The robotic-based module 105 may be configured to determine a robotic-based location/position estimate 106 from the robotic data 94. For example, during the procedure, information for known or commanded insertion depth and/or articulation or roll angles for the instrument, as executed by one or more robotic arms or other instrument positioning devices, may be used to estimate the position of the instrument.

[0100] The vision-based position estimate 102, the position sensor-based position estimate 104, and the robotic-based position estimate 106 may be inputs into a location estimator module 108, as illustrated. Other inputs (not illustrated) may be provided to the location estimator module 108 as well. The location estimator module 108 may be implemented in hardware, software, or a combination thereof.

[0101] The location estimator module 108 may be configured to combine the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106 to output location data 96. The location estimator module may determine the combination using a probabilistic approach that assigns a confidence weight (or weighting factor) to the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106. In some embodiments, the location estimator module 108, and/or another component or module of the localization system 90, may determine the weighting factor for each of the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106. The weighting factors may be used to increase or decrease the contribution of the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106 to the determination of the output location data 96.

[0102] For example, in some cases, one of the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106 may be determined to be less reliable than another of the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106. The weighting factor of the less reliable one(s) may be decreased and/or the weighting factor of the more reliable one(s) may be increased. As a result, the output location data 96 may provide a more reliable position estimate for the instrument because the more reliable inputs have been weighted more heavily.

[0103] As another example, the weighting factor for one or more of the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106 may be set to zero to eliminate contribution of one or more of those input estimates to the determination of the location data 96.

[0104] The location estimator module 108 (and/or other component(s) of the localization system 90, such as the vision-based module 101, the position sensor-based module

103, and/or the robotic-based module 105) may be configured to determine the weighting factors for each of the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106. In general, the weighting factors may be decreased when a particular input position estimate is determined to be unreliable and/or increased when a particular input position estimate is determined to be reliable.

[0105] An advantage of some of the robotically-enabled medical systems described herein is that they include localization systems 90 that process multiple types of input data (e.g., the vision data 92, the position sensor data 93, and/or the robotic data 94) to produce multiple position estimates (e.g., the vision-based position estimate 102, the position sensor-based position estimate 104, and/or the robotic-based position estimate 106) that are combined (e.g., according to weighting factors) to determine a position estimate (e.g., location data 96) for the instrument. This may be advantageous because, if a particular data input is determined to be less reliable (at a certain instance or in a certain situation), the contribution of that data input to the finally determined position estimate may be reduced or eliminated.

[0106] Additionally, the systems described herein may be advantageous because, since there are multiple data inputs and input position estimates, these may be compared to each other to determine the reliability and accuracy of the various data inputs and position estimates. As will be described below, comparison between multiple data inputs and input position estimates may be used to determine and or set weighting factors. This can further improve the finally determined position estimate for the instrument, which can improved navigation and tracking of the instrument during a medical procedure.

[0107] The remainder of this disclosure describes how instrument position may be estimated and improved with comparison of input data or input position estimates. For ease of description, particular use cases of instrument buckling and instrument hysteresis are described by way of example. Other use cases are possible as well.

#### **A. Example of Instrument Buckling.**

[0108] This section describes instrument buckling and provides a first example where an instrument position estimate may be determined or improved with comparison of various input data or input position estimates.

[0109] FIG. 17A illustrates an example of a medical instrument 100 experiencing a buckling condition. The instrument 100 may be, e.g., the endoscope 13 (FIG. 1), the

ureteroscope 32 (FIG. 3), the instrument 34 (FIG. 4), the ureteroscope 56 (FIG. 8), the laparoscope 59 (FIG. 9), the instrument 70 (FIG. 13), or the instrument 86 (FIG. 14) described above, or any other medical instrument described herein, such as instrument 200 (described below with reference to FIG. 19). As illustrated in FIG. 17A, the instrument 100 includes an elongated shaft 113 extending between a proximal end 114 and a distal end 115. The proximal end 114 may be connected to an instrument driver of an instrument positioning device 111, such as a robotic arm. As described above, the instrument positioning device 111 can move to insert or retract the instrument 100 into a patient. The instrument positioning device 111 can also be configured to articulate (e.g., control the shape or pose) of the instrument 100. For ease of illustration, the anatomy of the patient is not illustrated beyond a general representation that a portion of the elongated shaft 113 (including the distal end 115) may be positioned internal to the patient and another portion of the elongated shaft 113 (including the proximal end 114) and the instrument positioning device 111 may be positioned external to the patient. It will be appreciated, however, that internal to the patient, the elongated shaft 113 may follow the general shape of the patient's anatomy into which the instrument 100 is inserted.

[0110] To illustrate a buckling condition, in FIG. 17A, a first state of the instrument 100 is illustrated in solid lines and a second state of the instrument 100 is illustrated in dashed lines. In the second state (dashed lines) the instrument 100 has buckled (i.e., experienced a buckling condition). As illustrated, moving from the first state to the second state, the instrument positioning device 111 has advanced a first distance  $D1$ . The proximal end 114 of the elongated shaft 113 of the instrument 100, which is attached to the instrument positioning device 111, has also advanced the distance  $D1$ . The distal end 115 of the elongated shaft 113, however, has advanced only a distance  $D2$ , which is less than the distance  $D1$ . As illustrated, the elongated shaft 113 has buckled, bowed, bent, deflected, or otherwise deformed in an unintended way, such that the instrument 100 has experienced a buckling condition as illustrated in dashed lines in FIG. 17A.

[0111] Buckling may occur, for example, when the instrument 100 is advanced into the patient. The instrument positioning device 111 may advance the instrument 100 into the patient the distance  $D1$ . Absent buckling, one would generally expect the distal tip 115 of the instrument 100 to also advance by the distance  $D1$ . In some cases, however, the distal tip 115 may become caught or blocked within the patient's anatomy, such that the distal tip 115 only

advances the distance D2, which is less than the distance D1. In some instances, the distal tip 115 may not advance at all, such that the distance D2 is zero. When the distal tip 115 becomes caught or blocked, the instrument buckles, and the elongated shaft 113 deforms (e.g., buckles, bows, bends, or otherwise deforms) in an unintended way.

[0112] It should be appreciated that while FIG. 17A illustrates the elongated shaft 113 disposed in a generally straight manner in the first state (solid lines) and in a gently curved manner in the second or buckled state (dashed lines), in general, the elongated shaft 113 may follow the patient's anatomy when positioned within the body and buckling may be manifest by any number of deformations of the elongated shaft 113. Regardless of the shape formed by the elongated shaft 113, a buckling condition has occurred when a motion D2 at the distal end 115 is less than an anticipated motion of the distal end 115 based on, for example, a motion D1 at the proximal end 114.

[0113] A robotically-enabled medical system including the instrument 100 may be configured to provide a position estimate for, for example, the distal end 115 of the instrument 100. The system can include the localization system 90 described above (e.g., in FIGs. 15 and 16). As noted previously, the localization system 90 processes and combines multiple types of input data to determine the position estimate.

[0114] Movement of the instrument positioning device 111 can generate or be based on robotic data 94. For example, the robotic data 94 can indicate that the instrument 100 has moved forward by the distance D1. The robotic-based module 105 may process the robotic data 94 to provide a robotic-based position estimate 106, which indicates that the distal end 115 of the instrument 100 has advanced the distance D1 from its previous position. As shown, in FIG. 17A, however, the distal tip 115 has only advanced the distance D2 (not the distance D1) because the instrument 100 has buckled.

[0115] The localization system 90 may receive as an input the position sensor data 93 from a position sensor. In this example, the position sensor may be positioned at the distal end 115 of the elongated shaft 113. As the instrument 100 moves from the first state (solid lines) to the second state (dashed lines), the position sensor (positioned at the distal tip 115) can provide the position sensor data 93 to the localization system 90. The position sensor-based module 103 can process the position sensor data 93 to provide a position sensor-based position estimate 104 that indicates that the distal end 115 has advanced the distance D2.

[0116] The localization system 90 can compare the robotic-based position estimate 106 and the position sensor-based position estimate 104 to determine weighting factors for each. In this example, the localization system 90 can determine that the movement indicated by the robotic-based position estimate 106 exceeds the movement indicated by the position sensor-based position estimate 104 by the difference between D1 and D2. The localization system 90 may be configured to recognize from this difference that a buckling condition has occurred and may accordingly decrease the weighting factor for the robotic-based position estimate 106 and/or increase the weighting factor for the position sensor-based position estimate 104. The localization system 90 may then combine the robotic-based position estimate 106 the position sensor-based position estimate 104 according to the determined weighting factors to provide and output a position estimate for the instrument 100 as location data 96. Because the localization system 90 has determined that the instrument 100 has buckled (by comparing the robotic-based position estimate 106 and position sensor-based position estimate 104) and adjusted the weighting factors accordingly, the accuracy of the estimated position output as location data 96 may be improved.

[0117] Similar comparisons may be made between the vision-based position estimate 102 and the position sensor-based position estimate 104 and/or the robotic-based position estimate 106 to detect buckling and provide a position estimate with increased accuracy. These comparisons will be described in greater detail below following the discussion of the example of instrument hysteresis.

#### **B. Example of Instrument Hysteresis.**

[0118] Instrument hysteresis provides another example that illustrates that an instrument position estimate may be determined or improved with comparison of various input data or input position estimates. It is to be appreciated that the term “hysteresis,” as used herein, may refer to a specific class of hysteresis condition that a medical instrument can experience. This specific class of hysteresis may relate to the condition where a medical instrument returns or transitions towards a natural state from a deformed shape. A very specific example is where a medical device returns from a buckled state to a unbuckled state (or a less buckled state). An example of this type of hysteresis condition is now explained.

[0119] FIG. 17B illustrates an example of the medical instrument 100 experiencing a type of hysteresis condition. As before, the instrument 100 may be, e.g., the endoscope 13 (FIG.

1), the ureteroscope 32 (FIG 3), the instrument 34 (FIG 4), the ureteroscope 56 (FIG. 8), the laparoscope 59 (FIG. 9), the instrument 70 (FIG. 13), or the instrument 86 (FIG. 14) described above, or any other medical instrument described herein, such as the instrument 200 (FIG. 19) described below.

[0120] In FIG. 17B, a first state of the instrument 100 is illustrated in solid lines and a second state of the instrument 100 is illustrated in dashed lines. In the second state (dashed lines), the instrument 100 has experienced hysteresis. As illustrated, in the first state (solid lines) the elongated shaft 113 of the instrument 100 is in a buckled, bowed, bent, or deflected position. Moving from the first state to the second state, the instrument positioning device 111 may advance a first distance  $D1$ . The proximal end 114 of the elongated shaft 113 of the instrument 100, which is attached to the instrument positioning device 111, also advances the distance  $D1$ . In some examples of hysteresis, the instrument positioning device 111 and the proximal end 114 may not advance at all (i.e., the distance  $D1$  may be zero).

[0121] When the instrument 100 experiences hysteresis, however, the distal end 115 of the elongated shaft 113 advances a distance  $D2$ , which is greater than the distance  $D1$ . This may be caused by the buckled, bowed, bent, or deflected elongated shaft 113 of the instrument relaxing to a more extended position. Hysteresis may also occur when an instrument 113 which is blocked or caught on the patient anatomy suddenly becomes free. In both of these cases, the distal end 115 advances a distance  $D2$ , which is greater than the distance  $D1$  advanced by the proximal end 114 and instrument positioning device 111.

[0122] Again, it should be appreciated that while FIG. 17B illustrates the elongated shaft 113 disposed in a generally curved manner in the first state (solid lines) and in a gently straight manner in the second state (dashed lines), in general, the elongated shaft 113 may follow the patient's anatomy when positioned within the body and hysteresis may be manifest with the elongated shaft 113 in any number of positions. Regardless of the shape formed by the elongated shaft 113, a hysteresis condition has occurred when a motion  $D2$  at the distal end 115 is greater than an anticipated motion at the distal end 115 based on, for example, a motion  $D1$  at the proximal end 114.

[0123] In terms of the localization system 90, during a hysteresis condition, movement of the instrument positioning device 111 can generate robotic data 94. The robotic data 94 can indicate that the instrument 100 has moved forward by the distance  $D1$ . The robotic-

based module 105 may process the robotic data 94 to provide a robotic-based position estimate 106, which indicates that the distal end 115 of the instrument 100 has advanced the distance D1 from its previous position. As shown in FIG. 17B, however, the distal tip 115 has advanced the distance D2 because the instrument 100 has experienced hysteresis.

[0124] As the instrument 100 moves from the first state (solid lines) to the second state (dashed lines), a position sensor (positioned at the distal tip 115) can provide position sensor data 93 to the localization system 90. The position sensor-based module 103 can process the position sensor data 93 to provide a position sensor-based position estimate 104 that indicates that the distal end 115 has advanced the distance D2.

[0125] The localization system 90 can compare the robotic-based position estimate 106 and the position sensor-based position estimate 104 to determine weighting factors for each. In this example, the localization system 90 can determine that the movement indicated by the position sensor-based position estimate 104 exceeds the movement indicated by the robotic-based position estimate 106 by the difference between D1 and D2. The localization system 90 may be configured to recognize from this difference that a hysteresis condition has occurred and may accordingly, decrease the weighting factor for the robotic-based position estimate 106 and increase the weighting factor for the position sensor-based position estimate 104. The localization system 90 may then combine the robotic-based position estimate 106 and the position sensor-based position estimate 104 according to the determined weighting factors to determine and output a position estimate for the instrument as location data 96. Because the localization system 90 has determined that the instrument 100 has experienced a hysteresis condition (by comparing the robotic-based position estimate 106 and the position sensor-based position estimate 104) and adjusted the weighting factors accordingly, the accuracy of the estimated position output as location data 96 may be improved.

[0126] Similar comparisons may be made between the vision-based position estimate 102 and the position sensor-based position estimate 104 and/or the robotic-based position estimate 106 to detect hysteresis and provide a position estimate with increased accuracy. These comparisons will be described in greater detail below.

### **C. Example Methods for Determining Instrument Position with Comparison of Input Data.**

[0127] FIG. 18A is a flowchart illustrating an example method 200 for determining or improving the accuracy of a position estimate for the medical instrument 100 based on a

comparison of the robotic data 94 and the position sensor data 93. The method 200 may be implemented in certain robotic systems, such as the robotic systems illustrated in FIGs. 1-15 and others. The method 200 may be implemented in or by localization system 90 of FIGs. 15 and 16. In some embodiments, one or more computer devices may be configured to execute the method 200. The computer devices may be embodied by a processor (or processors) and computer-readable memory in one or more components discussed above. The computer-readable memory may store instructions that may be executed by the processor(s) to perform the method 200. The instructions may include one or more software modules. By way of example and not limitation, the computer devices may be in the tower 30 shown in FIG. 1, the cart shown in FIGs. 1-4, the beds shown in FIGs. 5-10, etc.

[0128] The method 200 shown in FIG. 18A begins at block 201. At block 201, a first motion estimate for an instrument is obtained based on robotic data (e.g., the robotic data 94) regarding physical manipulation of the instrument. As discussed above, the robotic data 94 can include data related to physical movement of the instrument 100 or part of the instrument (e.g., the distal end 115). An example of robotic data 94 can include command data instructing the distal end 115 to reach a specific anatomical site and/or change its orientation (e.g., with a specific pitch, roll, yaw, insertion, and/or retraction). The robotic data 94 can include data representing mechanical movement of the elongated shaft 113 of the instrument 100, for example motion of one or more pull wires or tendons to drive the actual movement or control the pose of the medical instrument 100. The robotic data 94 can include data relating to the movement of one or more of the instrument positioning devices 111, such as the robotic arms described previously. Positions or movement (changes in position) may be determined from the robotic data 94.

[0129] The motion estimate can include an estimate of the movement of the instrument 100. The motion estimate may be determined over an interval. In some implementations, the interval is a time interval. For example, at block 201, the method 200 can involve determining an estimate, based on the robotic data 94, for the change in position during a time interval such as about 0.1 seconds, 0.2 seconds, 0.25 seconds, 0.5 seconds, 0.75 seconds, 1 second, 1.5 seconds, 2 seconds, or 5 seconds. Other time intervals, both shorter and longer than these listed examples are also possible.

[0130] In some implementations, the interval is a distance interval. For example, at block 201, the method 200 can involve determining an estimate, based on the robotic data 94, for the change in position during a distance interval such as about 0.1 mm, 0.2 mm, 0.25 mm, 0.5 mm, 0.75 mm, 1 mm, 1.5 mm, 2 mm, 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, or 50 mm. Other distance intervals, both shorter and longer than these listed examples are also possible. The distance interval may represent a distance moved by the instrument position device 111, the proximal end 114 of the elongated shaft 113, and/or the distal end 115 of the elongated shaft 113; a commanded insertion distance; a commanded travel distance of the instrument 100; a measured insertion distance; a measured travel distance of the instrument 100; an estimated travel distance of the instrument 100 as determined by the vision-based module 101, the position-sensor-based module 103, the robotic-based module 105, and/or the location estimator module 108, etc.

[0131] In some implementations, the interval is a rolling window or frame. The interval may be a rolling window or frame of time or distance, providing a motion estimate for the instrument 100 over a time or distance window immediately preceding the current time point. For example, at each time point, block 201 can involve determining a new motion estimate representing a change in position over a time interval immediately preceding the each time point.

[0132] In some implementations, block 201 involves obtaining the motion estimate from the robotic data 91 in conjunction with one or more other data inputs. For example, the motion estimate may be determined at block 201 using one or both the robotic data 91 and the preoperative model data 94, for example.

[0133] At block 203, a second motion estimate is obtained based on position sensor data (e.g., the position sensor data 93) received from at least one position sensor. As discussed above, the position sensor data 93 may be received from one or more position sensors. In some implementations, the position sensor is positioned on the instrument 100, for example, on the distal end 114 of the instrument 100. A position of the position sensor may be derived from the position sensor data 93 relative to a coordinate frame. The coordinate frame for the position sensor may be registered to a coordinate frame of the preoperative model, such that the position may be determined relative to the preoperative model.

[0134] The position sensor may be any type of sensor for determining position. For example, the position sensor may be an EM sensor as described above. The EM sensor can

provide position sensor data 93 from which the position of the EM sensor may be derived relative to an EM field produced by an EM field generator. In another example, the position sensor may be an EM field generator positioned on the instrument, and the position of the EM field generator may be determined relative to EM sensors positioned outside of the patient's body.

[0135] In other examples, the position sensor can be a shape-sensing fiber, an accelerometer, a gyroscope, and/or an ultrasonic sensor. In another example, the position sensor may be an imaging device. The imaging device may be positioned on the instrument. The output of the imaging device (e.g., images or video) may be analyzed to determine positional information.

[0136] A motion estimate may be obtained from the position sensor data 93 by analyzing the position sensor data 93 during an interval. In some implementations, the interval may be a time or distance interval as described above. The interval may be a rolling interval or frame.

[0137] In some implementations, the interval used for obtaining the motion estimate from the position sensor data 93 may be the same interval as the interval used for obtaining the motion estimate from the robotic data 94. For example, the intervals used at block 203 may match the interval used at block 201.

[0138] In some embodiments the order of block 201 and block 203 may vary. In some embodiments, block 201 and block 203 may occur at substantially the same time.

[0139] At block 205, the method 200 involves determining a motion estimate disparity based on a comparison of the first motion estimate and the second motion estimate. The motion estimate disparity may be representative or indicative of a difference between the motion estimate obtained from the robotic data 94 at block 201 and the motion estimate obtained from the position sensor data 93 at block 203. In some implementations, determining the motion estimate disparity involves taking a difference between the motion estimate obtained from the robotic data 94 at block 201 and the motion estimate obtained from the position sensor data 93 at block 203. In some embodiments, determining the motion estimate disparity involves taking a difference between a final position obtained from the robotic data 94 (e.g., during the interval) and a final position obtained from the position sensor data 93 (during the interval).

[0140] At block 207, the method 207 involves, based on the motion estimate disparity, updating: (a) a weighting factor for a location derivable from the robotic data (e.g., the robotic data 94), and/or (b) a weighting factor for a location derivable from the position sensor data (e.g., the position sensor data 93). As discussed above, the localization system 90 can use the weighting factors when combining the positions estimated from the different types of input data.

[0141] For example, block 207 can involve decreasing the weighting factor for a location derivable from the robotic data 94, and/or increasing the weighting factor for a location derivable from the position sensor data 93, when the motion estimate disparity indicates that the motion estimate based on the robotic data 94 (block 201) exceeds the motion estimate based on the position sensor data 93 (block 203). The motion estimate based on the robotic data 94 exceeding the motion estimate based on the position sensor data 93 may indicate that the instrument 100 has experienced a buckling condition. For example, as shown in FIG. 17A, buckling can occur when the instrument positioning device 111 and proximal end 114 of the instrument 100 move a greater distance than the distal end 115 of the instrument 100. In such a case, the motion estimate disparity indicates buckling because the motion estimate based on the robotic data 94 exceeds the motion estimate based on the position sensor data 93. Block 207 can involve decreasing the weighting factor for a location derivable from the robotic data 94, and/or increasing the weighting factor for a location derivable from the position sensor data 93. As a result, the localization system 90 outputs location data 96 that is derived more from the position sensor data 93 and less from the robotic data 94. This may result in a more accurate estimate of position for the instrument 100.

[0142] As another example, block 207 can involve decreasing the weighting factor for a location derivable from the robotic data 94, and/or increasing the weighting factor for a location derivable from the position sensor data 93, when the motion estimate disparity indicates that the motion estimate based on the position sensor data 93 (block 203) exceeds the motion estimate based on the robotic data 94 (block 201). The motion estimate based on the position sensor data 93 exceeding the motion estimate based on the robotic data 94 may indicate that the instrument 100 has experienced a hysteresis condition. For example, as shown in FIG. 17B, hysteresis can occur when the distal end 115 of the instrument 100 moves a greater distance than the instrument positioning device 111 and proximal end 114 of the instrument 100. In such a

case, the motion estimate disparity indicates hysteresis because the motion estimate based on the position sensor data 93 exceeds the motion estimate based on the robotic data 94. Block 207 can involve decreasing the weighting factor for a location derivable from the robotic data 94, and/or increasing the weighting factor for a location derivable from the position sensor data 93. As a result, the localization system 90 outputs location data 96 that is derived more from the position sensor data 93 and less from the robotic data 94. This may result in a more accurate estimate of position for the instrument 100.

[0143] In some implementations, the weighting factor for a location derivable from the robotic data 94 is decreased, and/or the weighting factor for a location derivable from the position sensor data 93 is increased in a manner related to the magnitude of the motion estimate disparity. For example, the greater the motion estimate disparity, the greater the increase and/or decrease of the respective weighting factor(s). In some embodiments, the weighting factor(s) are increased and/or decreased in proportion to the magnitude of the motion estimate disparity.

[0144] In some embodiments, the weighting factor(s) are updated only when the motion estimate disparity exceeds a threshold value. For example, a motion estimate disparity greater than a threshold value can indicate a buckling or hysteresis condition. The threshold value may be a distance, such as about 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 50 mm, 55 mm, or 60 mm. Other distances for the threshold, both shorter and longer than these listed examples are also possible.

[0145] In some embodiments, decreasing a weighting factor can include setting the weighting factor to zero, such that the related input data is not used at all in determining the location data 96 output from the localization system 90. For example, in some implementations, block 207 can involve updating the weighting factor for a location derivable from the robotic data 94 to zero. That is, in some implementations, when the motion estimate disparity indicates buckling or hysteresis, the weighting factor for a location derivable from the robotic data 94 is set to zero, such that the robotic data 94 is not used to determine the final position estimate for the instrument 100.

[0146] At block 209, a location/position estimate based on the updated weighting factor is determined. As described previously, the position estimate may be output from the localization system 90 as location data 96. The localization system 90 determines the position estimate based on one or more of the input data 91-94 and weights the contribution of each input

data according to the associated weighting factor(s). Accordingly, the method 200 can provide improved estimated positions for the instrument by reducing the contribution of the robotic data 94 and/or increasing the contribution of the position sensor data 93 in cases where, for example, the instrument 100 has experienced a buckling or hysteresis condition.

[0147] In some embodiments, the method 200 can also include providing an indication or alert that the instrument 100 has experienced a hysteresis or buckling condition. For example, when the motion estimate disparity indicates hysteresis or buckling, an indication (e.g., a visual or audio alert) can be provided to the physician. In another example, upon detection of a hysteresis or buckling condition, the method 200 can move (or modify movement) of the instrument 100. For example, the system may relax or reduce moment of the instrument. In some instances, action taken is at least partially dependent on the degree of the motion estimate disparity. For example, for motion estimate disparities below a certain threshold, the system may provide an alert, while for motion estimate disparities above a certain threshold, the system may relax or reduce moment of the instrument.

[0148] Some additional details for calculating estimated distances are now discussed before proceeding with the remaining disclosure. As discussed above, a rolling distance window may be used to compare estimated changes in movement determined from sensor locations (e.g., position sensor data 93) and robot commands (e.g. robotic data 94). The rolling window can be a data structure that stores the disparity as pairs of movement determined from sensor locations SL and movement determined from robot data RD. Thus, for a given point  $t$ , the disparity can be calculated by finding the difference between  $SL_t$  and  $RD_t$ . In another embodiment, rather than storing data that can be used to derive the disparity, the rolling window simply includes, for each point  $t$ , the disparity. The data structure used to store the values in the rolling window may include an array, multidimensional array, look-up table, or any other suitable data structure.

[0149] Much of the discussion herein focuses on a comparison of the disparity between movements determined from robot data and sensor locations. However, this approach alone may result in false positives. Such may be the case where the instrument is commanded to articulate (e.g., angular movement in a flexible device or via a wrist structure), which would result in no movement data in the robot data but some movement in the location sensor. To avoid such false-positives, the system may re-initialize the window (or windows) used to track historical disparities when robot data indicates that an articulation command is executed. The

system may re-initialize the window by zeroing out the data structure used to store the window of value. As initializing the window results in a loss of data, which may in turn result in failing to detect buckling, the system may use an articulation threshold to re-initialize the window only when an articulation command exceeds some angular amount. This would limit re-initialization for larger articulations which may have a larger impact on causing false positives.

[0150] FIG. 18B is a flowchart illustrating an example method 220 for determining a position estimate for the medical instrument 100 based on a comparison of vision data 92 and position sensor data 93. The method 220 may be implemented in certain robotic systems, such as the robotic systems illustrated in FIGs. 1-15 and others. The method 220 may be implemented in or by localization system 90 of FIGs. 15 and 16. In some embodiments, one or more computer devices may be configured to execute the method 200. The computer devices may be embodied by a processor (or processors) and computer-readable memory in one or more components discussed above. The computer-readable memory may store instructions that may be executed by the processor(s) to perform the method 220. The instructions may include one or more software modules. By way of example and not limitation, the computer devices may be in the tower 30 shown in FIG. 1, the cart shown in FIGs. 1-4, the beds shown in FIGs. 5-10, etc.

[0151] The method 220 begins at block 221. At block 221, a motion estimate is obtained based on vision data 92. As described above, vision data 92 may be received from an imaging device. The imaging device may be positioned on the instrument 100. The vision data 92 can include images or video. Vision data 92 may be used to determine a position estimate in a variety of ways. For example, an object-based analysis of the vision data 92 can detect and analyze objects present in the field of view of the vision data 92, such as branch openings or particles, to determine position. In some implementations, the vision data 92 is analyzed in conjunction with one or more other data inputs. For example, vision data 92 may be analyzed in conjunction with one or both of the robotic data 94 and preoperative model data 91 to determine a vision-based position estimate

[0152] At block 221, a vision-based motion estimate may be determined based on the position estimates derived from the vision data 92. For example, a change in position over an interval may be determined may be determined. In some implementations, the interval may be a time or distance interval as described above. The interval may be a rolling interval or frame.

[0153] At block 223, a motion estimate is obtained based on position sensor data 93. Block 223 may be substantially similar to the block 203 previously described. In some embodiments, the motion estimate obtained based on the position sensor data 93 is determined over the same interval as the motion estimate based on the vision data 92. For example, the intervals used at block 203 may match the interval used at block 201.

[0154] In some embodiments the order of block 221 and block 223 may vary. In some embodiments, block 221 and block 223 may occur at substantially the same time.

[0155] At block 225, the method 220 involves determining a motion estimate disparity. The motion estimate disparity may be representative or indicative of a difference between the motion estimate obtained from the vision data 92 at block 221 and the motion estimate obtained from the position sensor data 93 at block 223. The motion estimate disparity may be determined as described above.

[0156] At block 227, the method 227 involves updating a weighting factor for a location derivable from the vision data 92, and/or a weighting factor derivable from the position sensor data 93. For example, block 227 can involve decreasing the weighting factor for a location derivable from the vision data 92, and/or increasing the weighting factor for a location derivable from the position sensor data 93, when the motion estimate disparity indicates that the motion estimate based on the vision data 92 (block 221) exceeds the motion estimate based on the position sensor data 93 (block 223). The motion estimate based on the vision data 92 exceeding the motion estimate based on the position sensor data 93 may indicate that the instrument 100 has experienced a buckling condition (FIG. 17A). In such a case, the motion estimate disparity indicates buckling because the motion estimate based on the vision data 92 exceeds the motion estimate based on the position sensor data 93. Accordingly, block 207 can involve decreasing the weighting factor for a location derivable from the vision data 92, and/or increasing the weighting factor for a location derivable from the position sensor data 93. As a result, the localization system 90 outputs location data 96 that is derived more from the position sensor data 93 and less from the vision data 92. This may result in a more accurate estimate of position for the instrument 100.

[0157] As another example, block 227 can involve decreasing the weighting factor for a location derivable from the vision data 92, and/or increasing the weighting factor for a location derivable from the position sensor data 93 when the motion estimate disparity indicates

that the motion estimate based on the position sensor data 93 (block 223) exceeds the motion estimate based on the vision data 92 (block 221). The motion estimate based on the position sensor data 93 exceeding the motion estimate based on the robotic data 94 may indicate that the instrument 100 has experienced a hysteresis condition (FIG. 17B). In such a case, the motion estimate disparity indicates hysteresis because the motion estimate based on the position sensor data 93 exceeds the motion estimate based on the vision data 92. Accordingly, block 227 can involve decreasing the weighting factor for a location derivable from the vision data 92, and/or increasing the weighting factor for a location derivable from the position sensor data 93. As a result, the localization system 90 outputs location data 96 that is derived more from the position sensor data 93 and less from the vision data 92. This may result in a more accurate estimate of position for the instrument 100.

[0158] The weighting factor for a location derivable from the vision data 92 may be decreased, and/or the weighting factor for a location derivable from the position sensor data 93 may be increased in a manner similar to that discussed above with regard to block 207 of method 200.

[0159] At block 229, a location/position estimate based on the updated weighting factor is determined. As described previously, the position estimate may be output from the localization system 90 as location data 96. The localization system 90 determines the position estimate based on one or more of the input data 91-94 and weights the contribution of each input data according to the associated weighting factor. Accordingly, the method 220 can provide improved estimated positions for the instrument by reducing the contribution of the vision data 92 and/or increasing the contribution of the position sensor data 93 in cases where, for example, the instrument 100 has experienced a buckling or hysteresis condition.

#### **D. Example Systems for Determining Instrument Position with Comparison of Input Data.**

[0160] FIG. 19 is a block diagram illustrating an embodiment or a robotically-enabled medical system 300 configured to provide an estimate of instrument location with comparison of location input data using the methods described herein. The system 300 includes a processor 310 and memory 312. The memory 312 can store instructions that configure or instruct the processor 310 to execute, for example, the methods 200 and/or 220 described above.

[0161] The system 300 also includes an instrument 302. The instrument 302 may be, e.g., the endoscope 13 (FIG. 1), the ureteroscope 32 (FIG 3), the instrument 34 (FIG 4), the

ureteroscope 56 (FIG. 8), the laparoscope 59 (FIG. 9), the instrument 70 (FIG. 13), the instrument 86 (FIG. 14), or the instrument 100 described above, or any other medical instrument described herein, or variation(s) thereof. The instrument 302 may include a position sensor 304 and an imaging device 306. The instrument 302 may be attached to an instrument positioning device 308 and configured to manipulate and move the instrument 302. The instrument positioning device 308 may be a robotic arm or component(s) thereof. The instrument positioning device 308 may be controlled by a processor 310 in some embodiments.

[0162] The position sensor data 316 may be received from and/or generated by the position sensor 304. The position sensor 304 may be positioned on the instrument 302. The position sensor may be a shape-sensing fiber, an accelerometer, a gyroscope, an electromagnetic sensor, an imaging device, or an ultrasonic sensor.

[0163] The vision data 318 may be received from and/or generated by the imaging device 306. The imaging device 306 may be positioned on the instrument 304. The imaging device 306 may be any photosensitive substrate or structure configured to convert energy representing received light into electric signals, for example, a charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) image sensor. In some examples, the imaging device 306 can include one or more optical fibers. For example, the imaging device 102 may be a fiber optic bundle configured to transmit light representing an image from the distal end of the instrument 300 to an eyepiece and/or image sensor. Images captured by the imaging device 306 can then be transmitted as individual frames or series of successive frames (e.g., a video) to a computer system for storage or display. The images captured by the imaging device 306 may be used as vision data 92 by the localization system 90 to determine the estimated position for the instrument 100.

[0164] The robotic command and kinematics data 320 may be received from and/or generated by the instrument positioning device 308. As discussed above, robotic command and kinematics data 320 can include data related to physical movement of the instrument 300, such as data instructing instrument 300 to reach a specific anatomical site and/or change its orientation (e.g., with a specific pitch, roll, yaw, insertion, and/or retraction). The robotic command and kinematics data 320 can also include data representing mechanical movement the instrument 300, such as data related to motion of one or more pull wires or tendons that drive the actual movement or control the pose of the instrument 300.

[0165] The position sensor data 316, vision data 318, and robotic data 320 may be provided as data inputs to the processor 310. The processor 310 can execute the methods described herein to determine and output information regarding a location/position estimate 326 of the instrument 302. In the illustrated embodiment, information regarding the position estimate 326 is output to a display 324. The position estimate 326 may be stored in some embodiments. Implementing the methods described herein, the position estimate 326 may exhibit improved accuracy in cases where the instrument 300 experiences buckling or hysteresis.

### **3. Implementing Systems and Terminology**

[0166] Implementations disclosed herein provide systems, methods and apparatus for determining instrument position with comparison of input data. Various implementations described herein provide for improved navigation and tracking of the instrument during a medical procedure.

[0167] 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.

[0168] The position estimation and robotic motion actuation functions described herein may be stored as one or more instructions on a processor-readable or computer-readable medium. The term “computer-readable medium” refers to any available medium that may be accessed by a computer or processor. By way of example, and not limitation, such a medium may comprise random access memory (RAM), read-only memory (ROM), electrically erasable programmable read-only memory (EEPROM), flash memory, compact disc read-only memory (CD-ROM) or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that may be used to store desired program code in the form of instructions or data structures and that may be accessed by a computer. It should be noted that a computer-readable medium may be tangible and non-transitory. As used herein, the term “code” may refer to software, instructions, code or data that is/are executable by a computing device or processor.

[0169] 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.

[0170] 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.

[0171] 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.”

[0172] As used herein, the term “approximately” refers to a range of measurements of a length, thickness, a quantity, time period, or other measurable value. Such range of measurements encompasses variations of +/-10% or less, preferably +/-5% or less, more preferably +/-1% or less, and still more preferably +/-0.1% or less, of and from the specified value, in so far as such variations are appropriate in order to function in the disclosed devices, systems, and techniques.

[0173] The 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.

## CLAIMS:

1. A non-transitory computer readable storage medium having stored thereon instructions that, when executed, cause one or more processors to at least:

obtain a first position estimate for an instrument based on robotic data indicating movement of a robotic positioning device configured to mechanically manipulate the instrument;

obtain a second position estimate for the instrument based on position sensor data received from at least one position sensor associated with the instrument;

determine a position estimate disparity between the first position estimate and the second position estimate based on a comparison of the first position estimate and the second position estimate;

update one or more confidence weights indicating a confidence of the first position estimate relative to the second position estimate based at least in part on the determined position estimate disparity, said updating comprising:

decreasing a confidence weight associated with the robotic data,

increasing a confidence weight associated with the position sensor data, or

decreasing a confidence weight associated with an image-based position

determination; and

determine a third position estimate for the instrument based on the updated one or more confidence weights.

2. The non-transitory computer readable storage medium of Claim 1, wherein the robotic data includes commands for controlling a shape and movement of the instrument using the robotic positioning device.

3. The non-transitory computer readable storage medium of Claim 1, wherein the instructions, when executed, further cause the one or more processors to determine that the instrument has experienced a hysteresis condition when the first position estimate indicates a first motion estimate that is less than a second motion estimate indicated by the second position estimate.

4. The non-transitory computer readable storage medium of Claim 1, wherein the robotic data includes kinematics data associated with the robotic positioning device.

5. The non-transitory computer readable storage medium of Claim 1, wherein the instructions, when executed, cause the one or more processors to determine that the instrument has experienced a buckling condition when the first position estimate indicates a first motion estimate that exceeds a second motion estimate indicated by the second position estimate.
6. The non-transitory computer readable storage medium of Claim 1, wherein said updating the one or more confidence weights involves setting a weighting factor associated with position estimation based on the robotic data to zero.
7. The non-transitory computer readable storage medium of Claim 1, wherein the instructions, when executed, further cause the one or more processors to determine that the position estimate disparity exceeds a predetermined disparity threshold value.
8. The non-transitory computer readable storage medium of Claim 7, wherein said updating the one or more confidence weights is in response to the determination that the position estimate disparity exceeds the disparity threshold value.
9. The non-transitory computer readable storage medium of Claim 1, wherein the instructions, when executed, further cause the one or more processors to:
  - determine a first motion estimate by determining a change in position of the instrument based on the robotic data during an interval; and
  - determine a second motion estimate by determining a change in position of the instrument based on the position sensor data during the interval.
10. The non-transitory computer readable storage medium of Claim 1, wherein the instructions, when executed, further cause the one or more processors to:
  - obtain a fourth position estimate for the instrument based on vision data received from an imaging device positioned on the instrument;
  - determine the position estimate disparity based at least in part on a comparison of the second position estimate and the fourth position estimate; and
  - based on the position estimate disparity, update a confidence weight indicating a confidence of the fourth position estimate.

11. The non-transitory computer readable storage medium of Claim 10, wherein the third position estimate is based at least in part on the updated confidence weight indicating the confidence of the fourth position estimate.

12. The non-transitory computer readable storage medium of Claim 10, wherein the instructions, when executed, further cause the one or more processors to determine that the instrument has experienced a hysteresis condition when the fourth position estimate indicates a first motion estimate that is less than a second motion estimate indicated by the second position estimate.

13. A robotic system comprising:

an instrument having an elongate body and at least one position sensor disposed on the elongate body;

an instrument positioning device attached to the instrument and configured to move the instrument;

at least one computer-readable memory having stored thereon executable instructions;

and

one or more processors in communication with the at least one computer-readable memory and configured to execute the instructions to cause the system to at least:

obtain a first position estimate for the instrument based on robotic data indicating movement of a robotic positioning device configured to mechanically manipulate the instrument;

obtain a second position estimate for the instrument based on position sensor data received from the at least one position sensor;

determine a position estimate disparity between the first position estimate and the second position estimate based on a comparison of the first position estimate and the second position estimate;

update one or more confidence weights indicating a confidence of the first position estimate relative to the second position estimate based at least in part on the determined position estimate disparity, said updating comprising:

decreasing a confidence weight associated with the robotic data,

increasing a confidence weight associated with the position sensor data, or

decreasing a confidence weight associated with an image-based position

determination; and

determine a third position estimate for the instrument based on the updated one or more confidence weights.

14. The system of Claim 13, wherein the at least one position sensor comprises an EM sensor.

15. The system of Claim 13, wherein the at least one position sensor comprises an imaging device positioned on the instrument, and wherein the instructions further cause the one or more processors to determine positional information from images captured by the imaging device.

16. The system of Claim 13, wherein the at least one position sensor comprises at least one of a shape-sensing fiber, an accelerometer, a gyroscope, an electromagnetic sensor, an imaging device, or an ultrasonic sensor.

17. A method for navigating an instrument within an interior region of a body, the method comprising:

obtaining a first position estimate for an instrument based on robotic data indicating movement of a robotic positioning device configured to mechanically manipulate the instrument;

obtaining a second position estimate for the instrument based on position sensor data received from at least one position sensor associated with the instrument;

determining a position estimate disparity between the first position estimate and the second position estimate based on a comparison of the first position estimate and the second position estimate;

updating one or more confidence weights indicating a confidence of the first position estimate relative to the second position estimate based at least in part on the determined position estimate disparity, said updating comprising:

decreasing a confidence weight associated with the robotic data,  
increasing a confidence weight associated with the position sensor data, or  
decreasing a confidence weight associated with an image-based position determination; and

determining a third position estimate for the instrument based on the updated one or more confidence weights.

18. The method of Claim 17, wherein updating the one or more confidence weights involves setting a confidence weight associated with the robotic data to zero when the position estimate disparity is beyond a threshold level.

19. The method of Claim 17, wherein updating the one or more confidence weights involves setting a confidence weight associated with the position sensor data to zero when the position estimate disparity is beyond a threshold level.

20. The method of Claim 17, wherein:

determining the position estimate disparity comprises determining a magnitude of a difference between the first position estimate and the second position estimate; and

updating the one or more confidence weights is based at least in part on the magnitude of the difference between the first position estimate and the second position estimate.

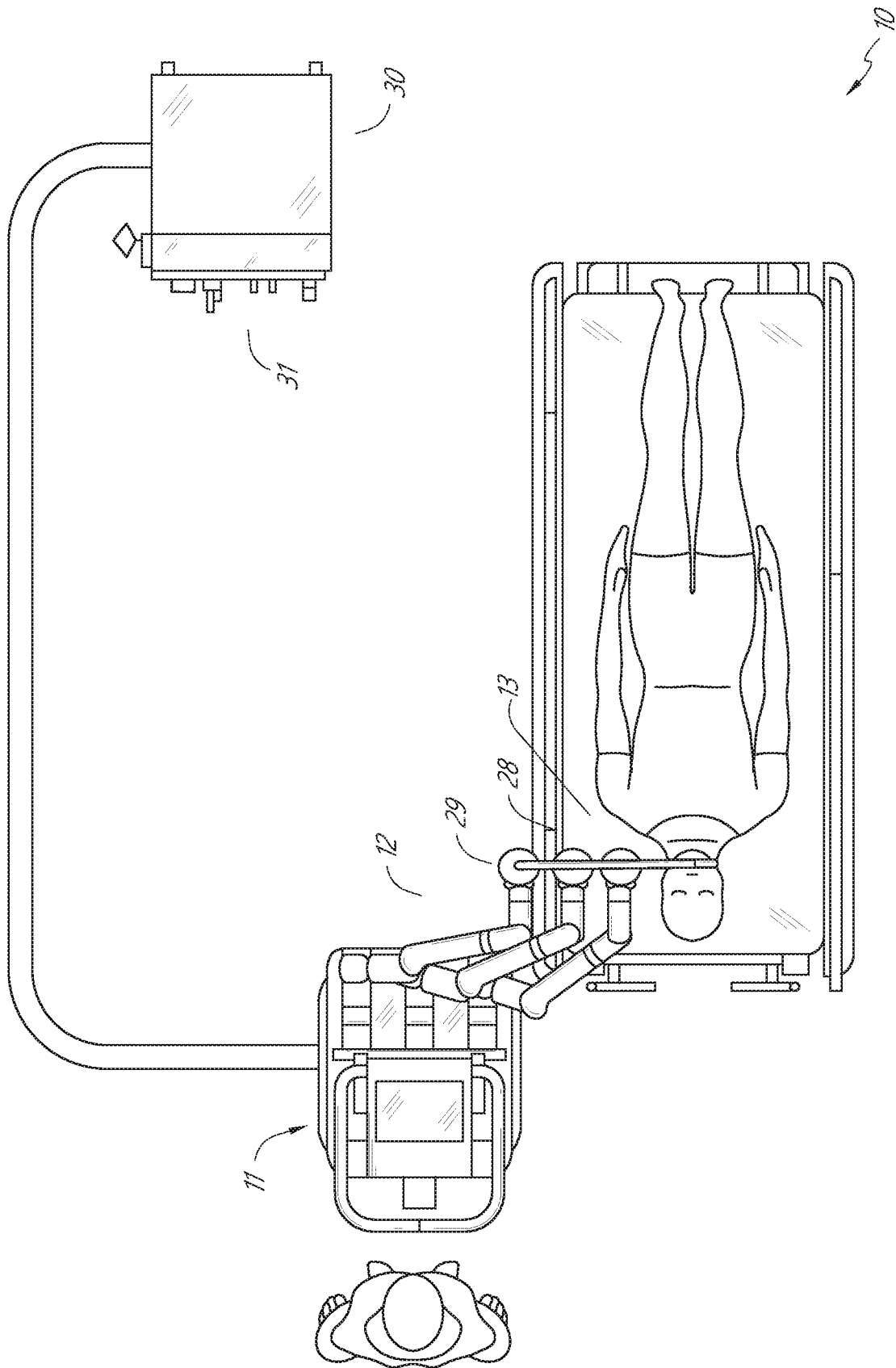


FIG. 1

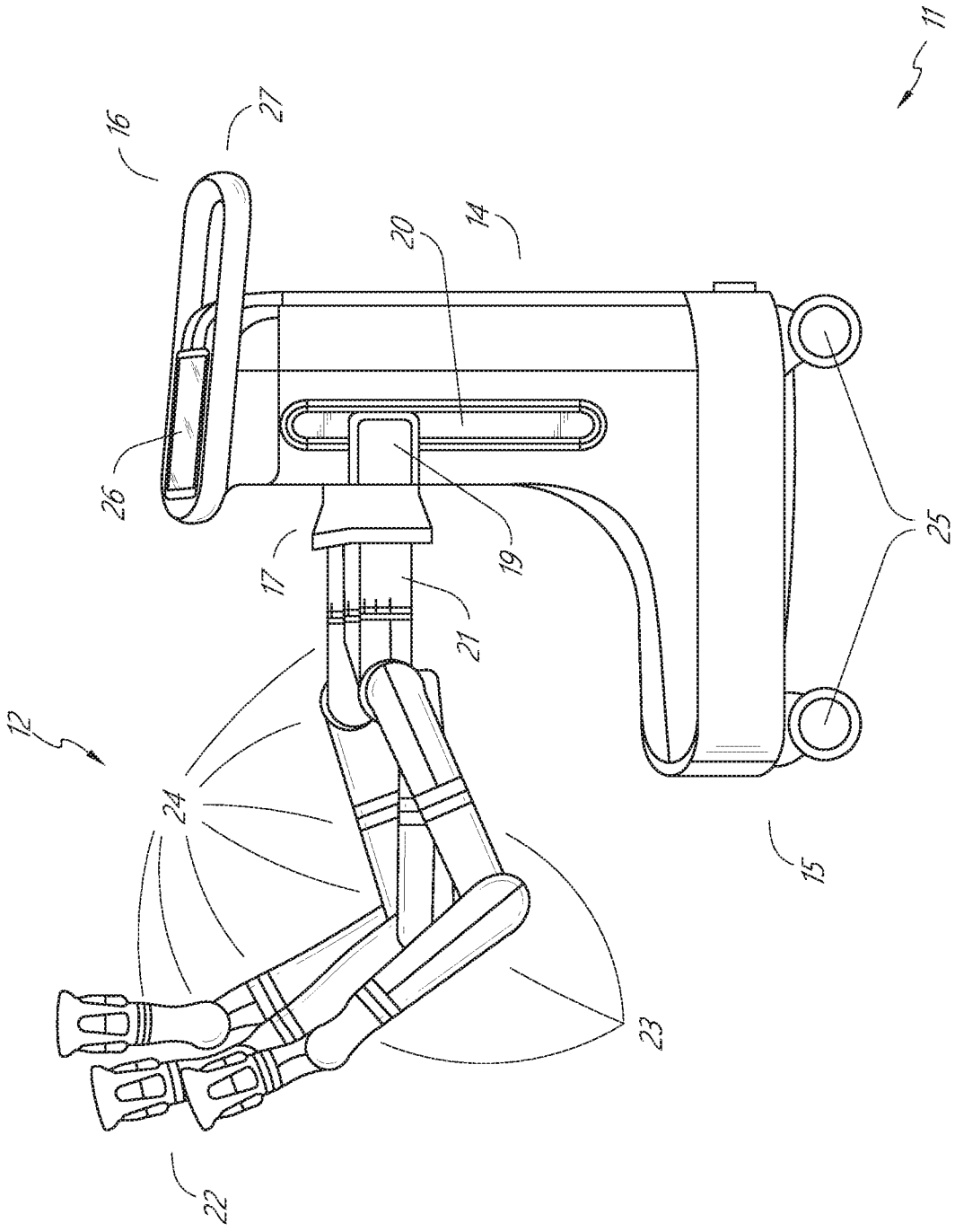


FIG. 2

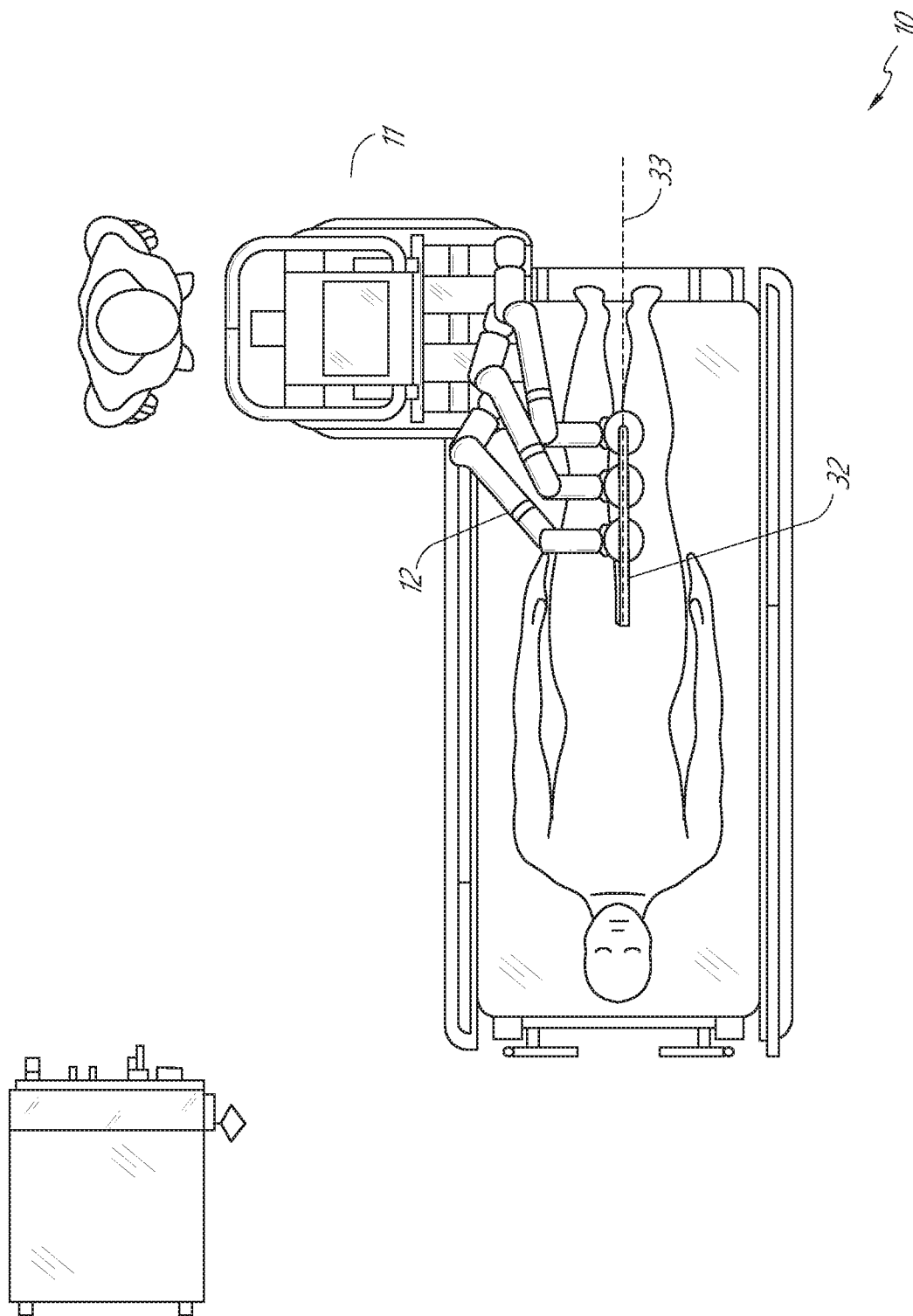
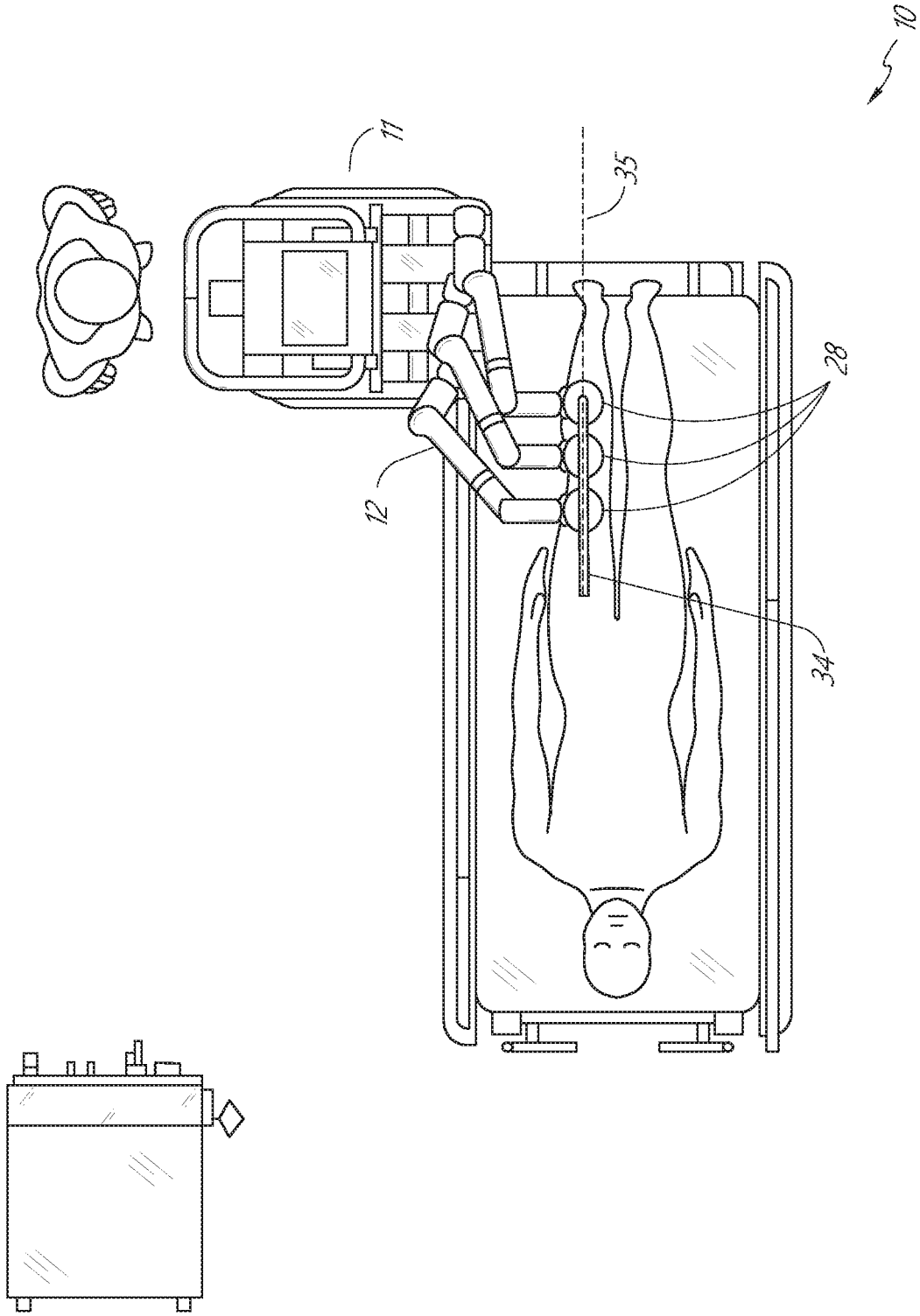


FIG. 3



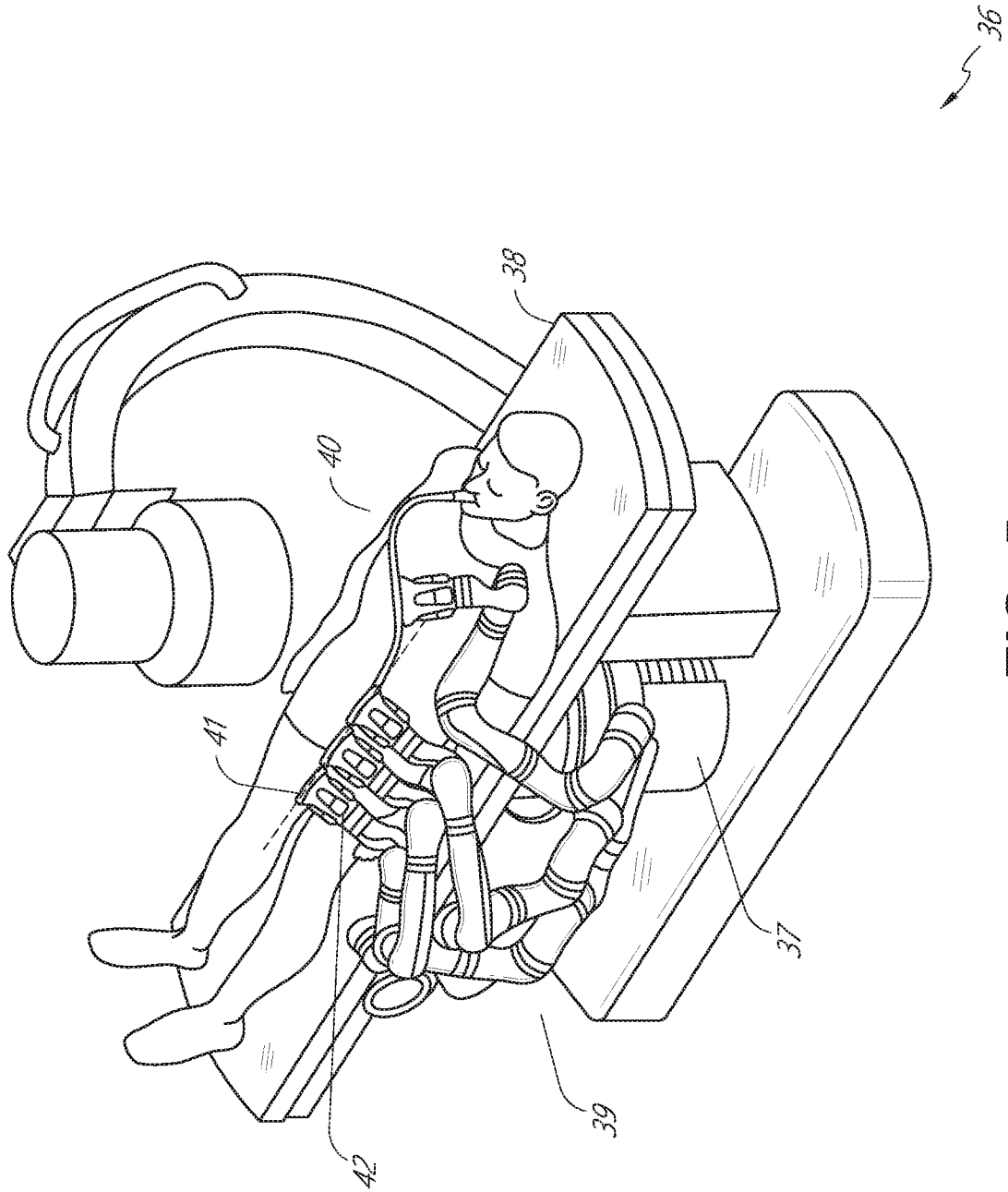


FIG. 5

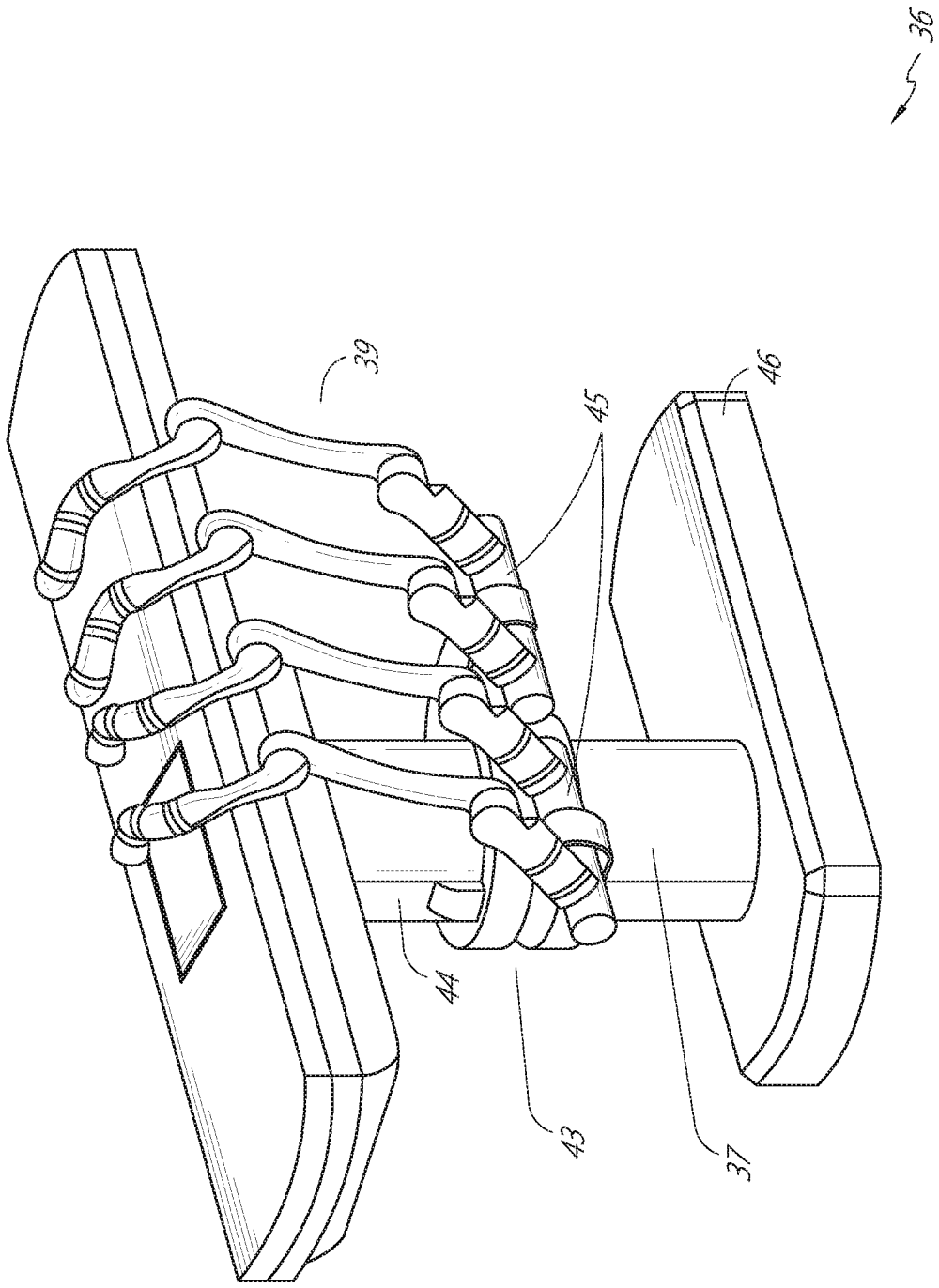


FIG. 6

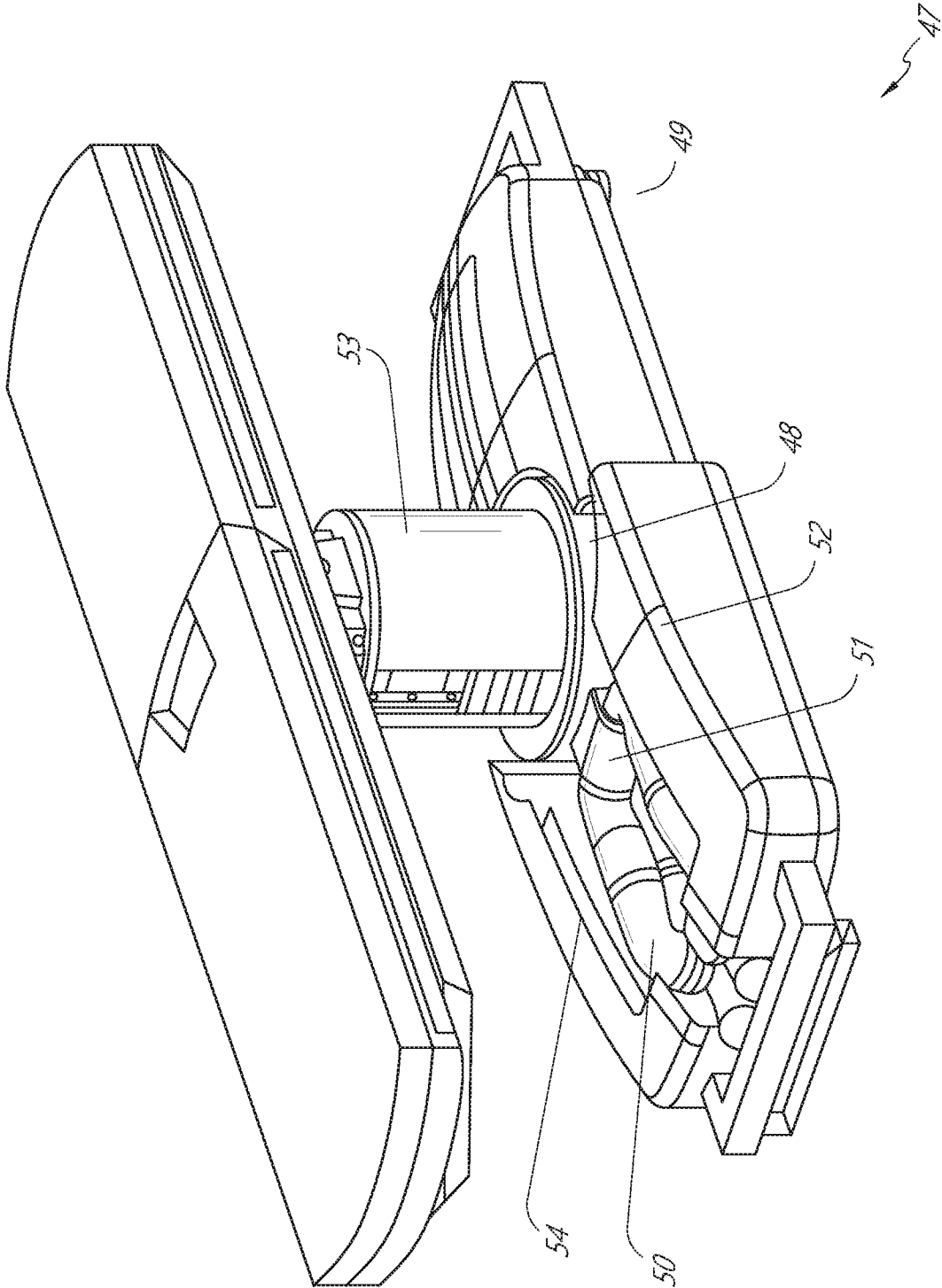


FIG. 7

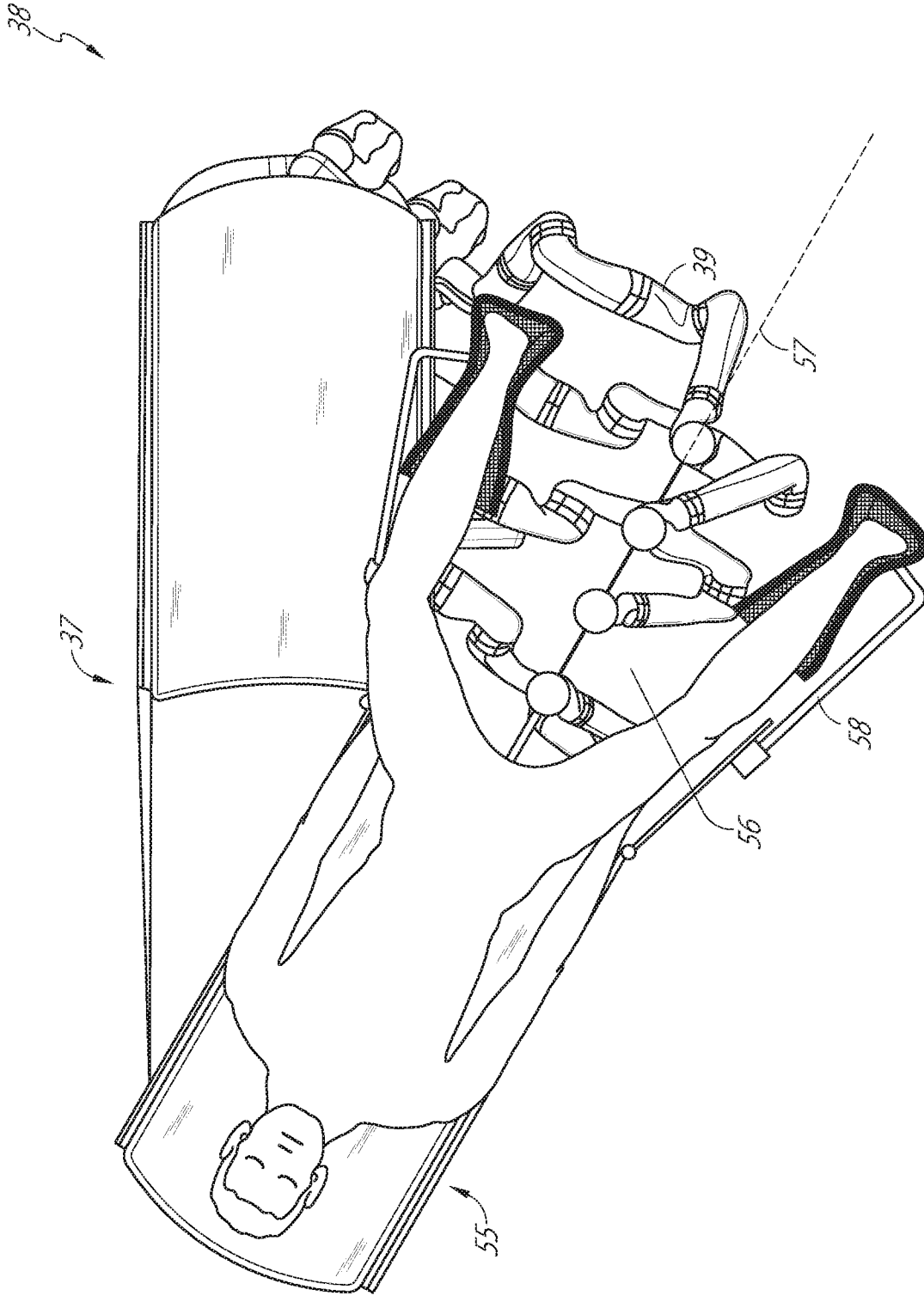


FIG. 8

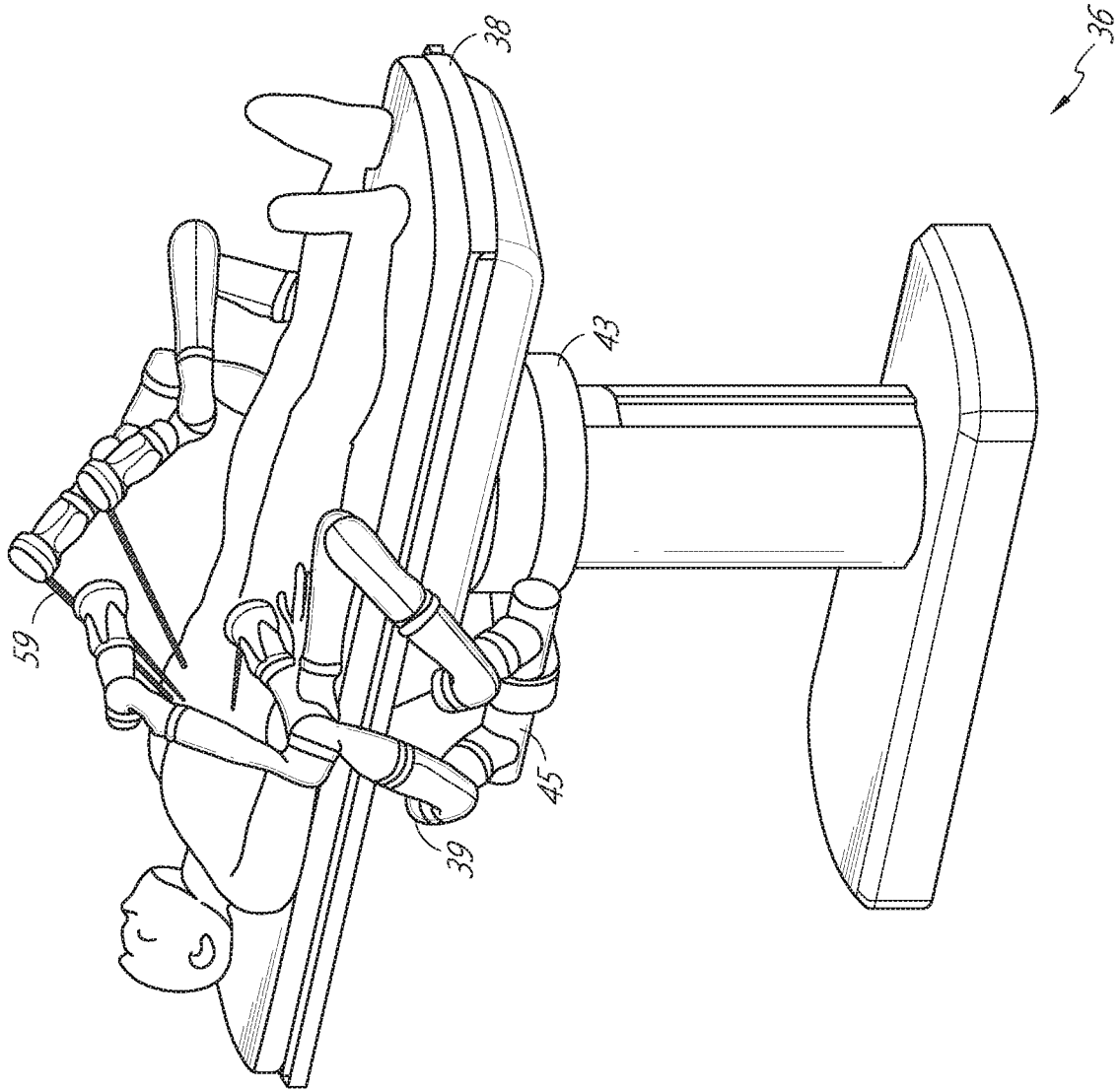


FIG. 9

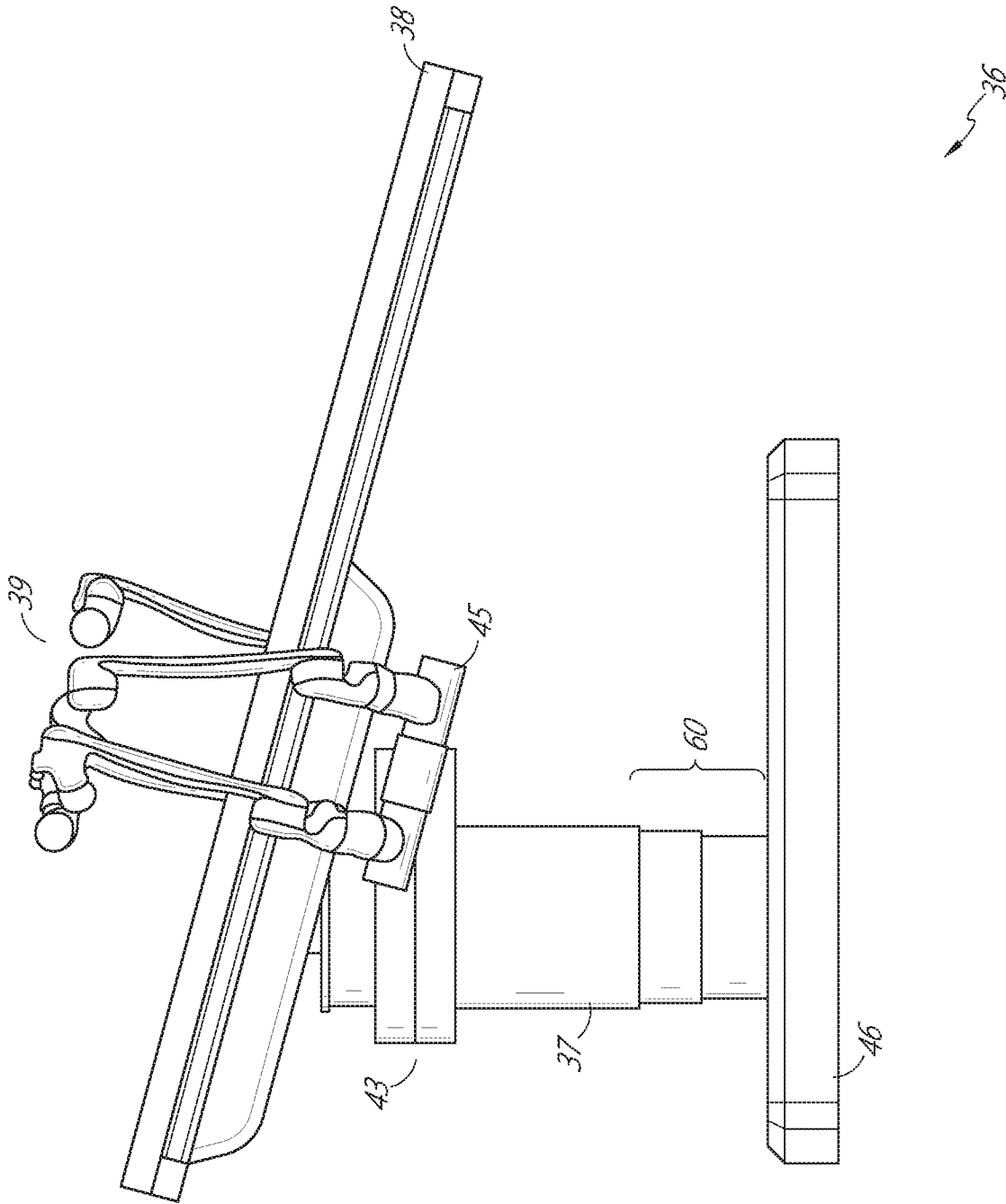


FIG. 10

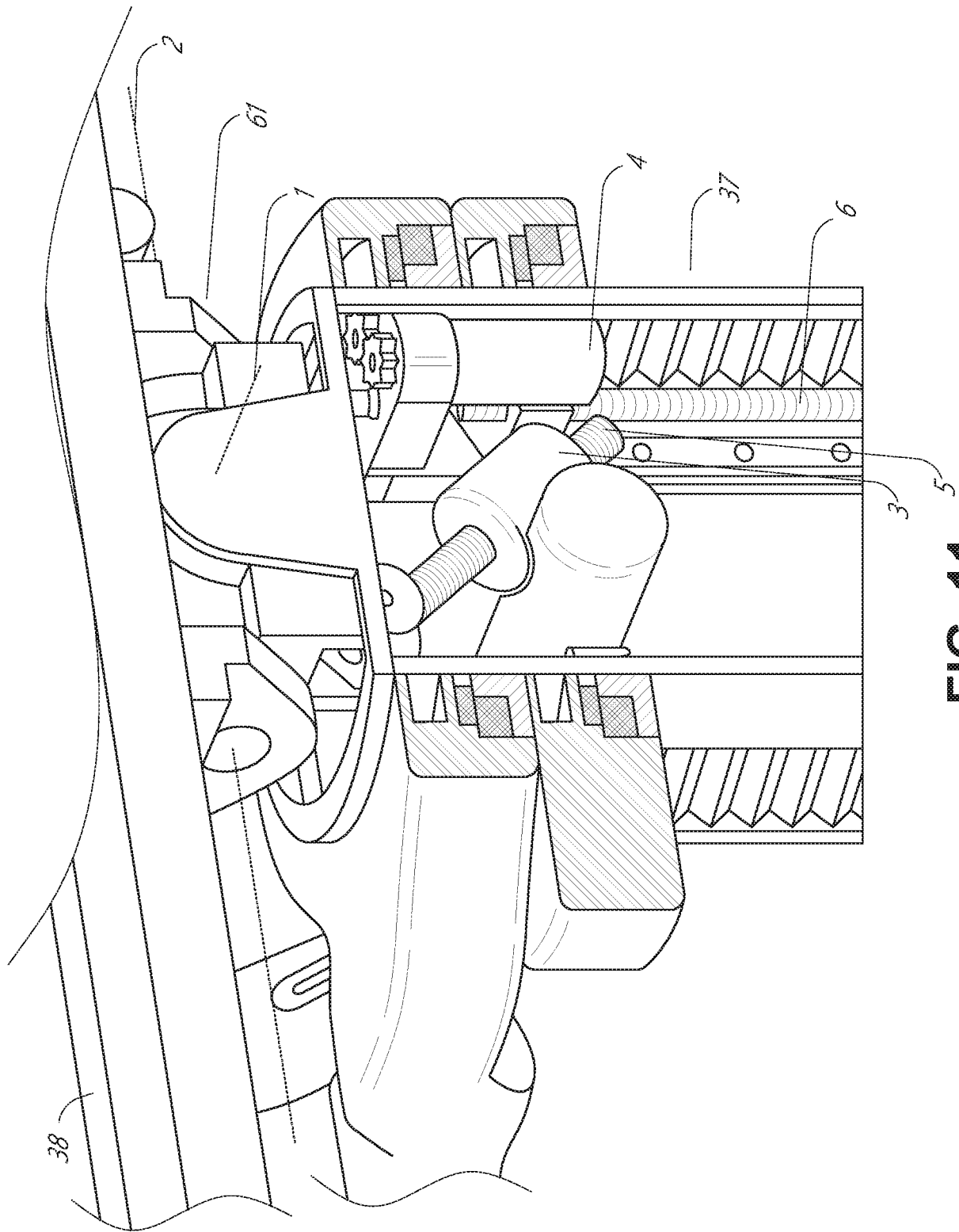


FIG. 11

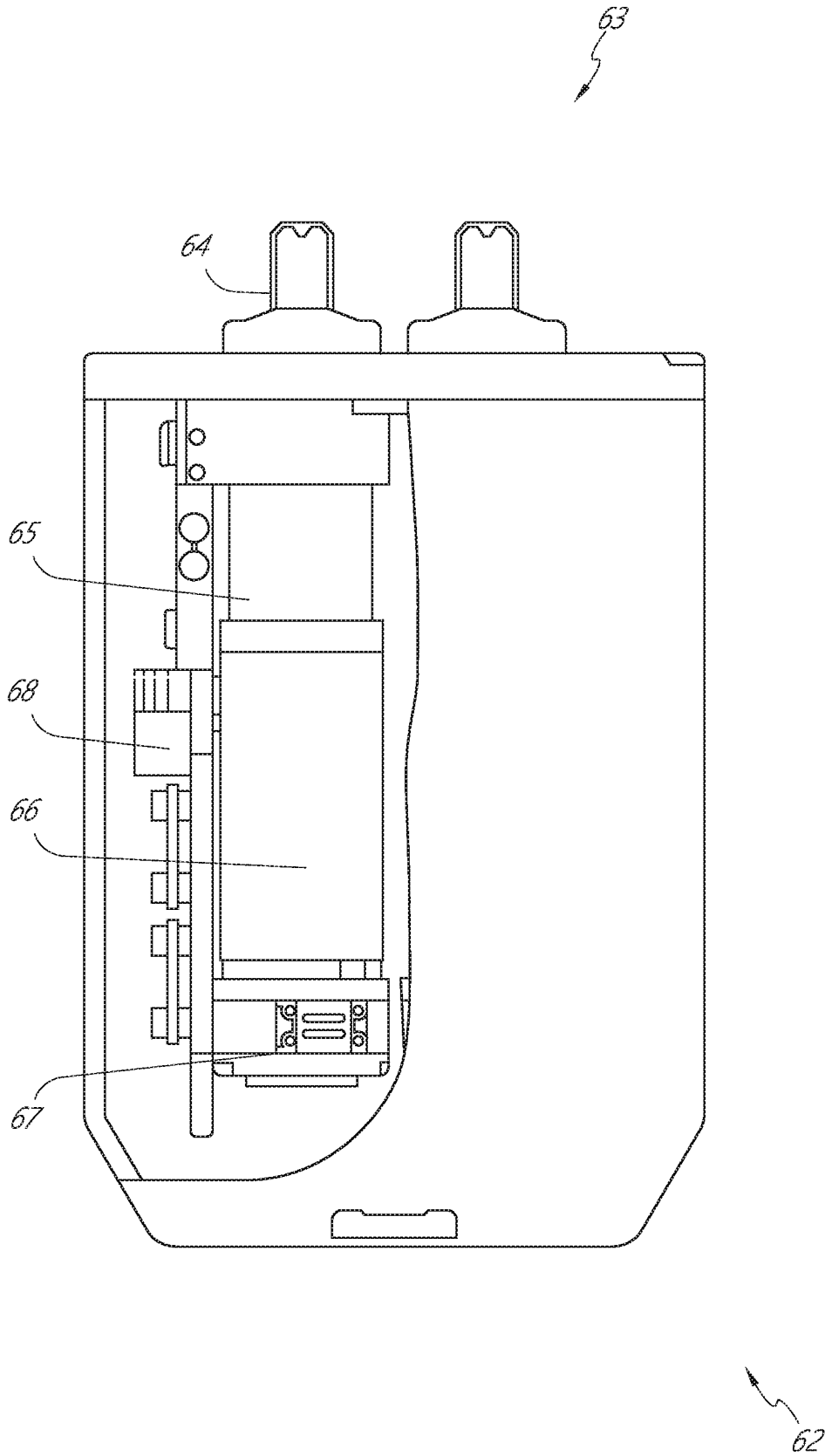


FIG. 12

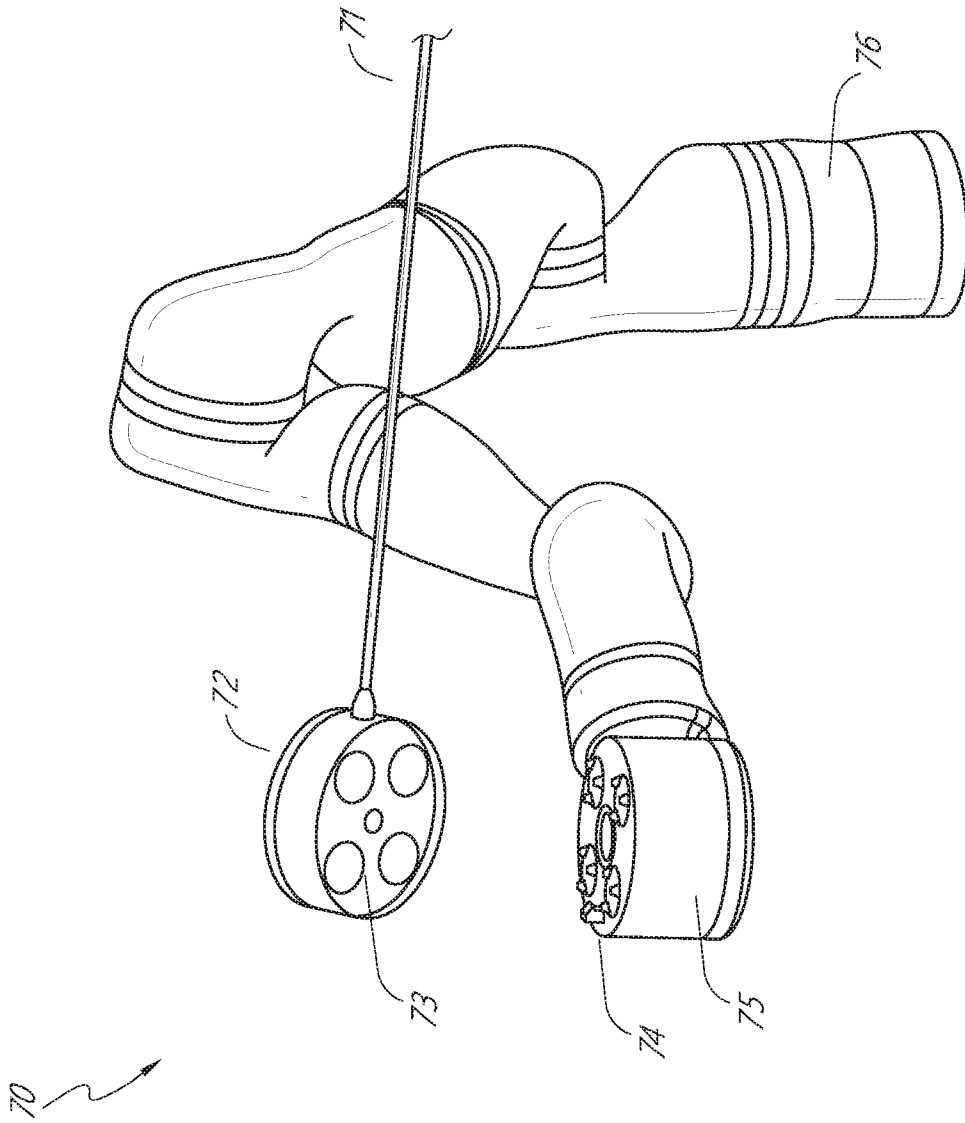


FIG. 13

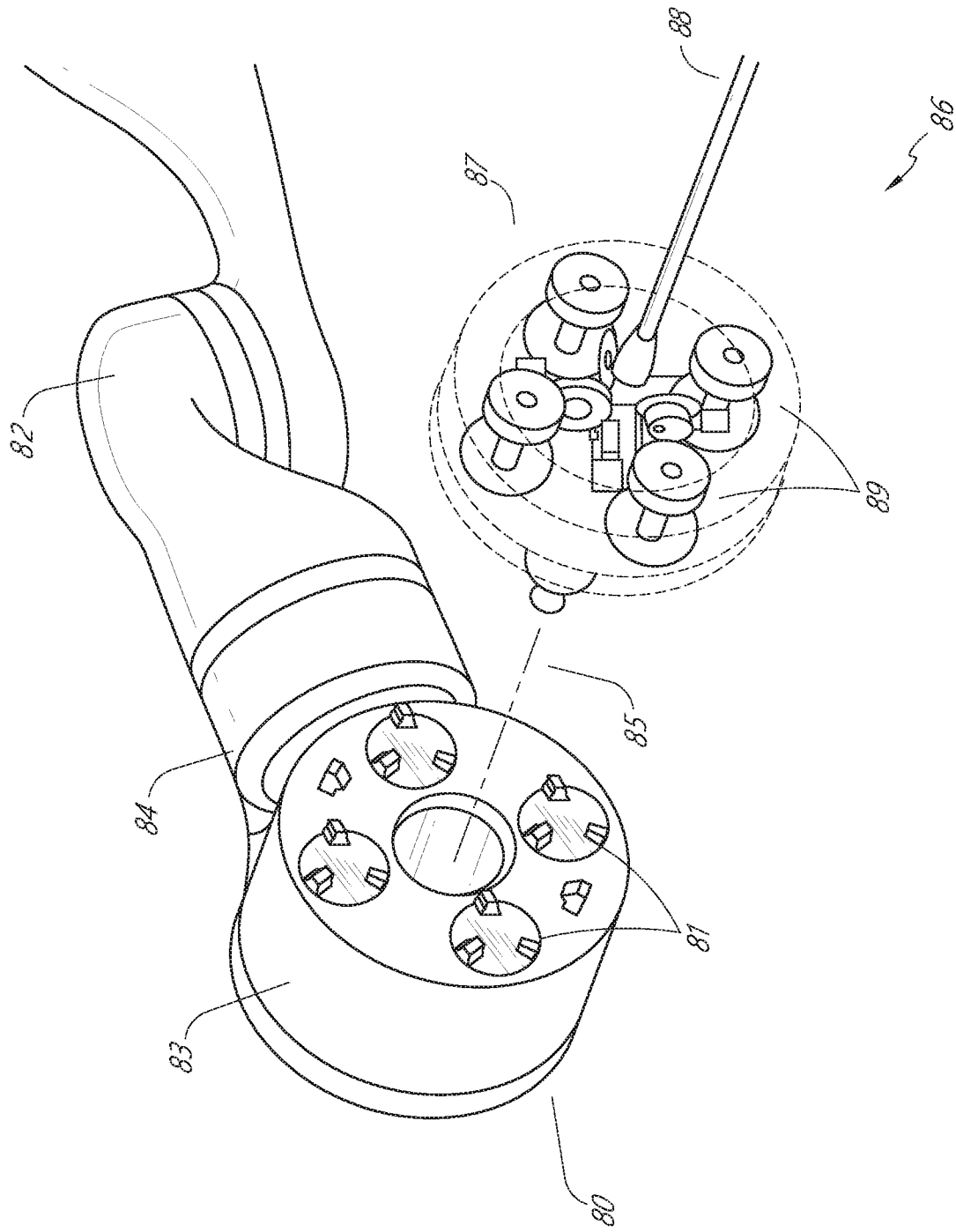


FIG. 14

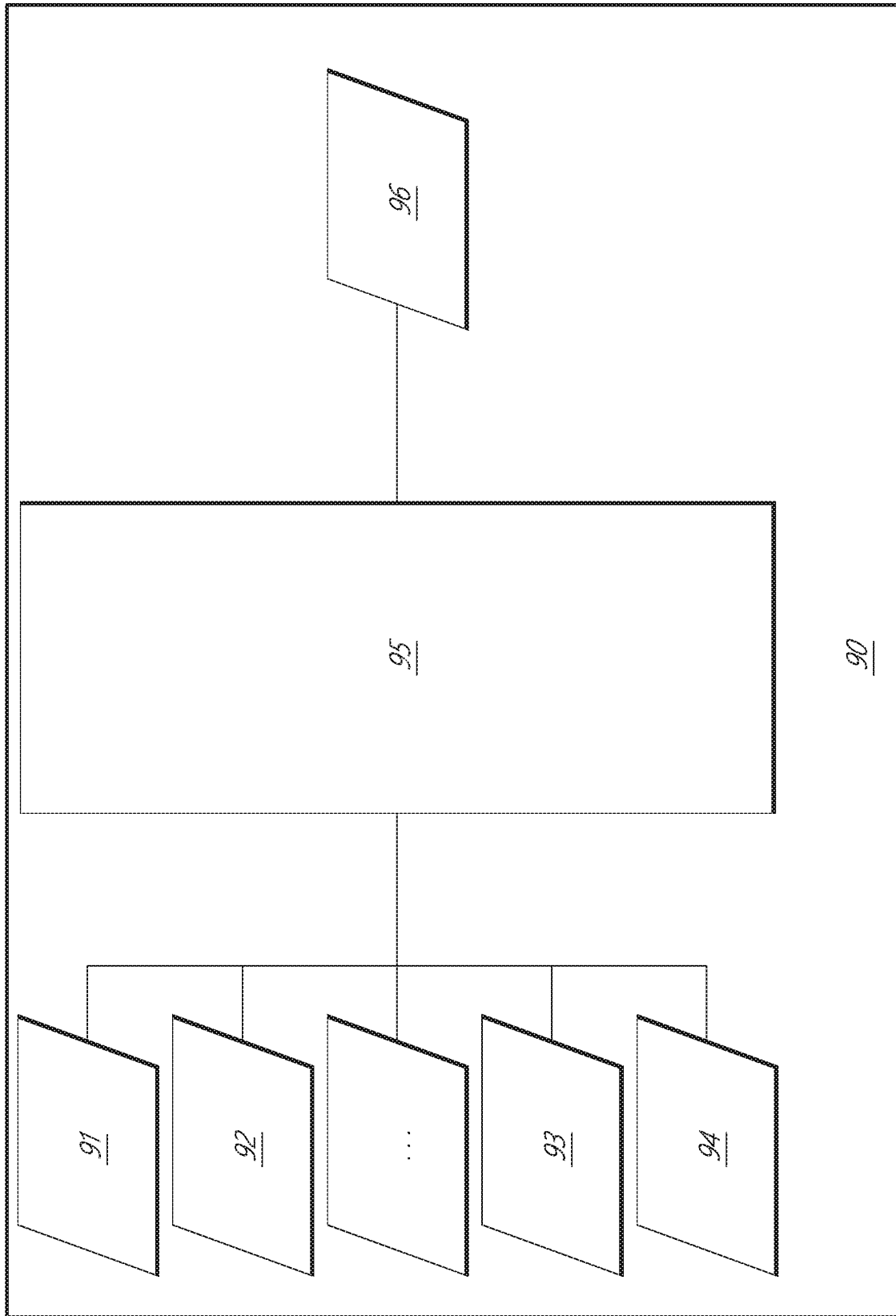


FIG. 15

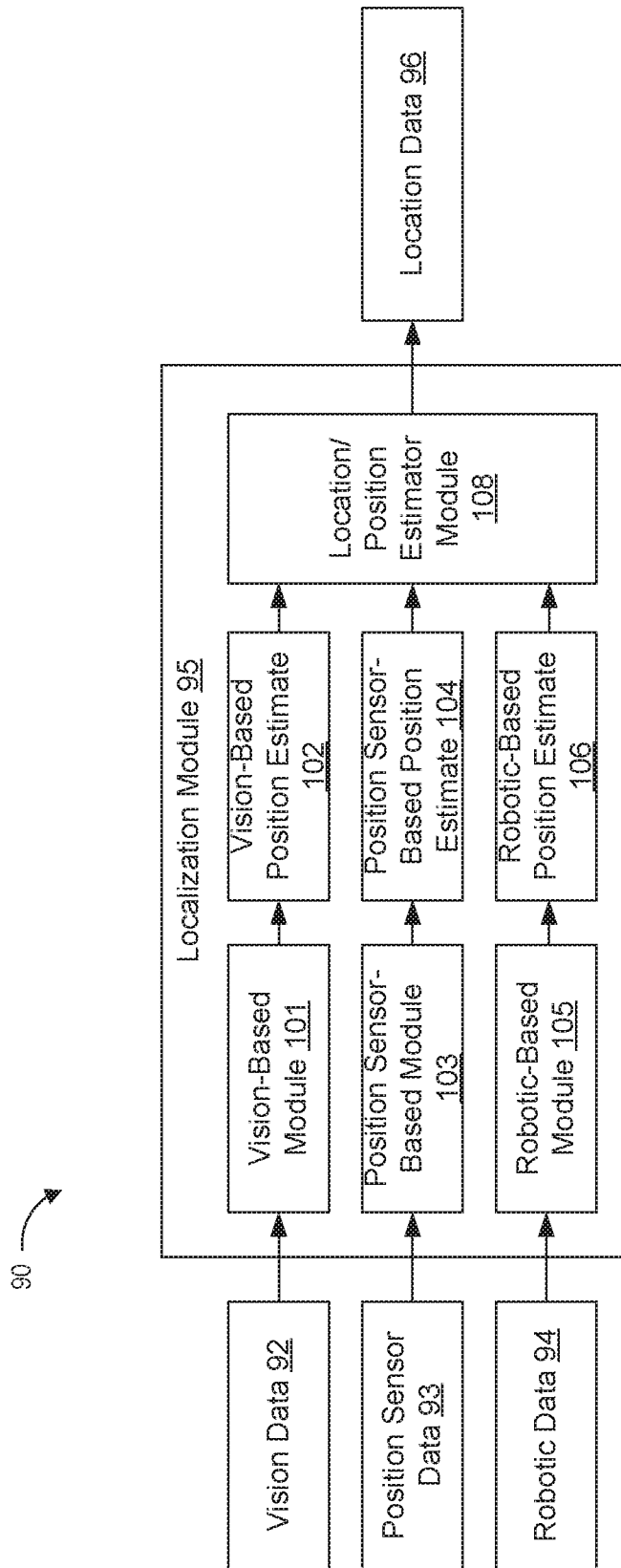


FIG. 16

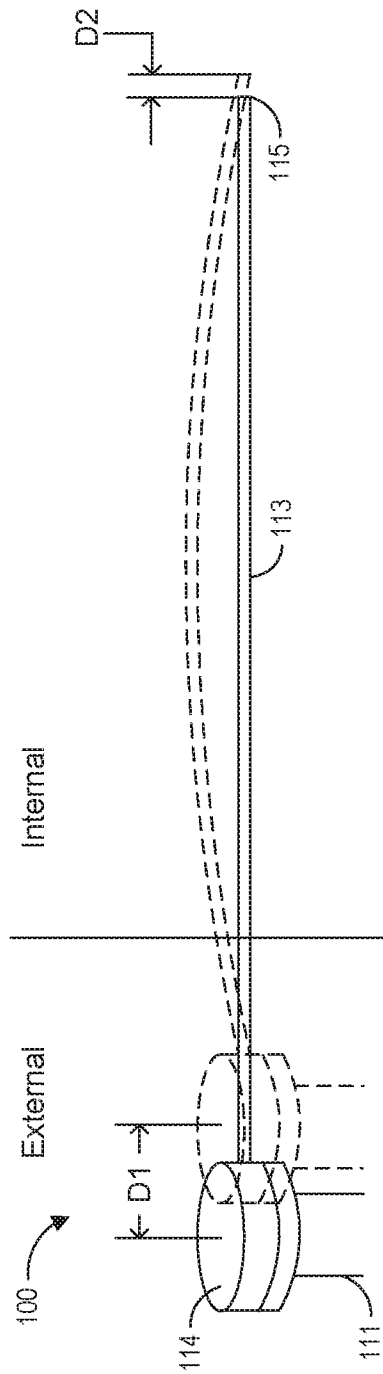


FIG. 17A

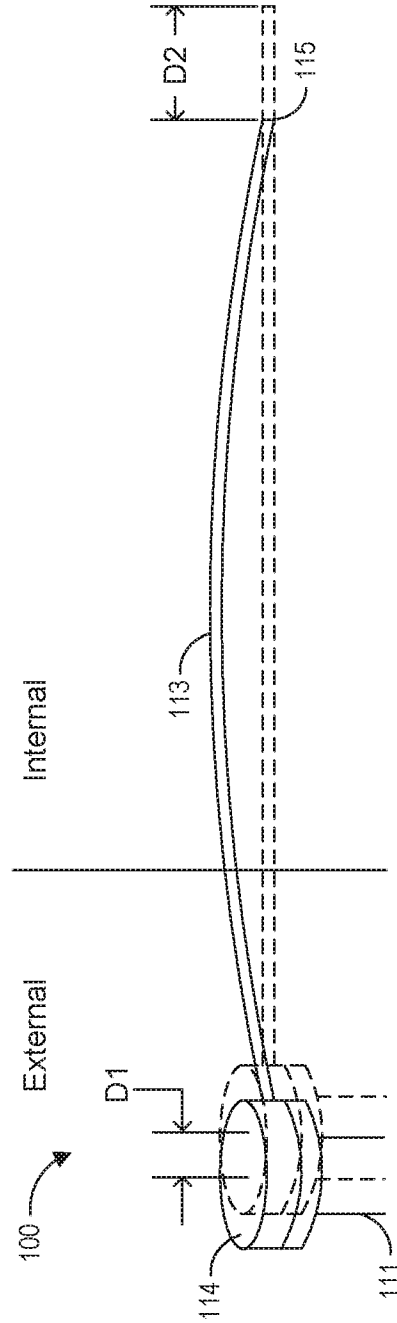


FIG. 17B

18/20

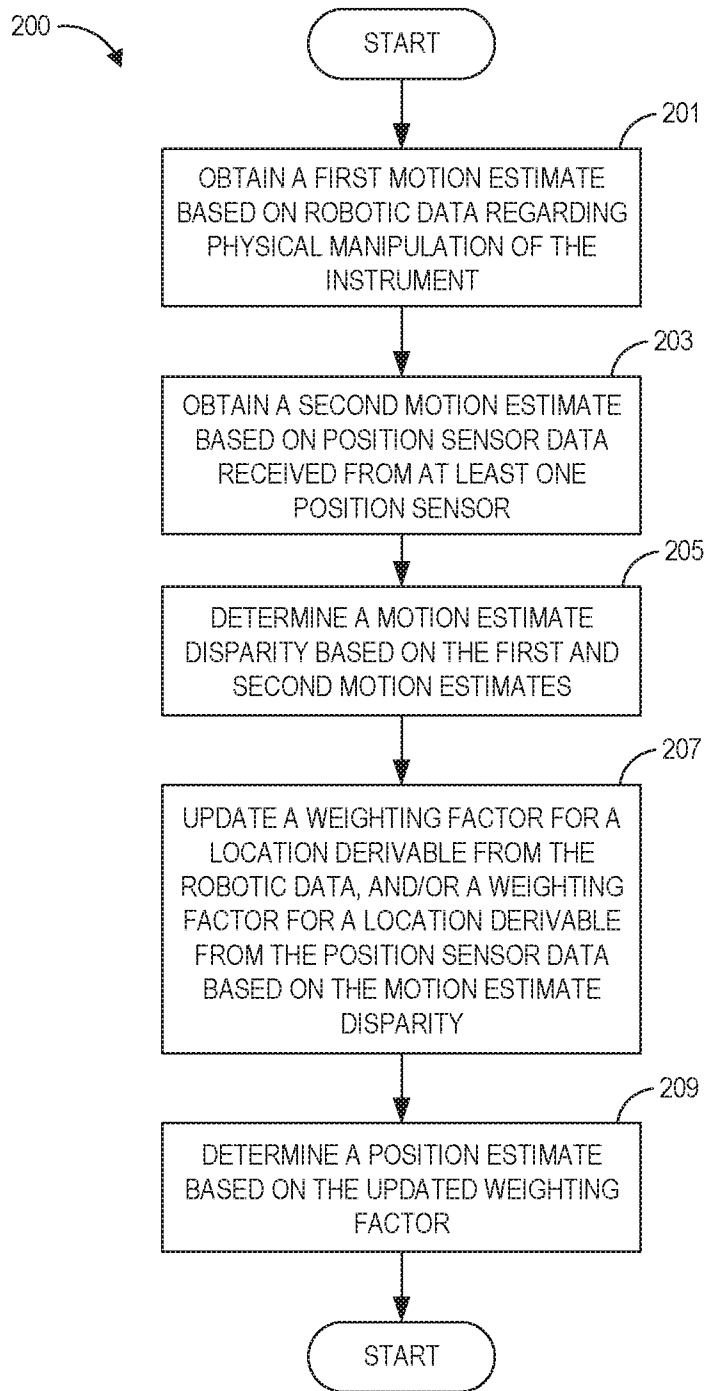


FIG. 18A

19/20

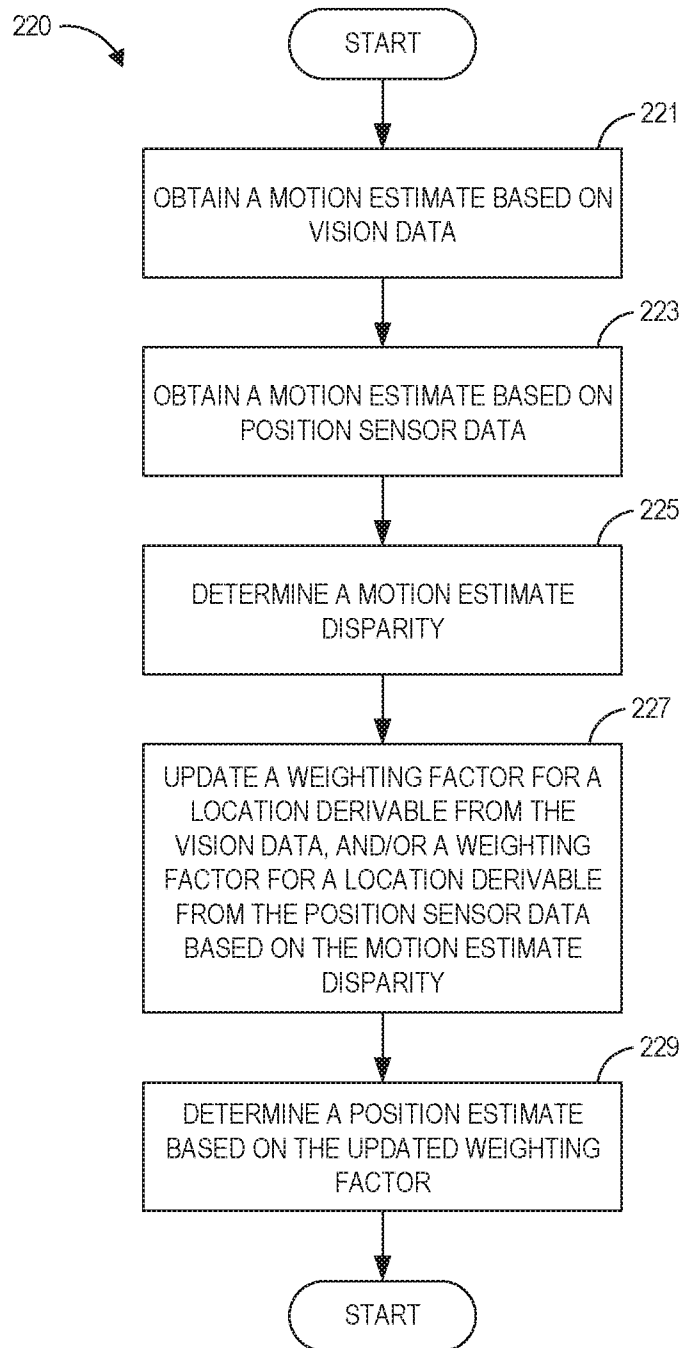


FIG. 18B

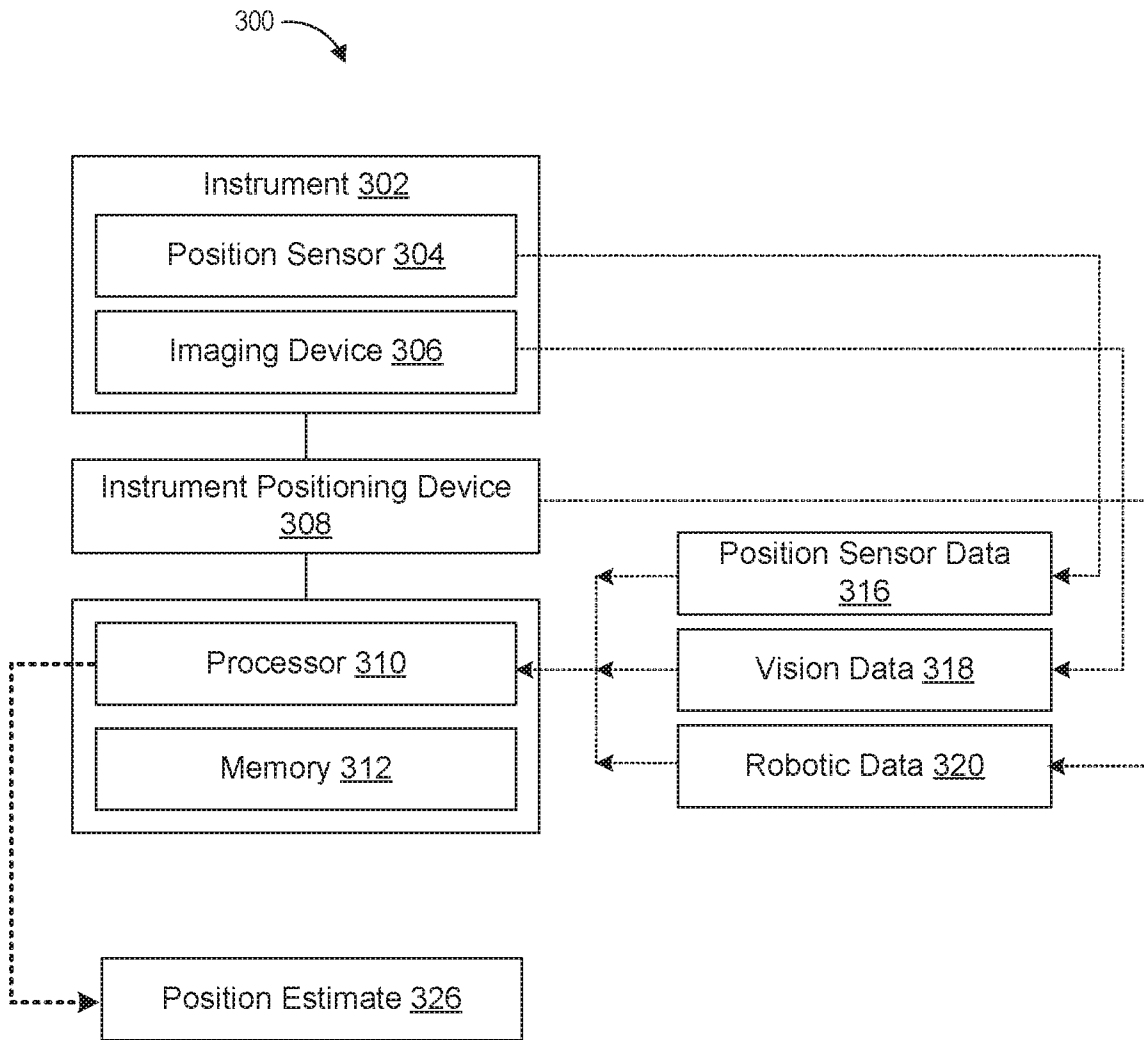


FIG. 19