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Ye et al.

(54) **ROBOTIC SYSTEMS AND METHODS FOR NAVIGATION OF LUMINAL NETWORK THAT DETECT PHYSIOLOGICAL NOISE**

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Publication Classification

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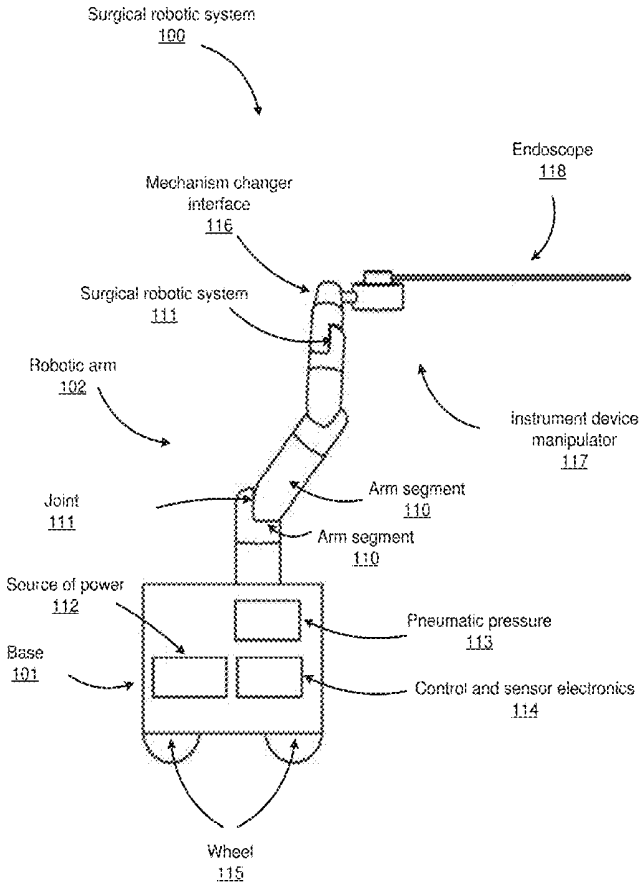
G06T 7/55	(2006.01)
G06T 7/262	(2006.01)
G06T 7/246	(2006.01)
A61B 1/005	(2006.01)
A61B 34/00	(2006.01)
A61B 5/06	(2006.01)
A61B 1/267	(2006.01)
A61B 5/00	(2006.01)

(52) **U.S. Cl.**

CPC ***A61B 1/00149*** (2013.01); *A61B 2034/742* (2016.02); ***G06T 7/55*** (2017.01); ***G06T 7/262*** (2017.01); ***G06T 7/248*** (2017.01); ***A61B 1/0057*** (2013.01); ***A61B 34/74*** (2016.02); ***A61B 1/00048*** (2013.01); ***A61B 5/062*** (2013.01); ***A61B 1/2676*** (2013.01); ***A61B 5/7285*** (2013.01); ***A61B 1/00009*** (2013.01); *G06T 2207/10068* (2013.01); *G06T 2207/30061* (2013.01); ***G06T 7/74*** (2017.01)

(57) **ABSTRACT**

Provided are robotic systems and methods for navigation of luminal network that detect physiological noise. In one aspect, the system includes a set of one or more processors configured to receive first and second image data from an image sensor located on an instrument, detect a set of one or more points of interest the first image data, and identify a set of first locations and a set of second location respectively corresponding to the set of points in the first and second image data. The set of processors are further configured to, based on the set of first locations and the set of second locations, detect a change of location of the instrument within a luminal network caused by movement of the luminal network relative to the instrument based on the set of first locations and the set of second locations.



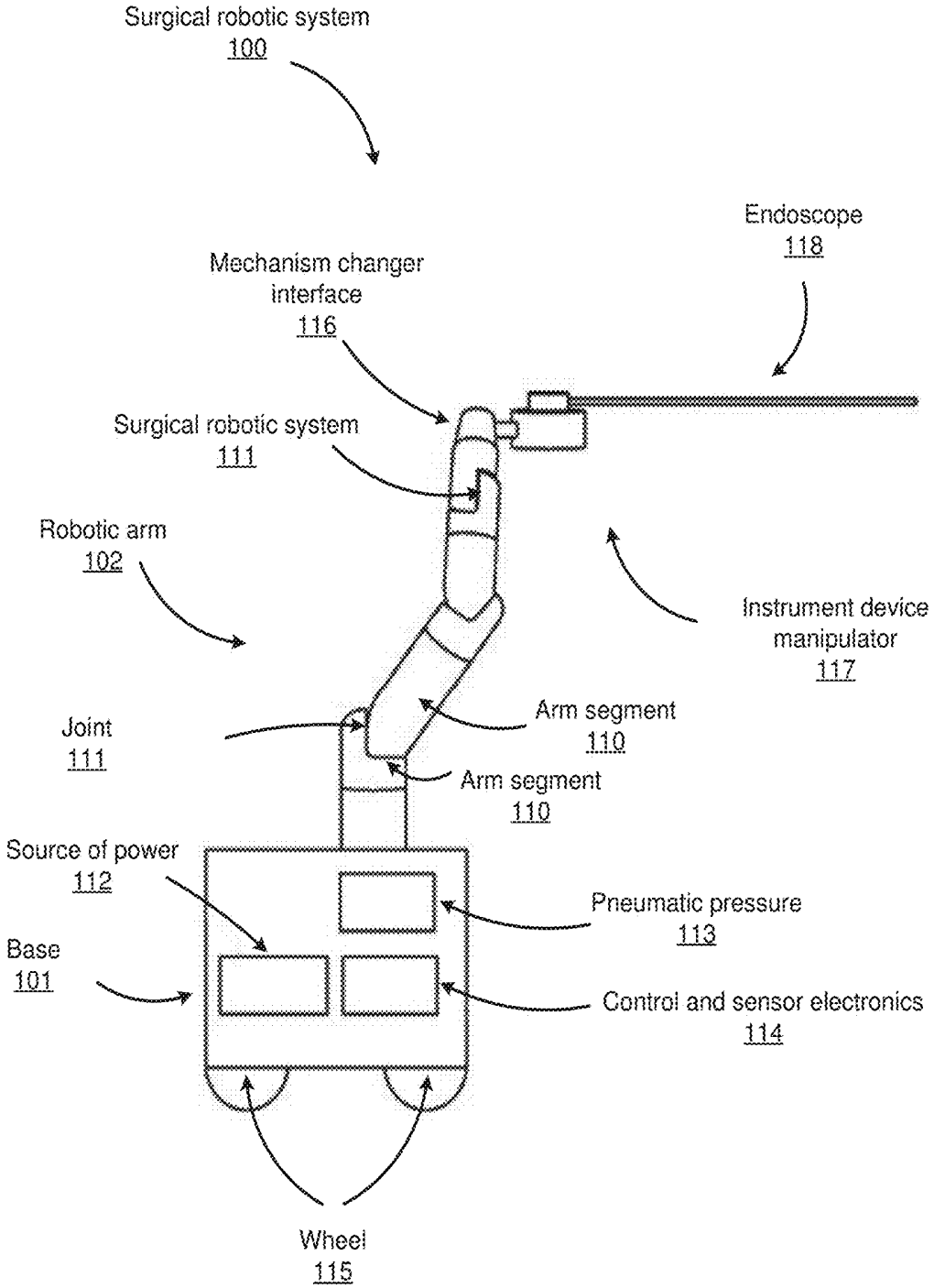

Surgical robotic system
100
Endoscope
118
Mechanism changer interface
116
Surgical robotic system
111
Robotic arm
102
Instrument device manipulator
117
Joint
111
Arm segment
110
Arm segment
110
Source of power
112
Pneumatic pressure
113
Base
101
Control and sensor electronics
114
Wheel
115

FIG. 1A

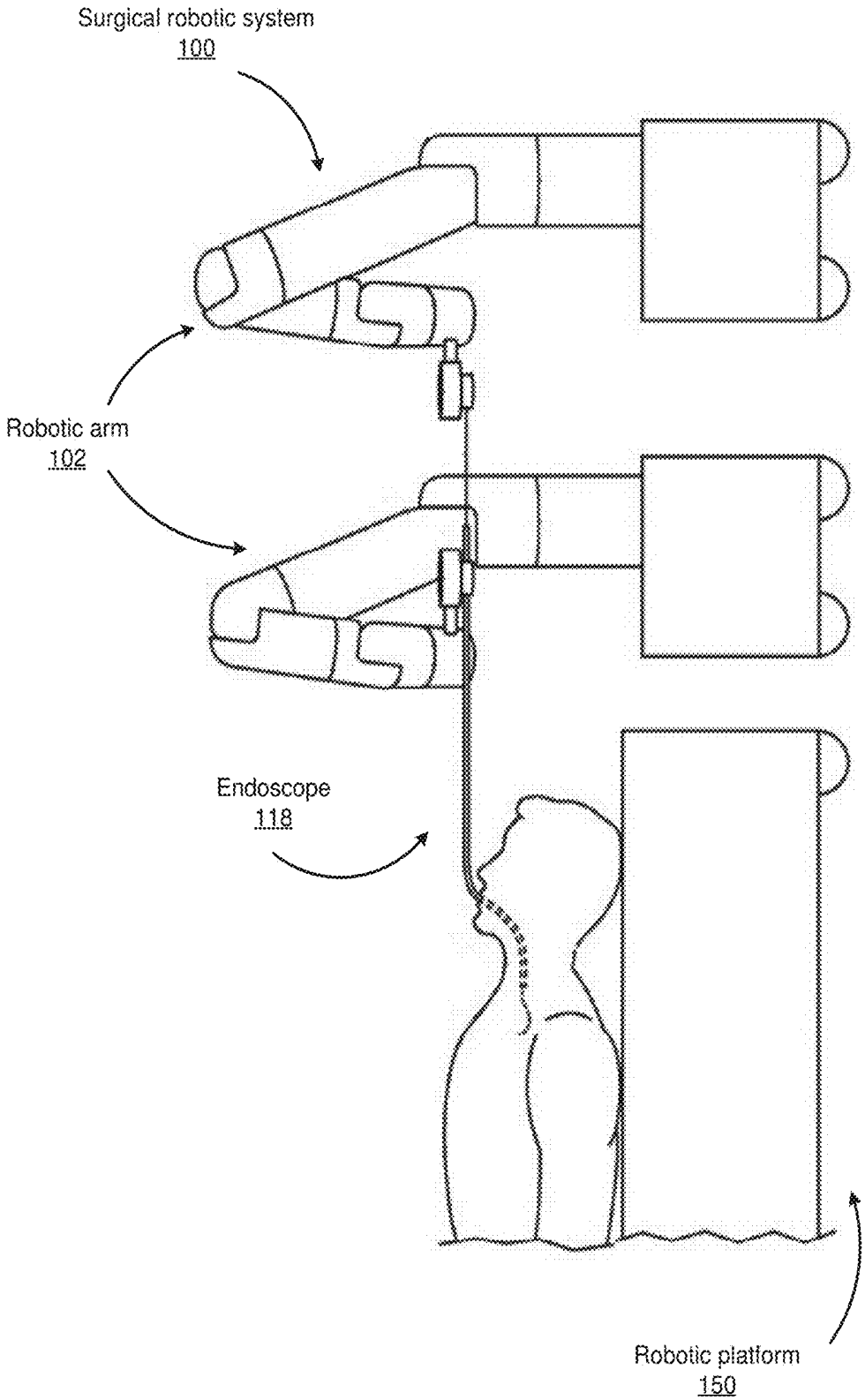

Surgical robotic system
100
Robotic arm
102
Endoscope
118
Robotic platform
150

FIG. 1B

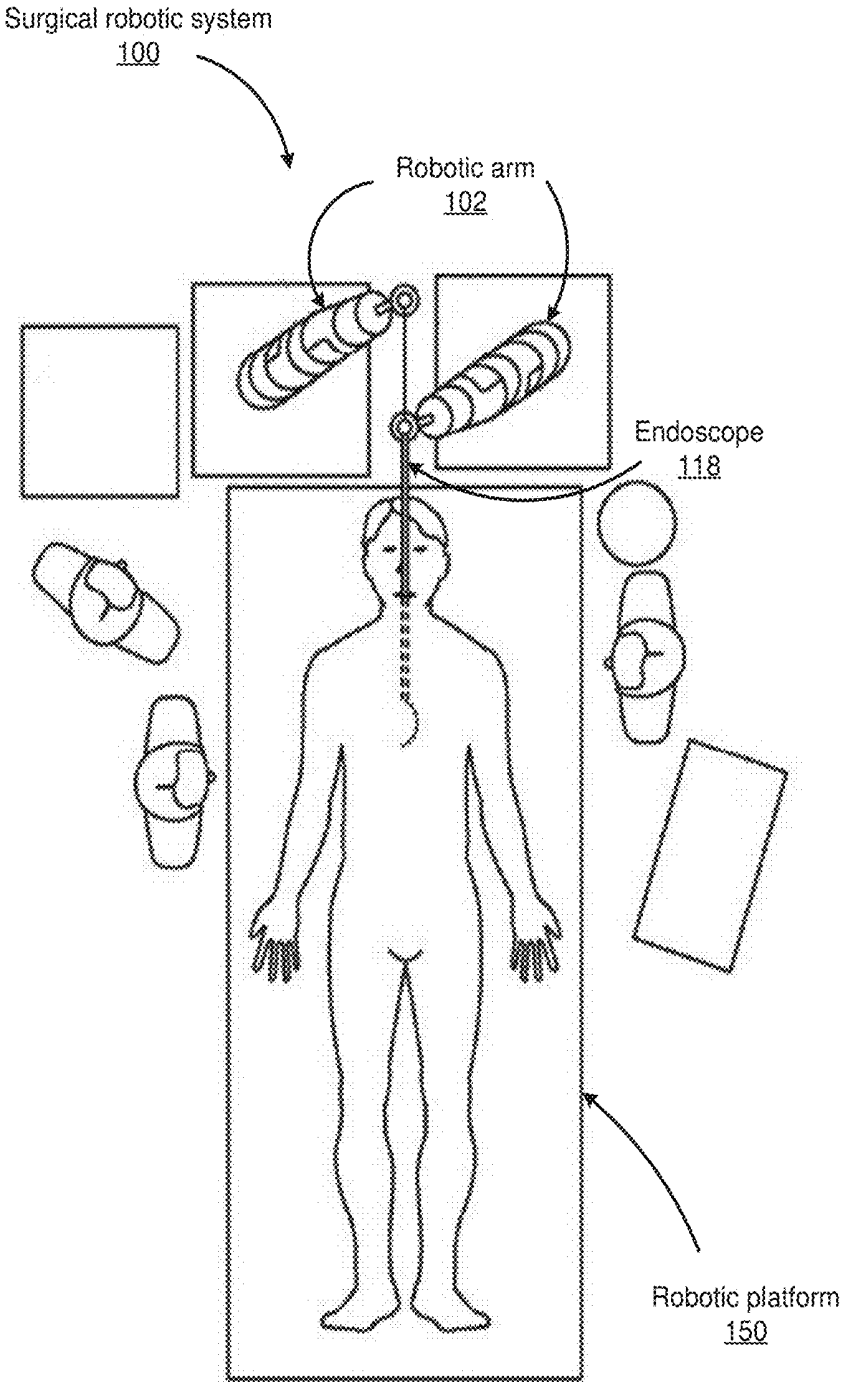

Surgical robotic system
100
Robotic arm
102
Endoscope
118
Robotic platform
150

FIG. 1C

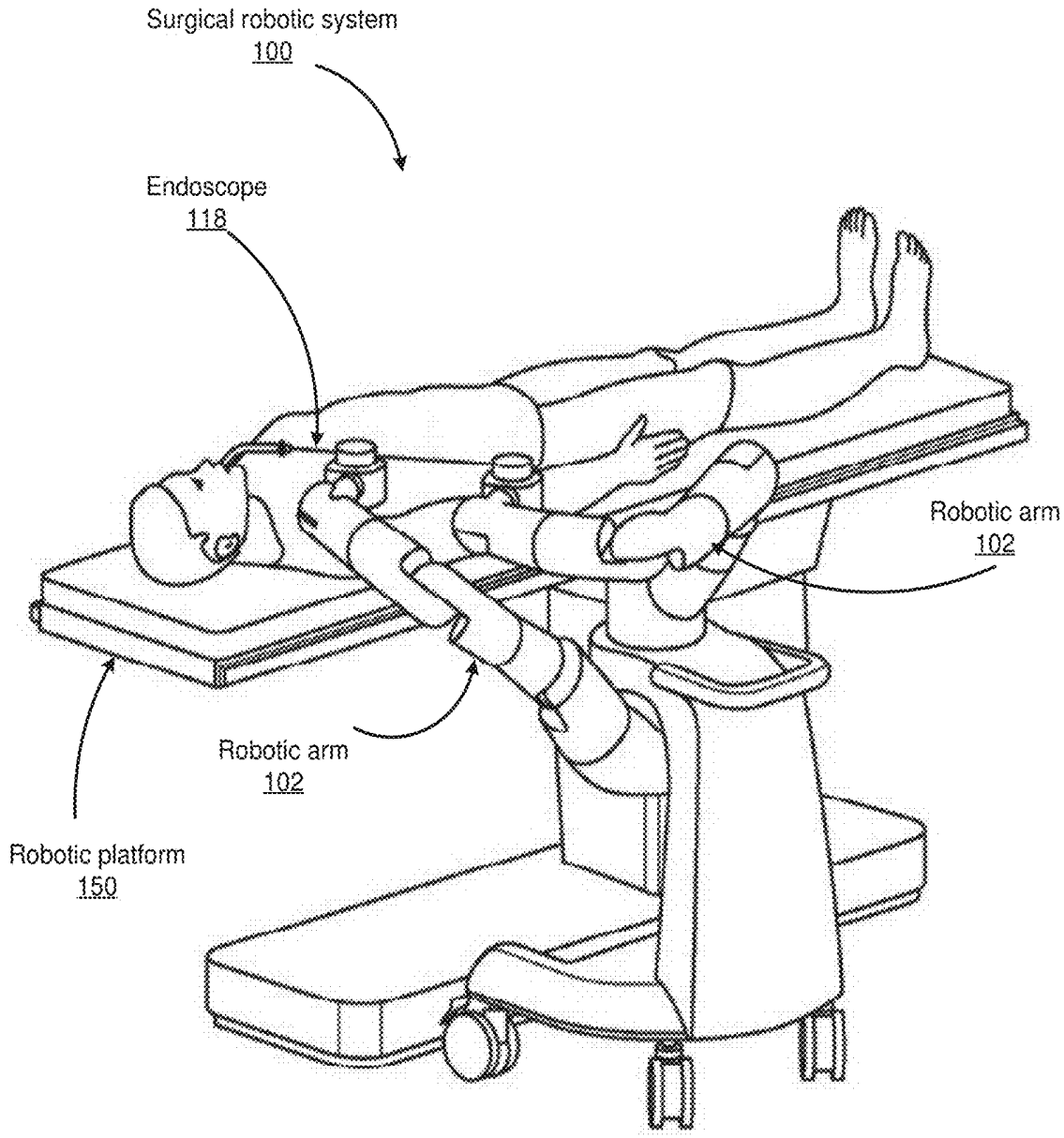

Surgical robotic system
100
Endoscope
118
Robotic arm
102
Robotic arm
102
Robotic platform
150

FIG. 1D

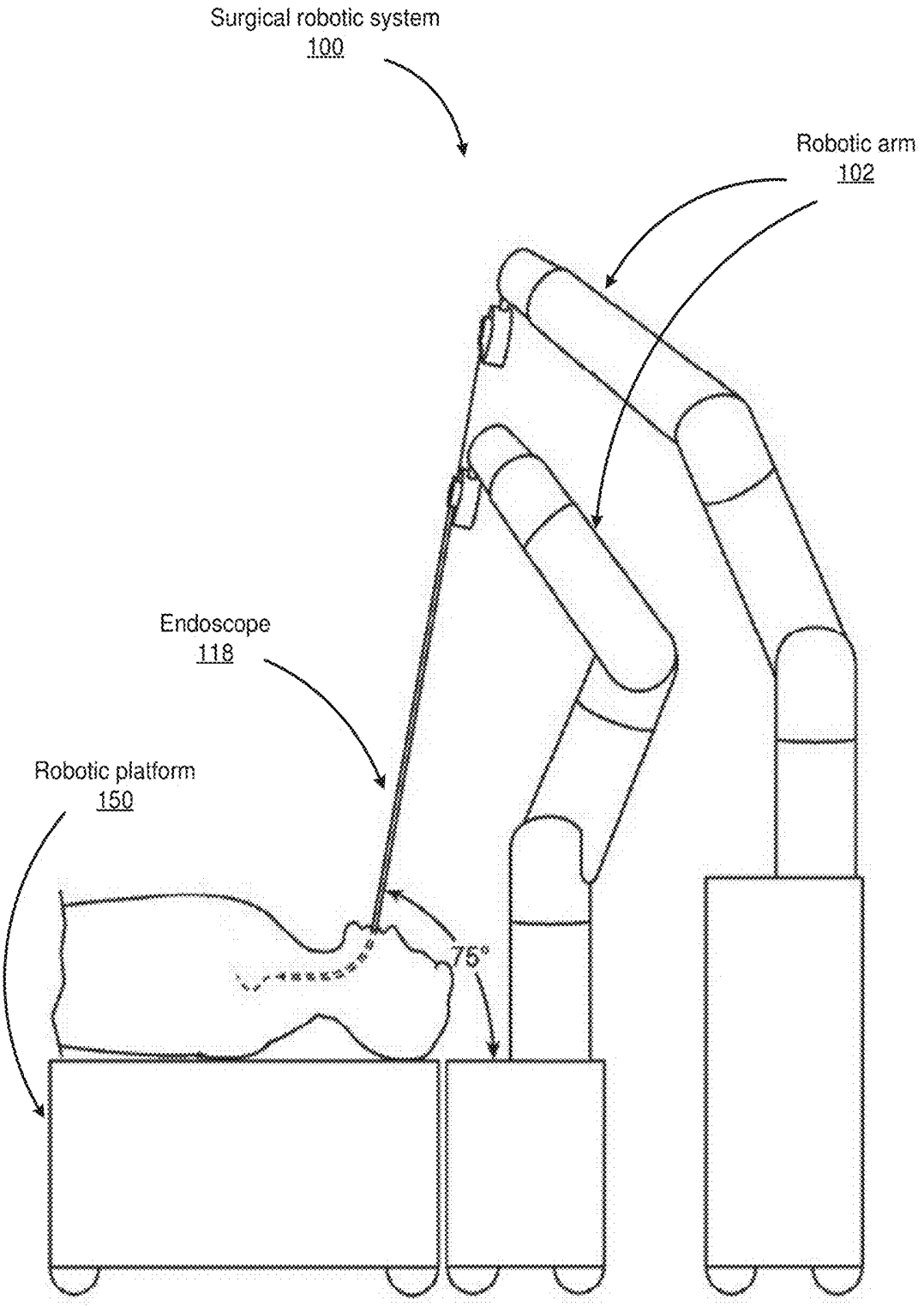

Surgical robotic system
100
Robotic arm
102
Endoscope
118
Robotic platform
150
75°

FIG. 1E

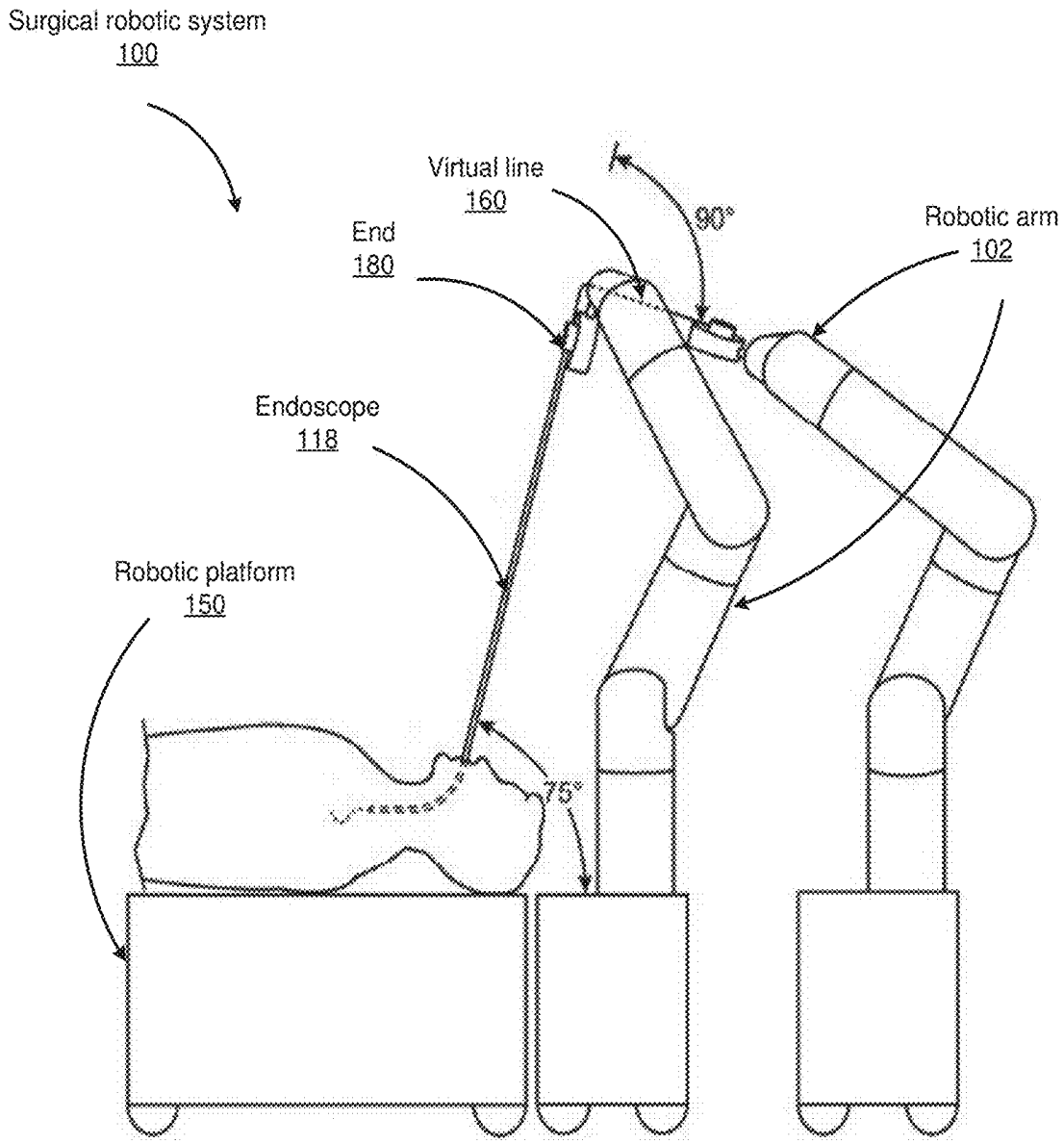

Surgical robotic system
100
Virtual line
160
90°
End
180
Robotic arm
102
Endoscope
118
Robotic platform
150
75°

FIG. 1F

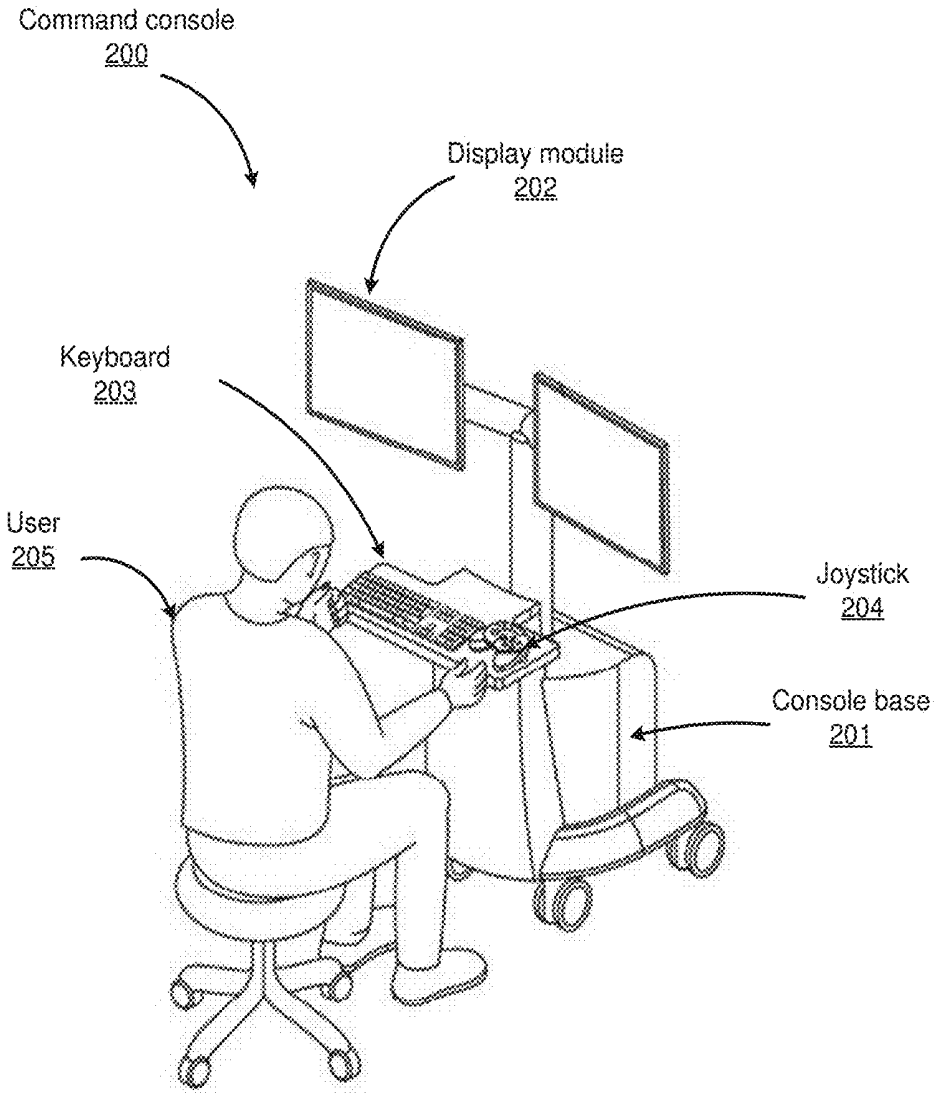

Command console
200
Display module
202
Keyboard
203
User
205
Joystick
204
Console base
201

FIG. 2

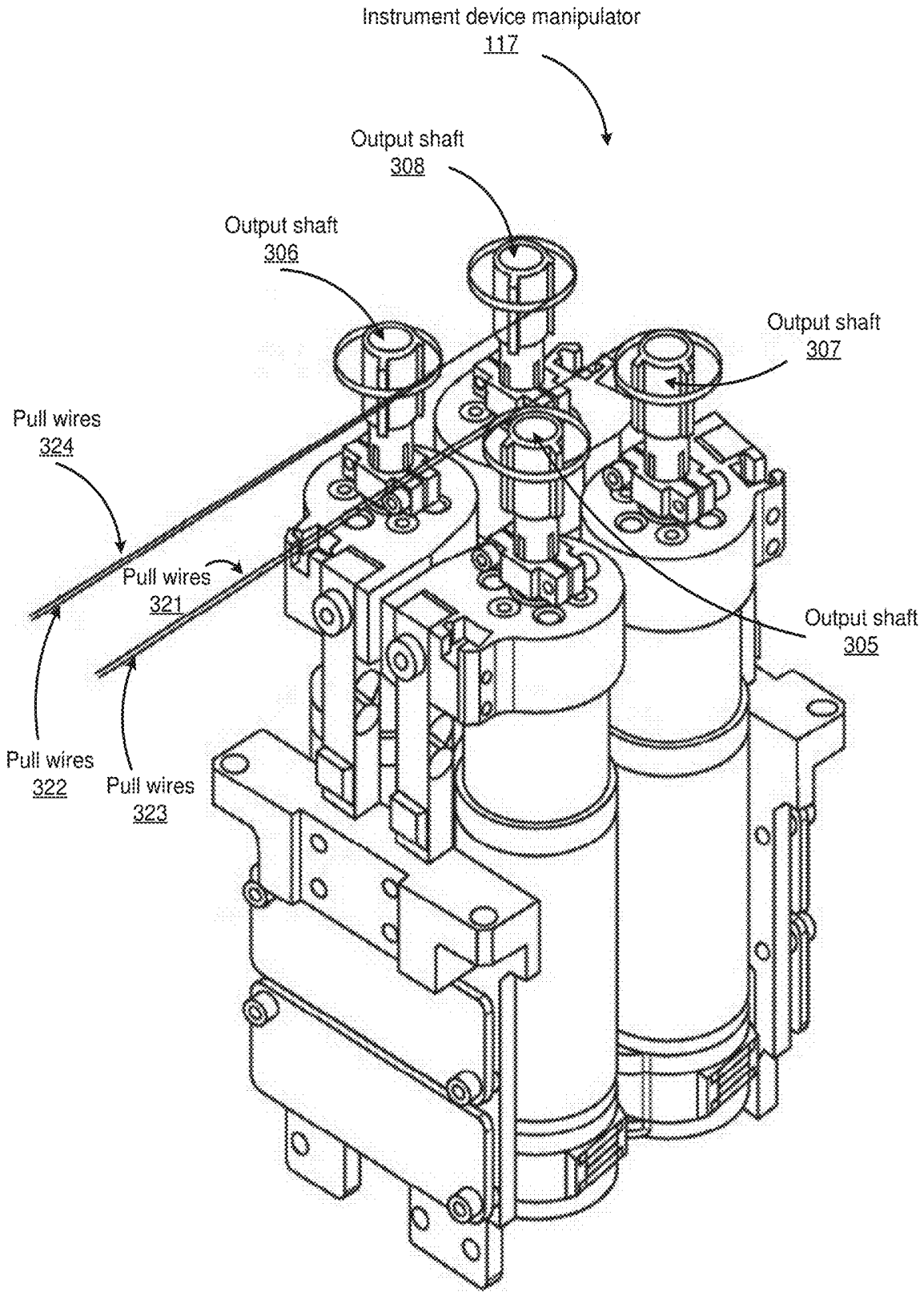

Instrument device manipulator
117
Output shaft
308
Output shaft
306
Output shaft
307
Pull wires
324
Pull wires
321
Output shaft
305
Pull wires
322
Pull wires
323

FIG. 3A

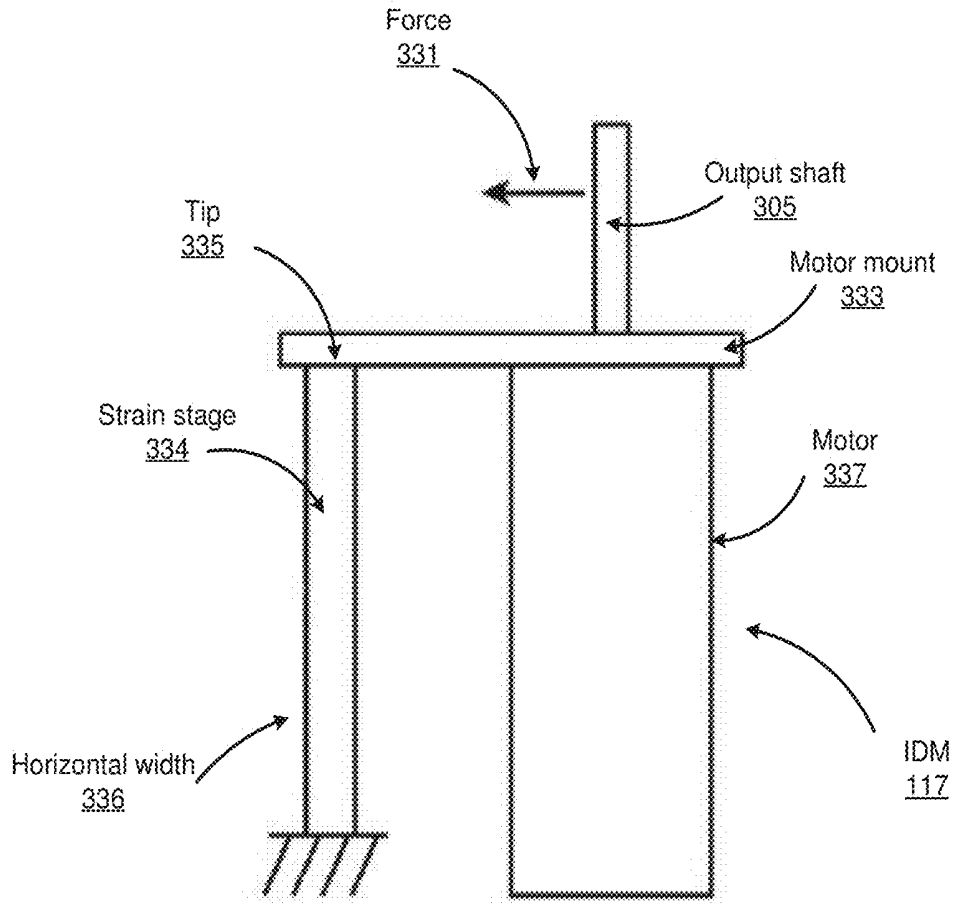

Force
331
Output shaft
305
Tip
335
Motor mount
333
Strain stage
334
Motor
337
Horizontal width
336
IDM
117

FIG. 3B

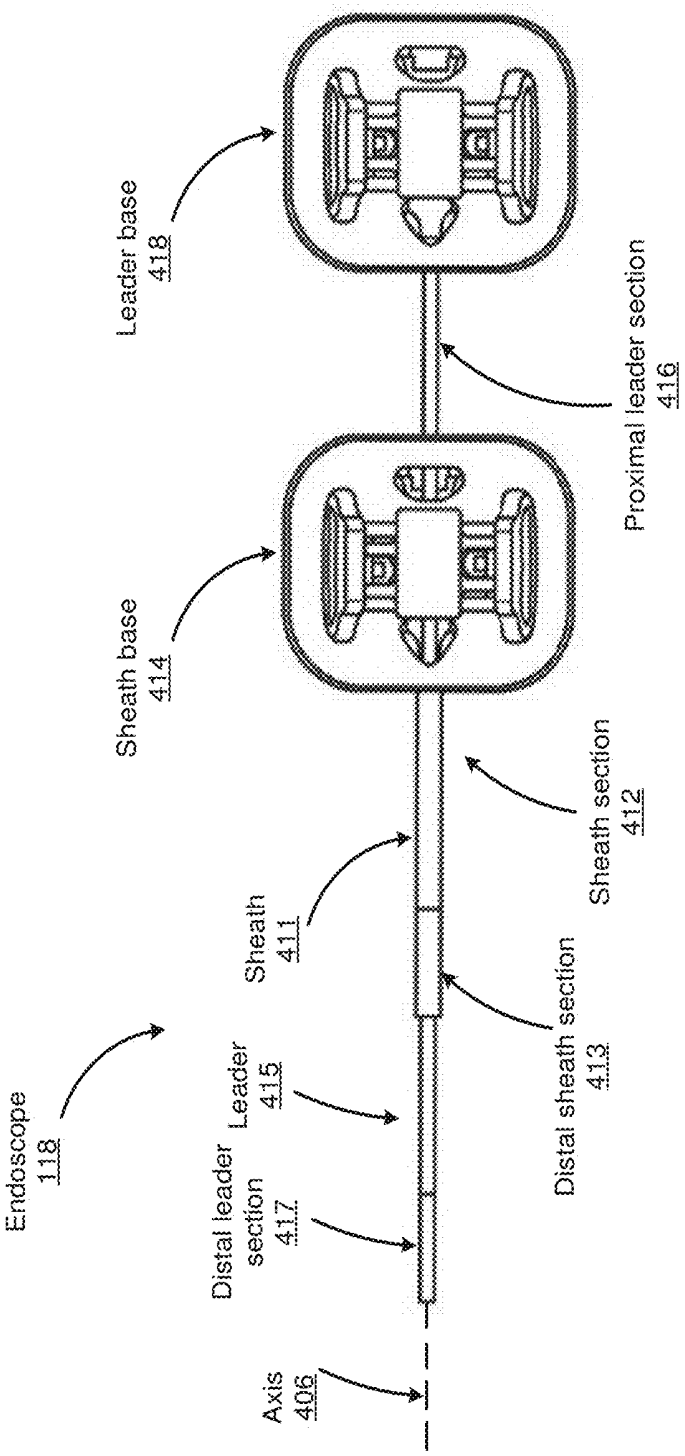

Leader base
418
Proximal leader section
416
Sheath base
414
Sheath section
412
Sheath
411
Distal sheath section
413
Endoscope
118
Leader
415
Distal leader
section
417
Axis
406

FIG. 4A

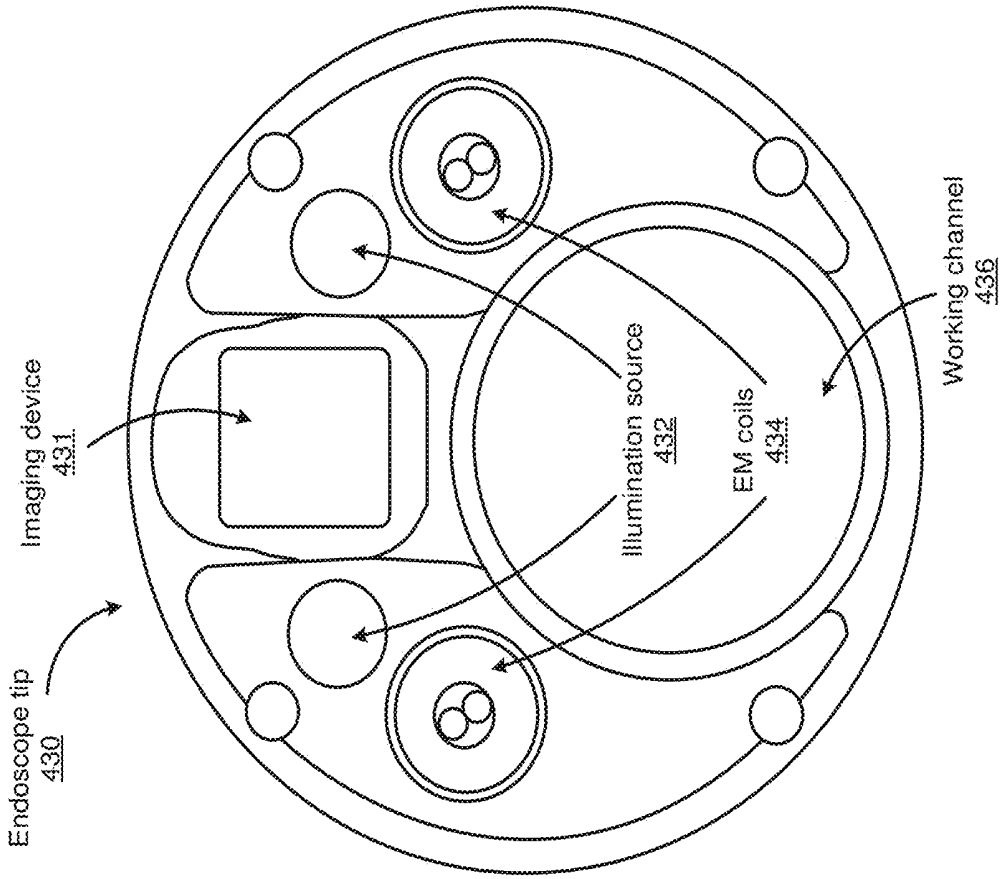

Endoscope tip
430
Imaging device
431
Illumination source
432
EM coils
434
Working channel
436

FIG. 4B

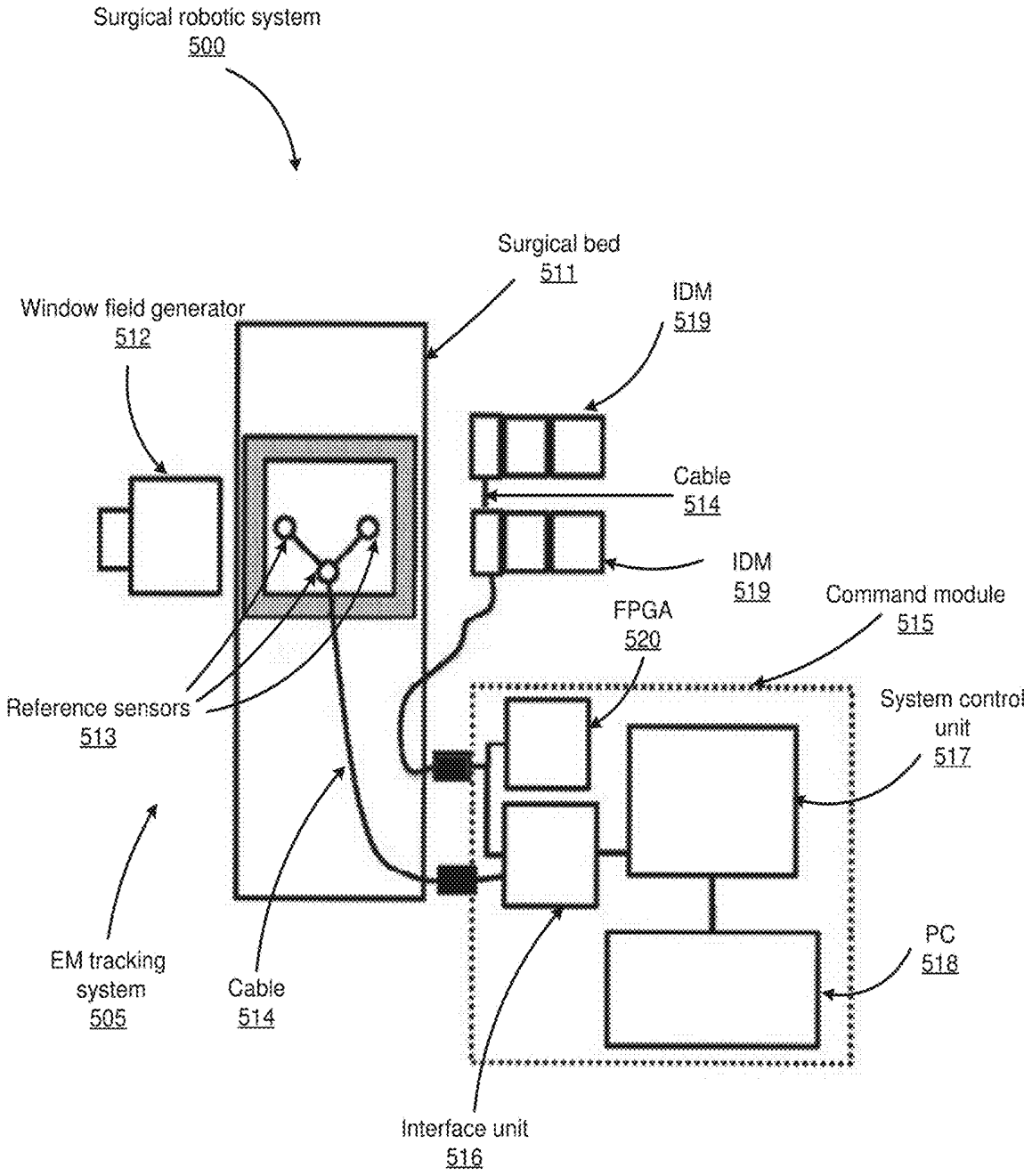

Surgical robotic system
500
Surgical bed
511
IDM
519
Window field generator
512
Cable
514
IDM
519
Command module
515
FPGA
520
Reference sensors
513
System control unit
517
PC
518
EM tracking system
505
Cable
514
Interface unit
516

FIG. 5

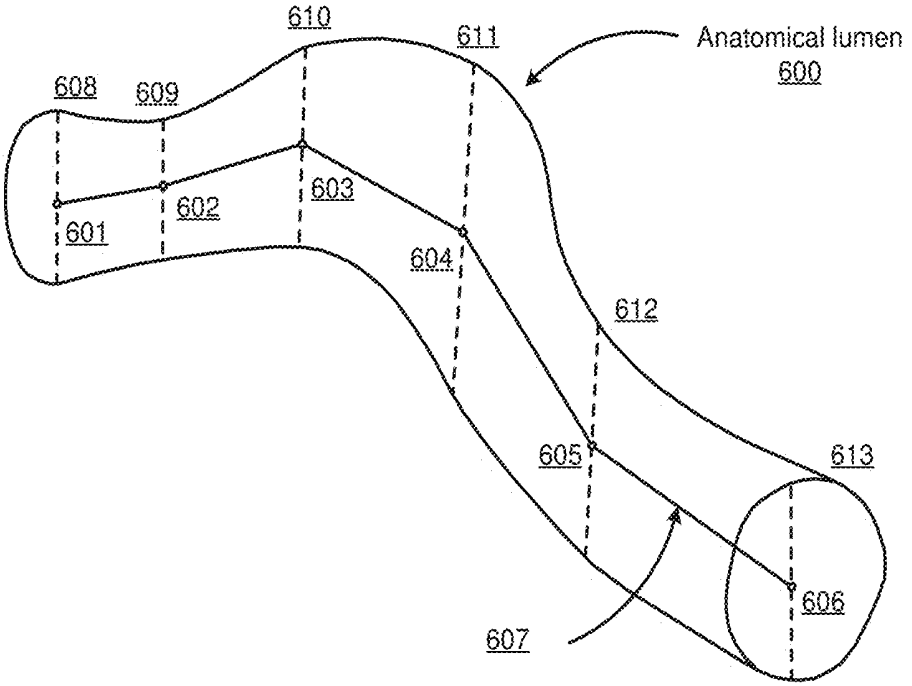

610
611
Anatomical lumen
600
608
609
603
602
601
604
612
605
613
606
607

FIG. 6A

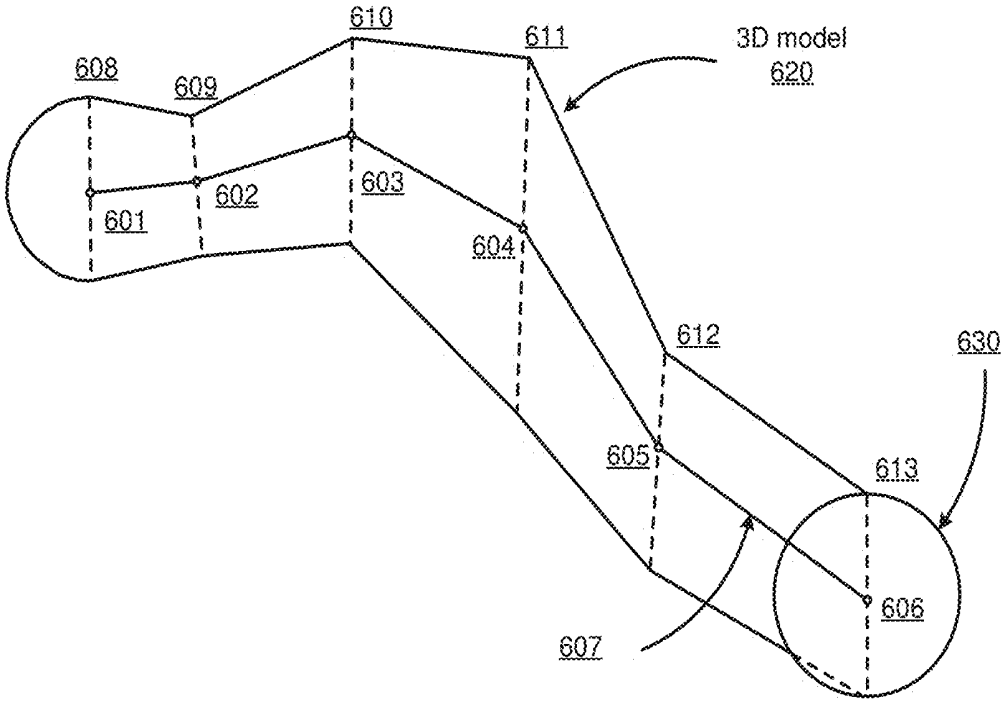

610
611
3D model
620
608
609
603
602
601
604
612
630
605
613
606
607

FIG. 6B

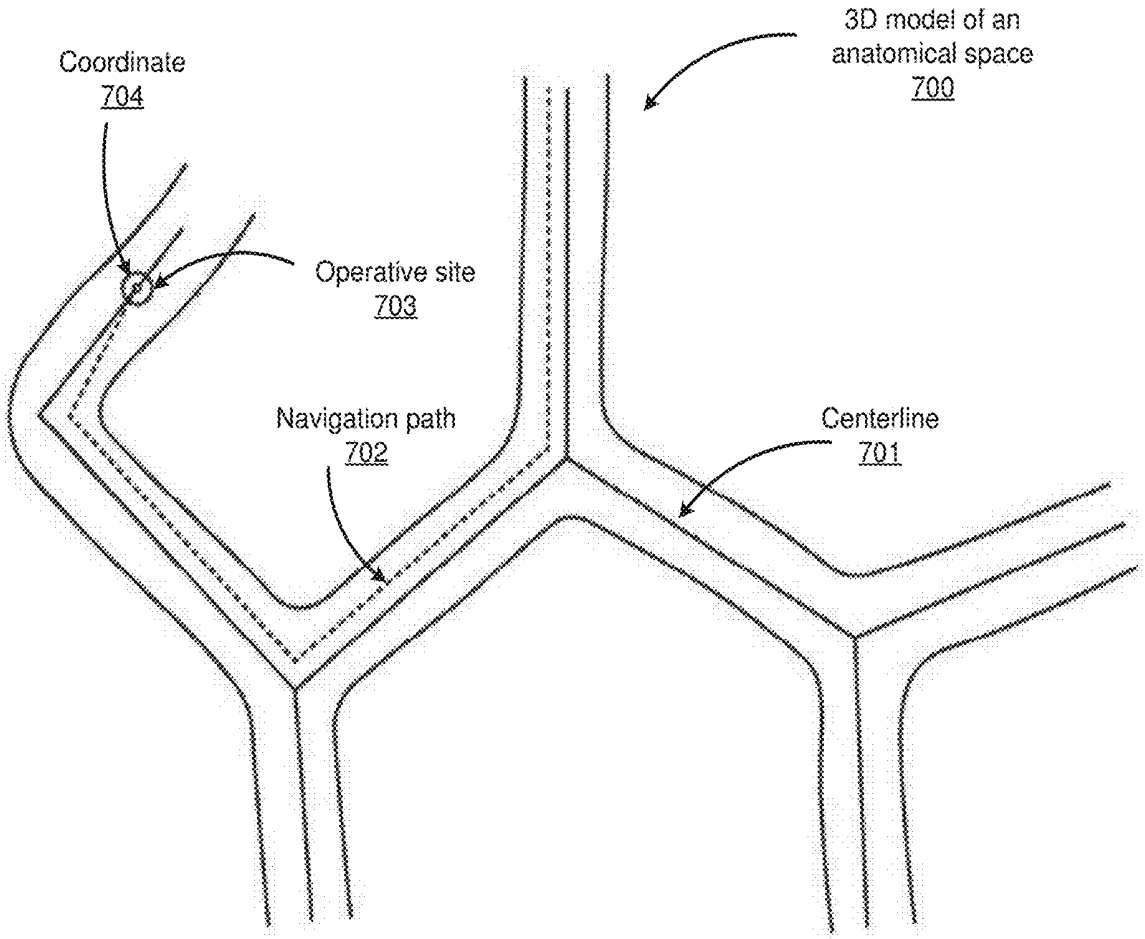

3D model of an anatomical space
700
Coordinate
704
Operative site
703
Navigation path
702
Centerline
701

FIG. 7

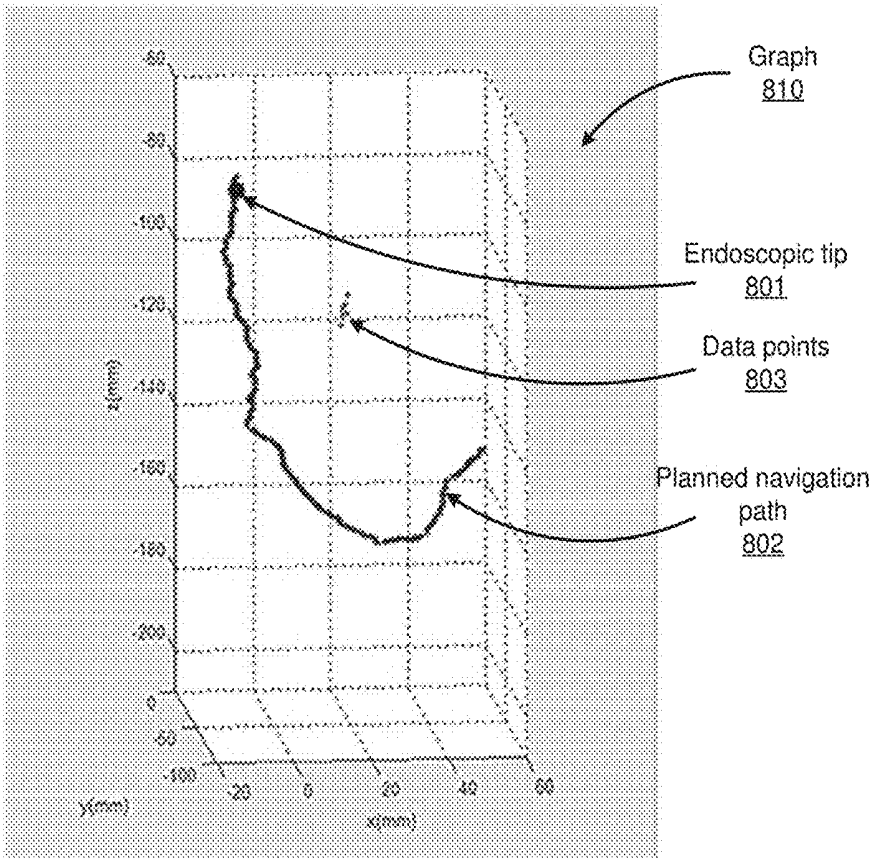

Graph
810
Endoscopic tip
801
Data points
803
Planned navigation
path
802

FIG. 8A

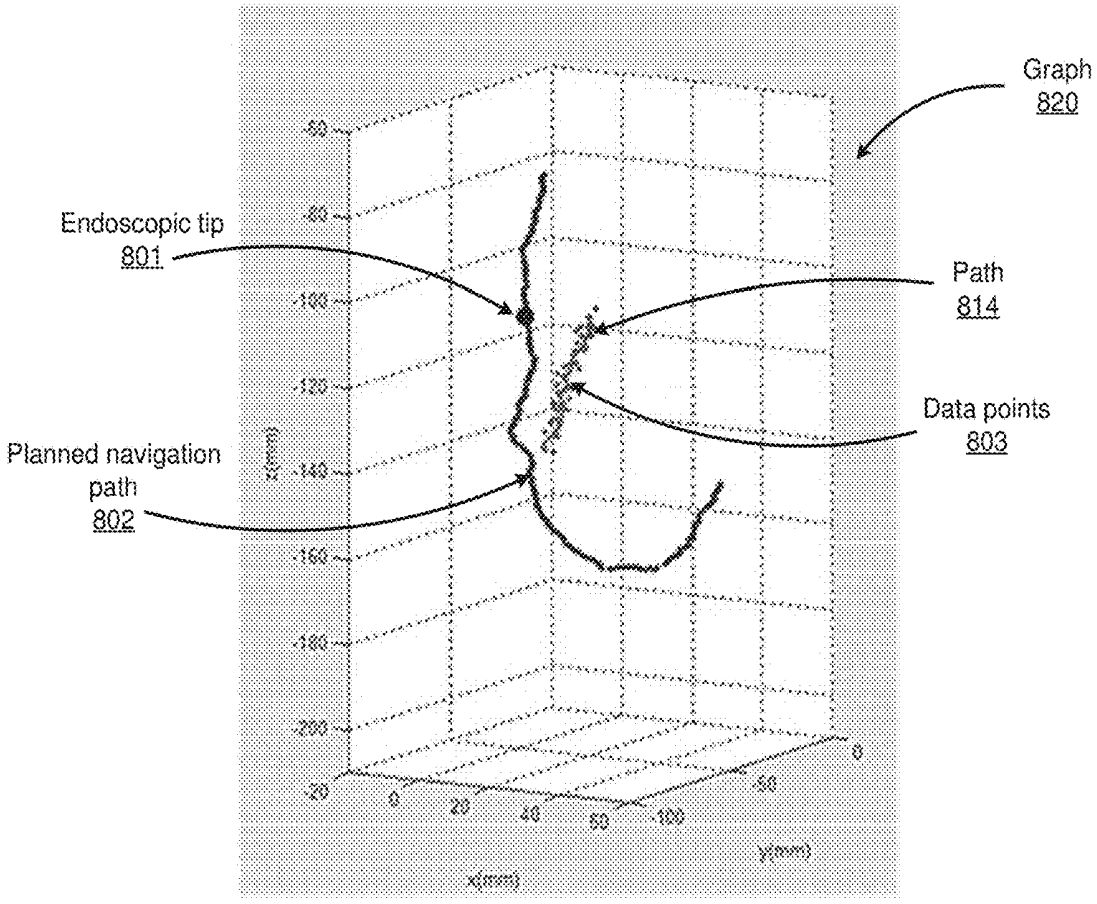

Graph
820
Endoscopic tip
801
Path
814
Data points
803
Planned navigation
path
802

FIG. 8B

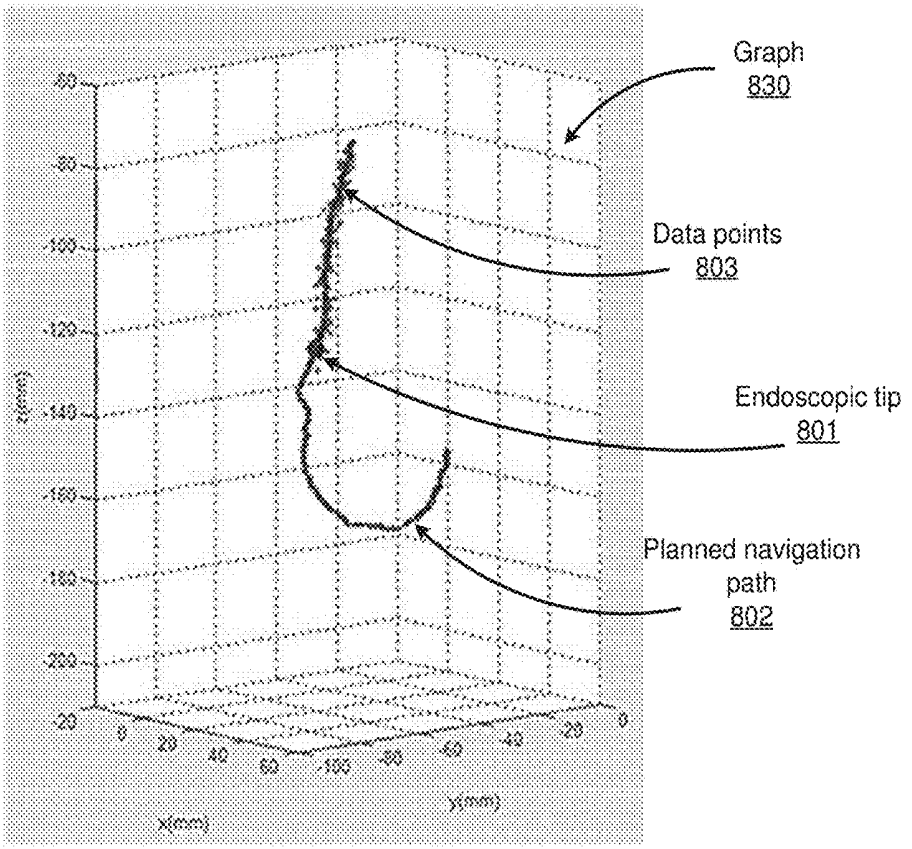

Graph
830
Data points
803
Endoscopic tip
801
Planned navigation
path
802

FIG. 8C

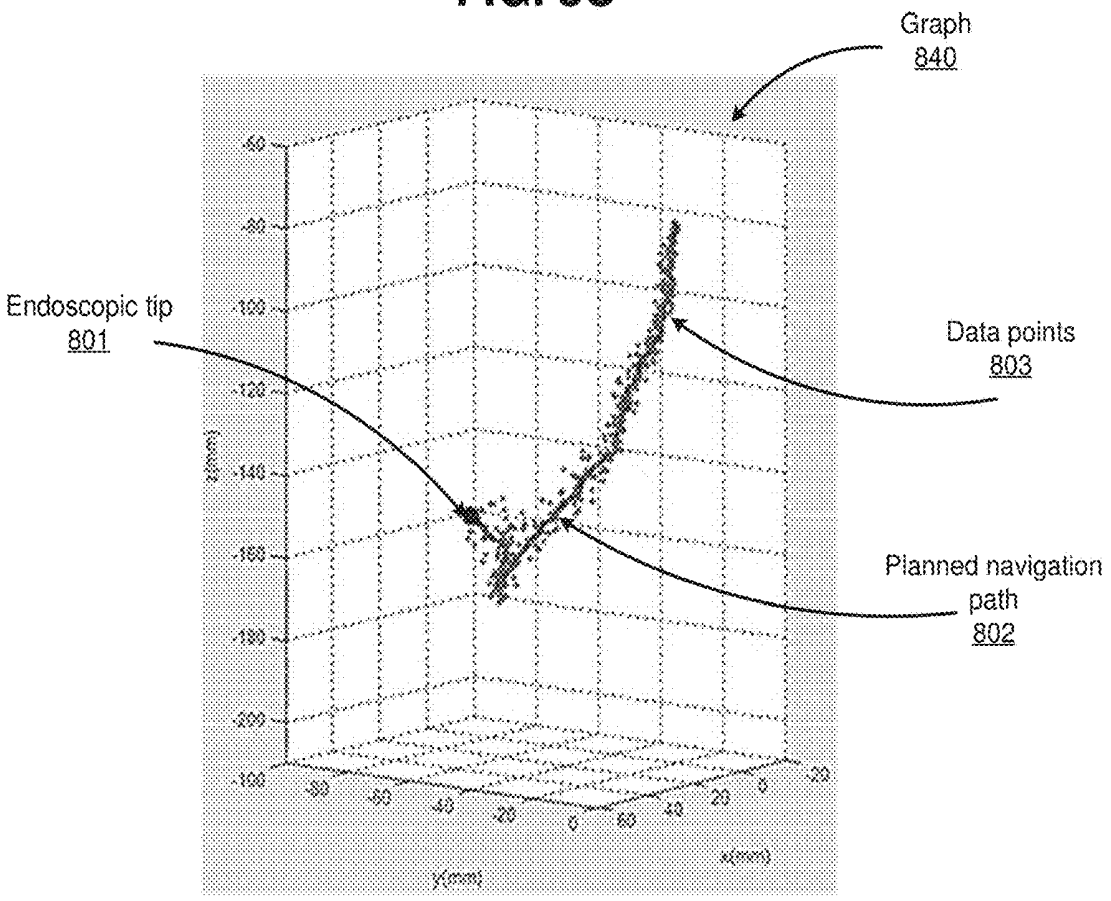

Graph
840
Endoscopic tip
801
Data points
803
Planned navigation
path
802

FIG. 8D

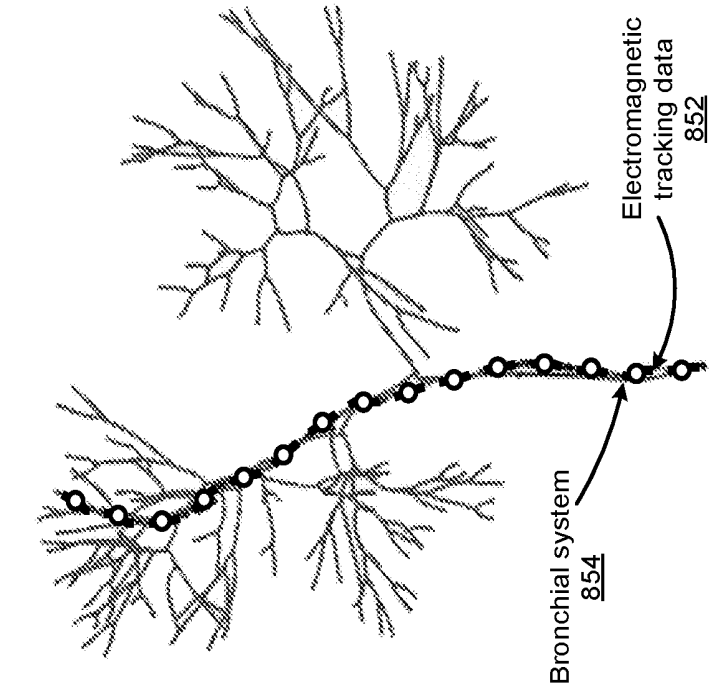

Electromagnetic tracking data
852
Bronchial system
854

FIG. 8F

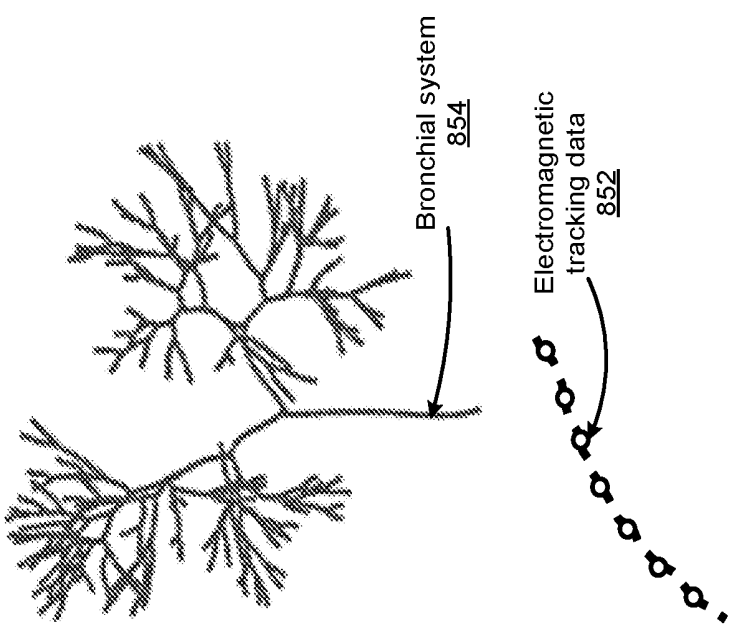

Bronchial system
854
Electromagnetic tracking data
852

FIG. 8E

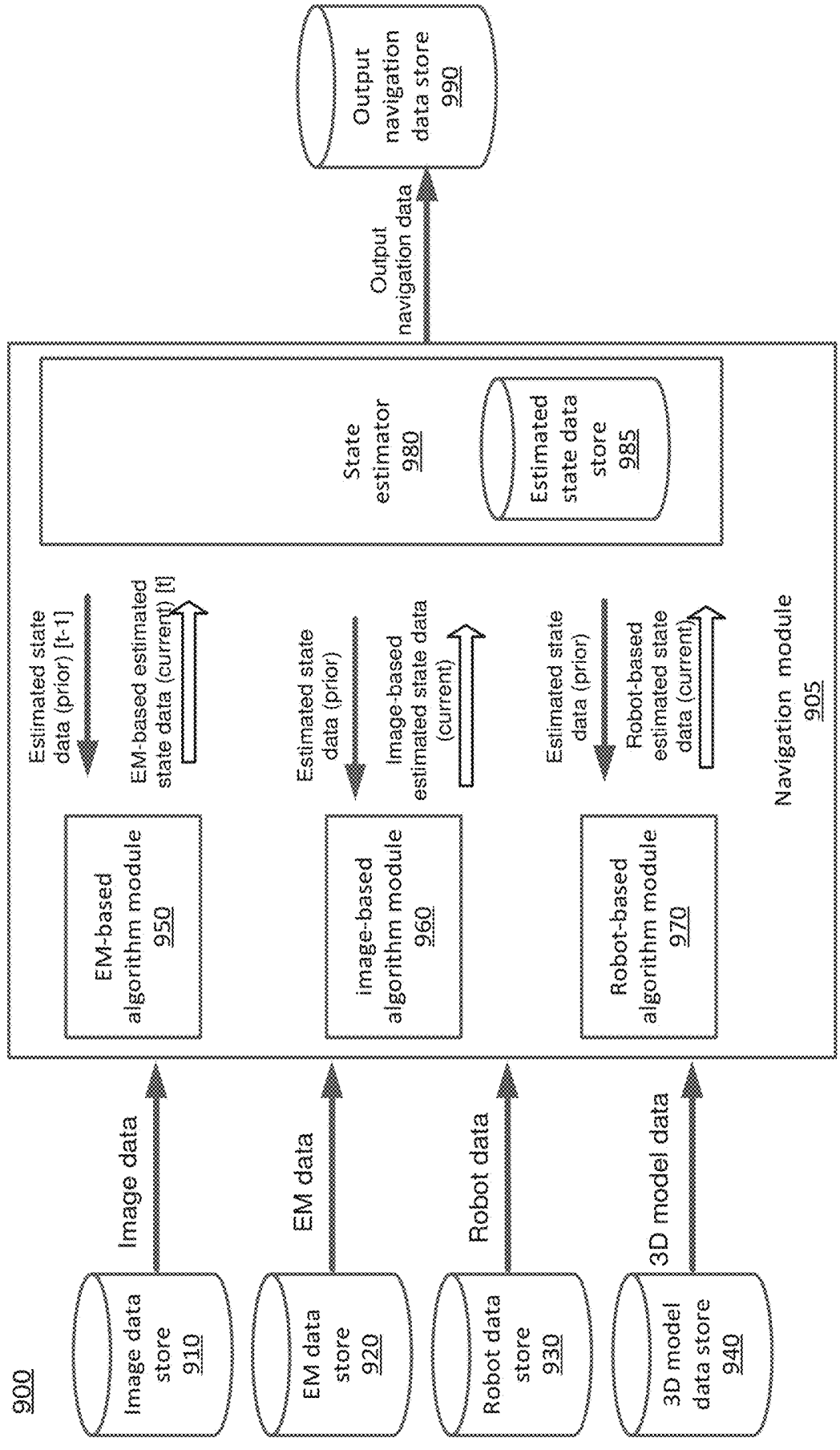

900
Image data store 910
EM data store 920
Robot data store 930
3D model data store 940
Image data
EM data
Robot data
3D model data
Navigation module 905
EM-based algorithm module 950
image-based algorithm module 960
Robot-based algorithm module 970
Estimated state data (prior) [t-1]
EM-based estimated state data (current) [t]
Estimated state data (prior)
Image-based estimated state data (current)
Estimated state data (prior)
Robot-based estimated state data (current)
State estimator 980
Estimated state data store 985
Output navigation data
Output navigation data store 990

FIG. 9A

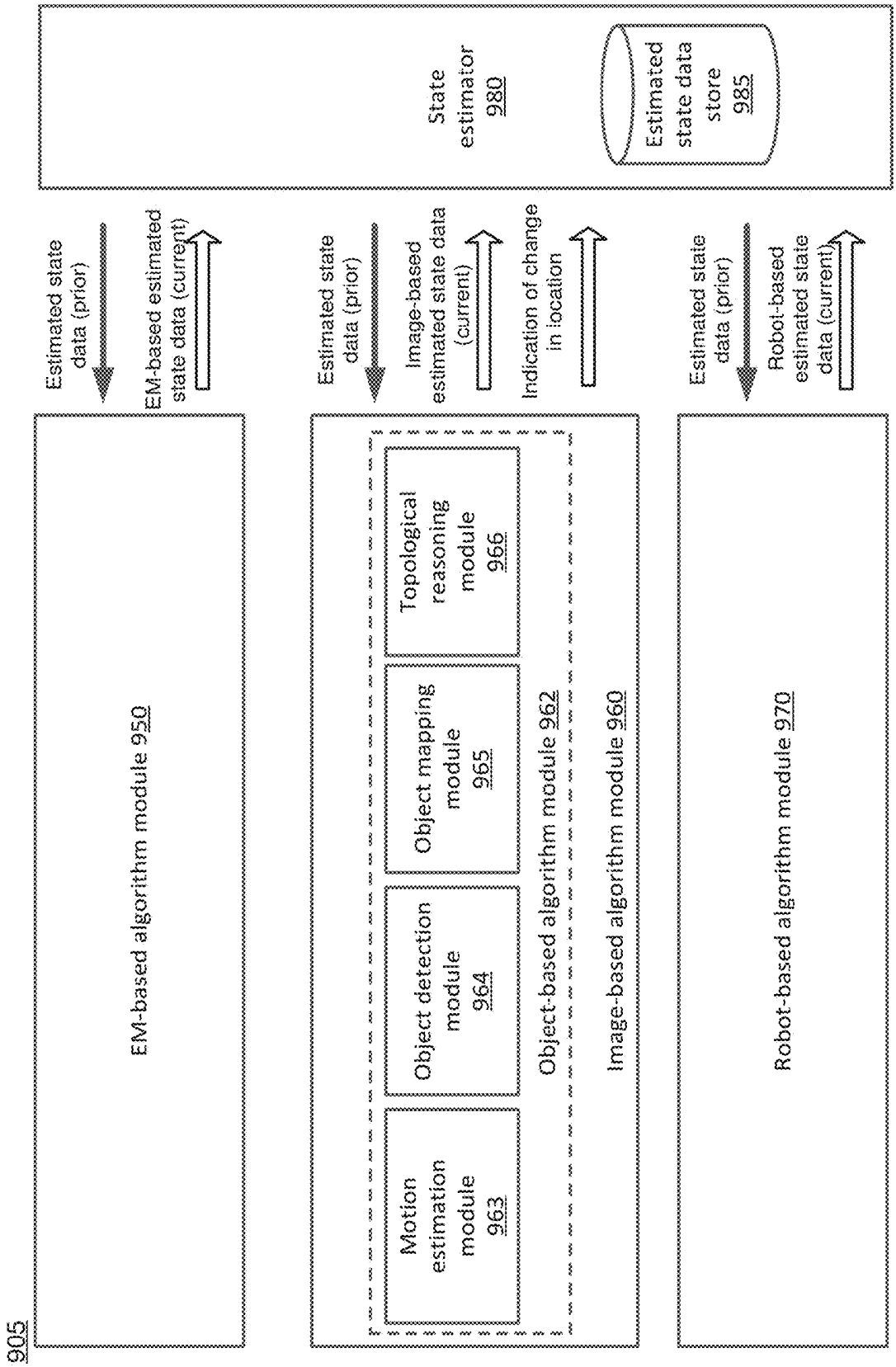

905
EM-based algorithm module 950
Estimated state data (prior)
EM-based estimated state data (current)
Image-based algorithm module 960
Object-based algorithm module 962
Motion estimation module 963
Object detection module 964
Object mapping module 965
Topological reasoning module 966
Estimated state data (prior)
Image-based estimated state data (current)
Indication of change in location
Robot-based algorithm module 970
Estimated state data (prior)
Robot-based estimated state data (current)
State estimator 980
Estimated state data store 985

FIG. 9B

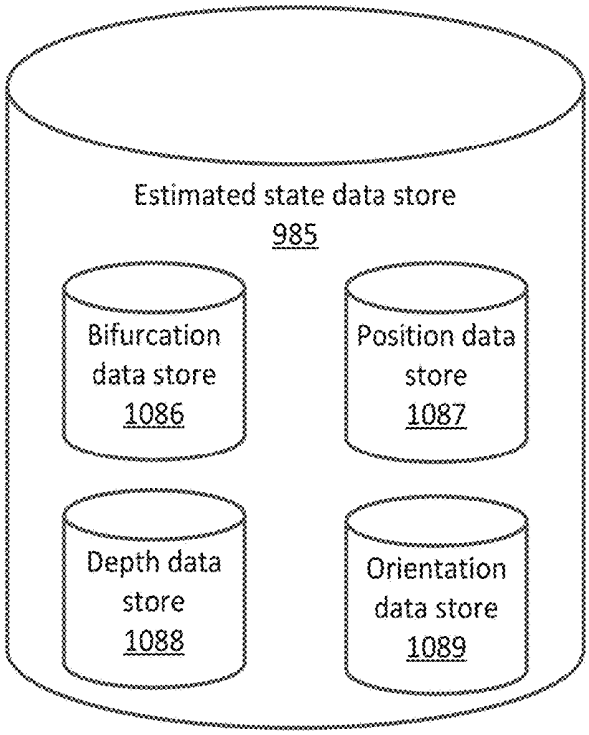


FIG. 9C

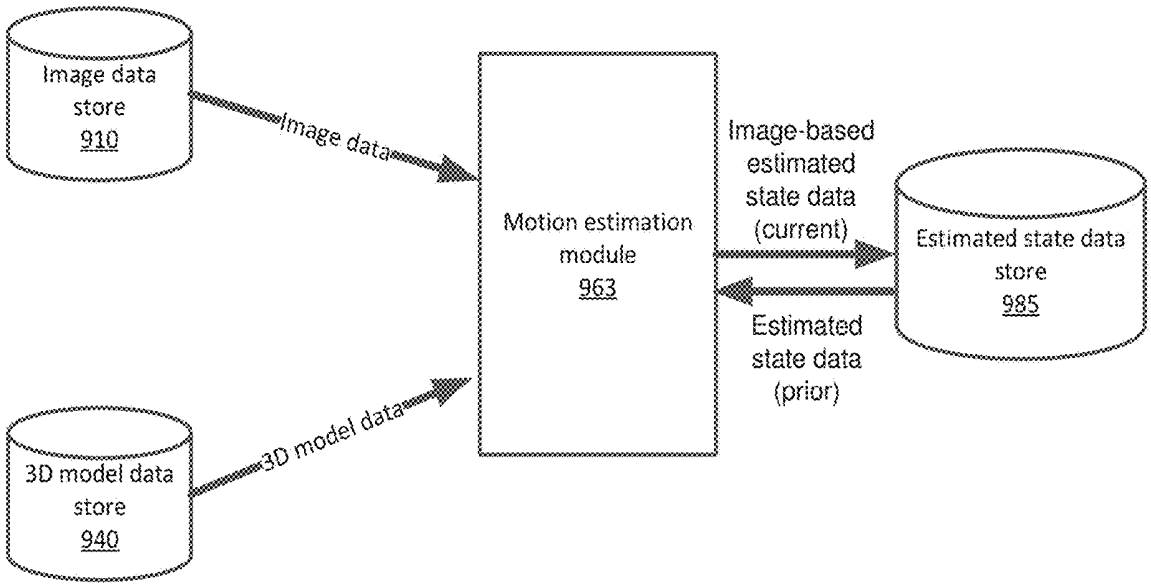


FIG. 10A

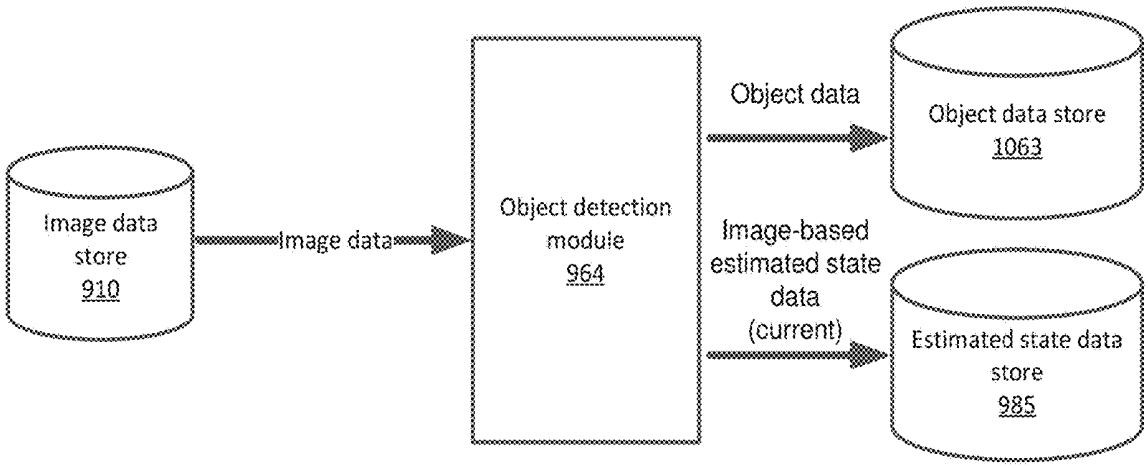


FIG. 10B

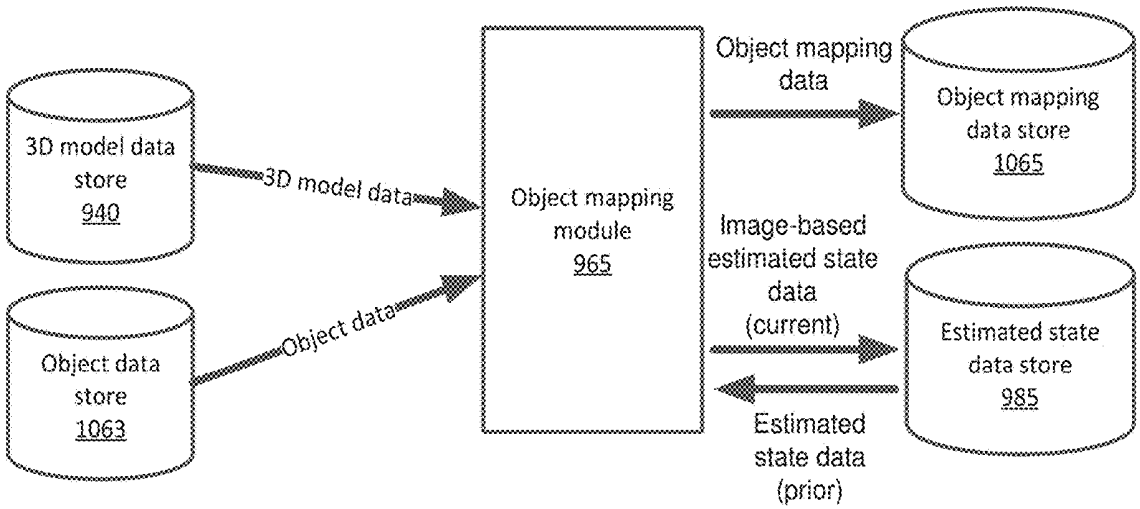


FIG. 10C

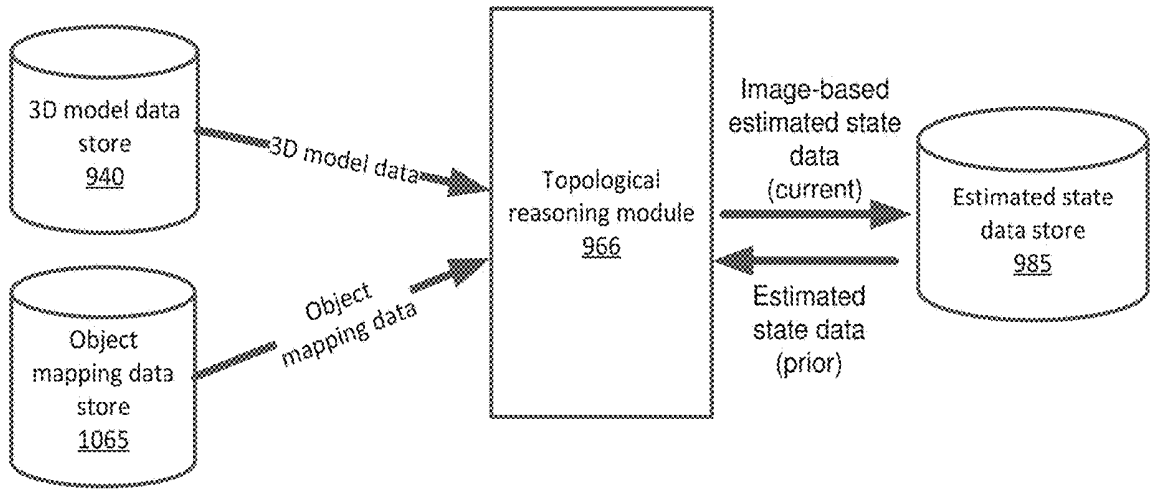

3D model data store 940
3D model data
Object mapping data store 1065
Object mapping data
Topological reasoning module 966
Image-based estimated state data (current)
Estimated state data (prior)
Estimated state data store 985

FIG. 10D

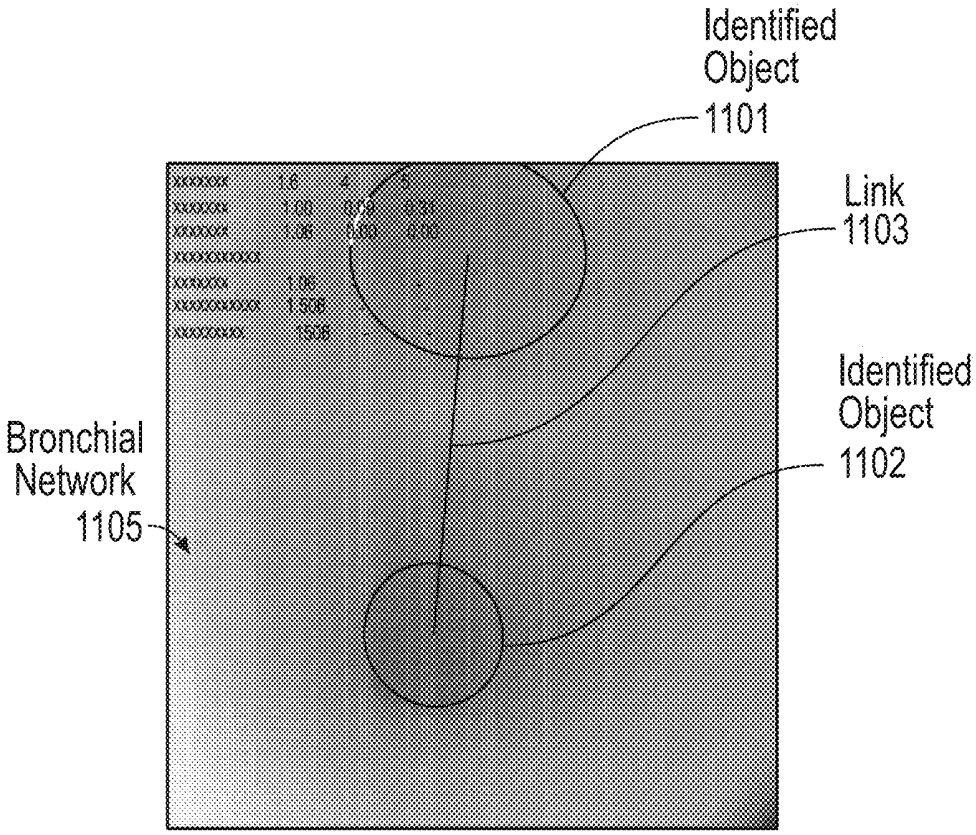


FIG. 11A

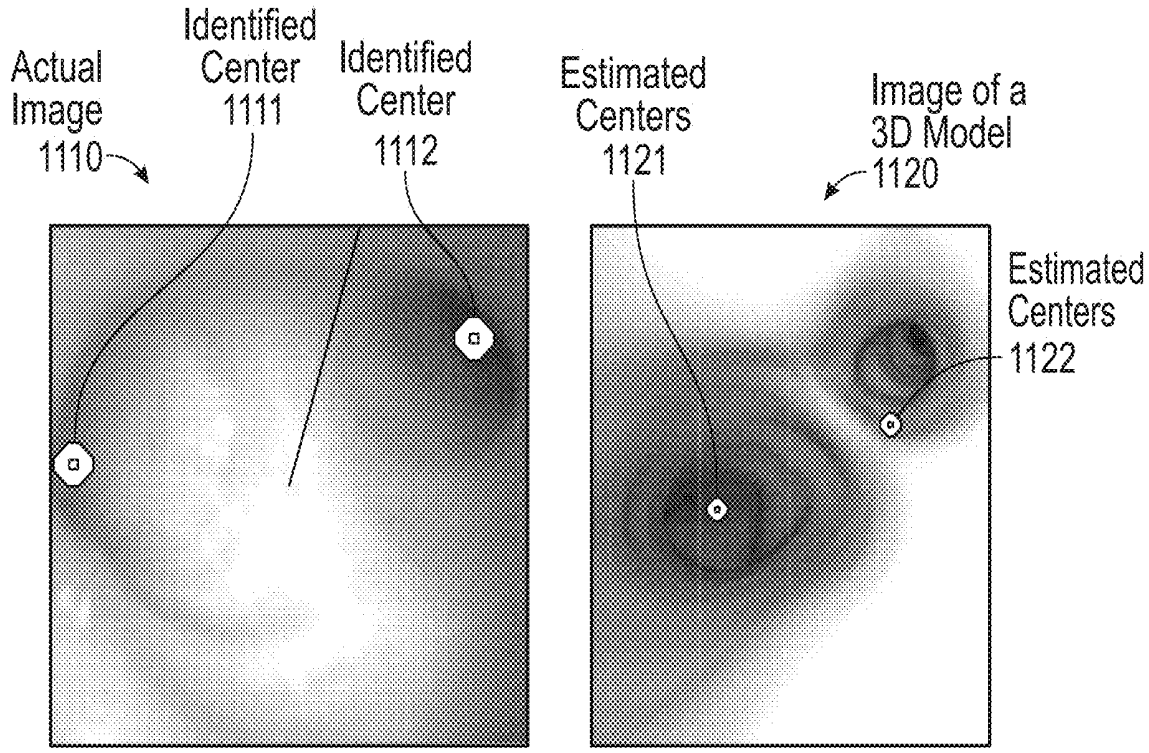


FIG. 11B

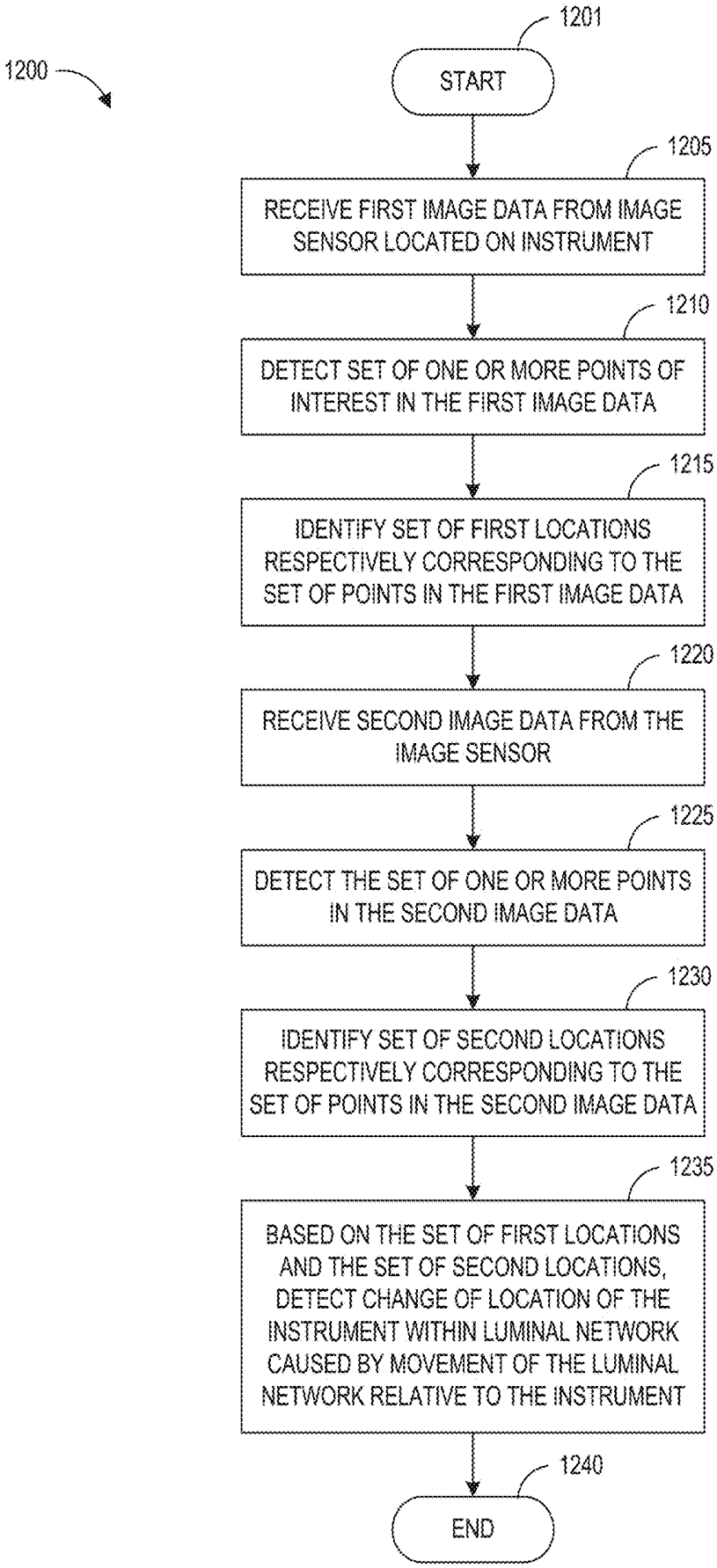

1200
1201
START
1205
RECEIVE FIRST IMAGE DATA FROM IMAGE SENSOR LOCATED ON INSTRUMENT
1210
DETECT SET OF ONE OR MORE POINTS OF INTEREST IN THE FIRST IMAGE DATA
1215
IDENTIFY SET OF FIRST LOCATIONS RESPECTIVELY CORRESPONDING TO THE SET OF POINTS IN THE FIRST IMAGE DATA
1220
RECEIVE SECOND IMAGE DATA FROM THE IMAGE SENSOR
1225
DETECT THE SET OF ONE OR MORE POINTS IN THE SECOND IMAGE DATA
1230
IDENTIFY SET OF SECOND LOCATIONS RESPECTIVELY CORRESPONDING TO THE SET OF POINTS IN THE SECOND IMAGE DATA
1235
BASED ON THE SET OF FIRST LOCATIONS AND THE SET OF SECOND LOCATIONS, DETECT CHANGE OF LOCATION OF THE INSTRUMENT WITHIN LUMINAL NETWORK CAUSED BY MOVEMENT OF THE LUMINAL NETWORK RELATIVE TO THE INSTRUMENT
1240
END

FIG. 12

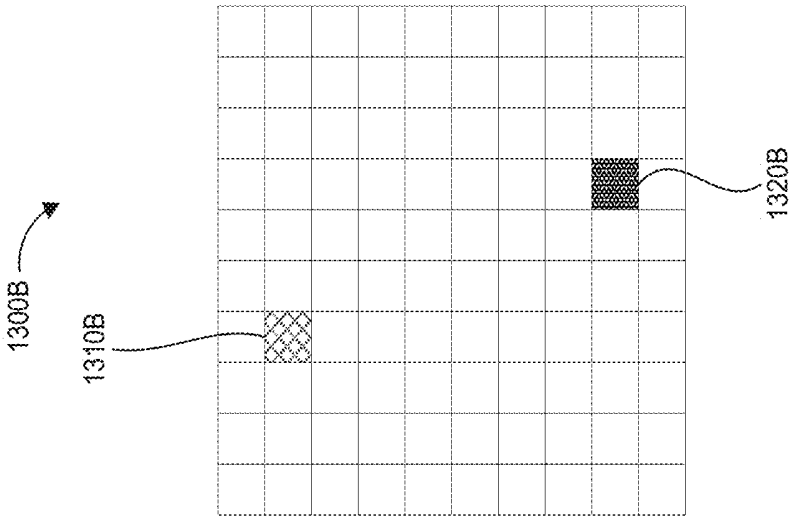


FIG. 13B

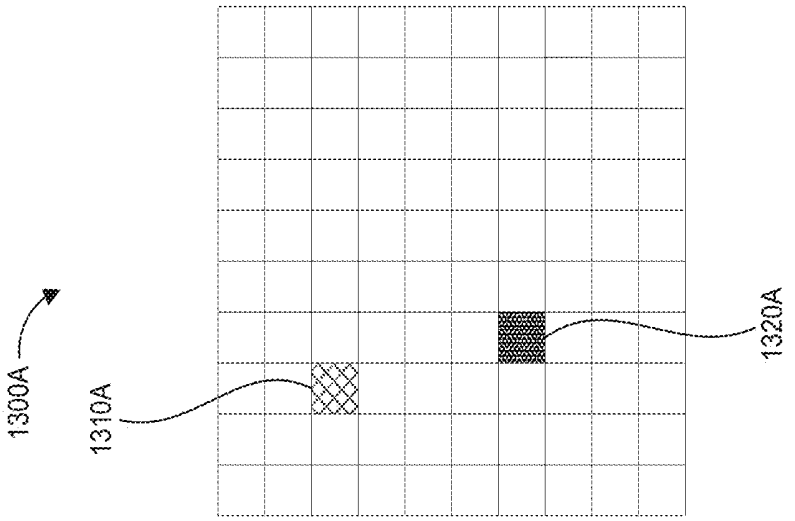


FIG. 13A

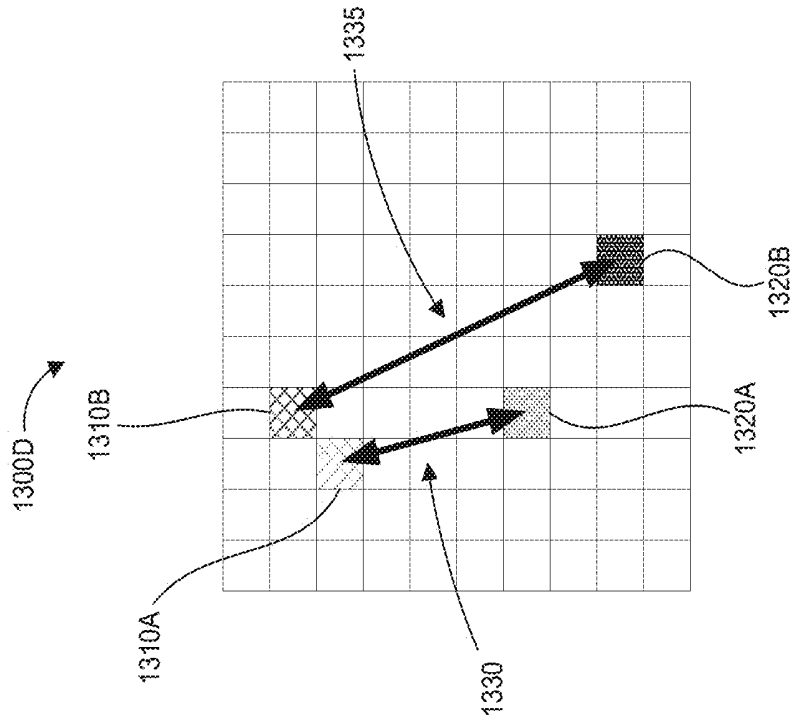


FIG. 13D

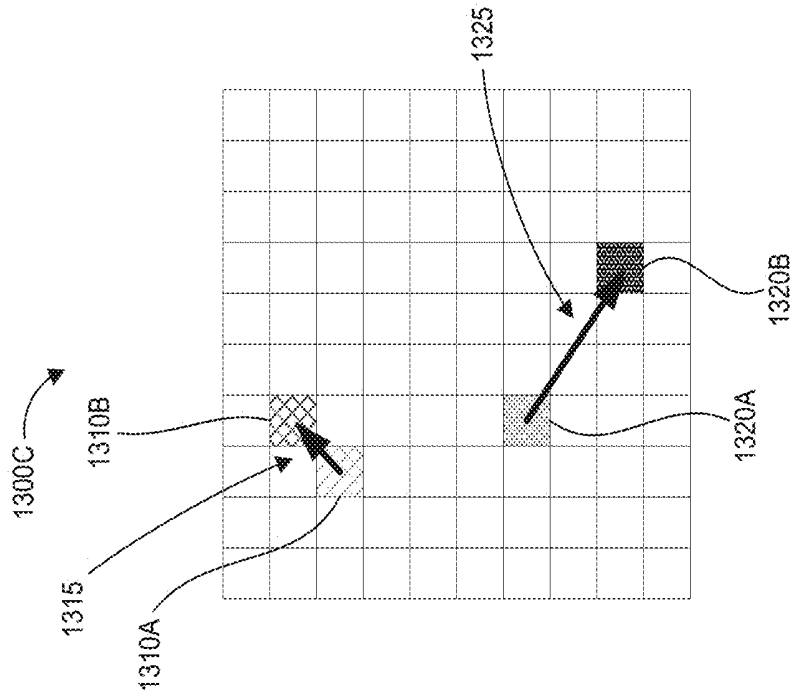


FIG. 13C

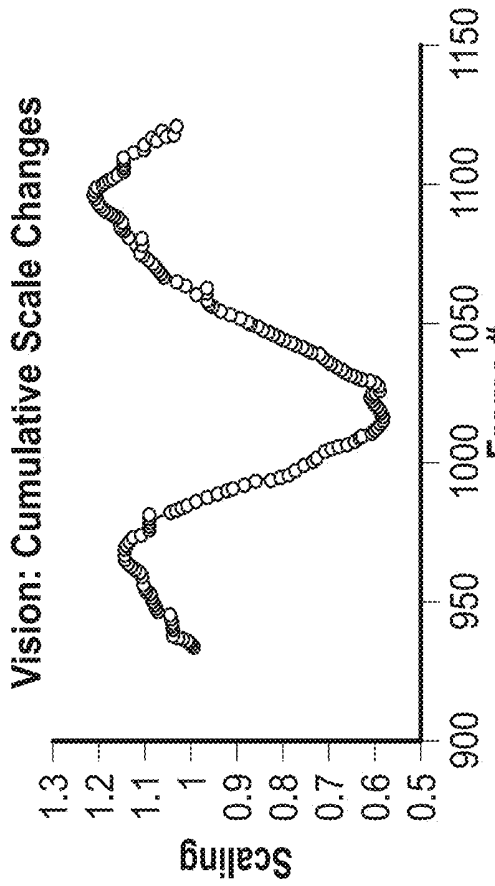


FIG. 15A

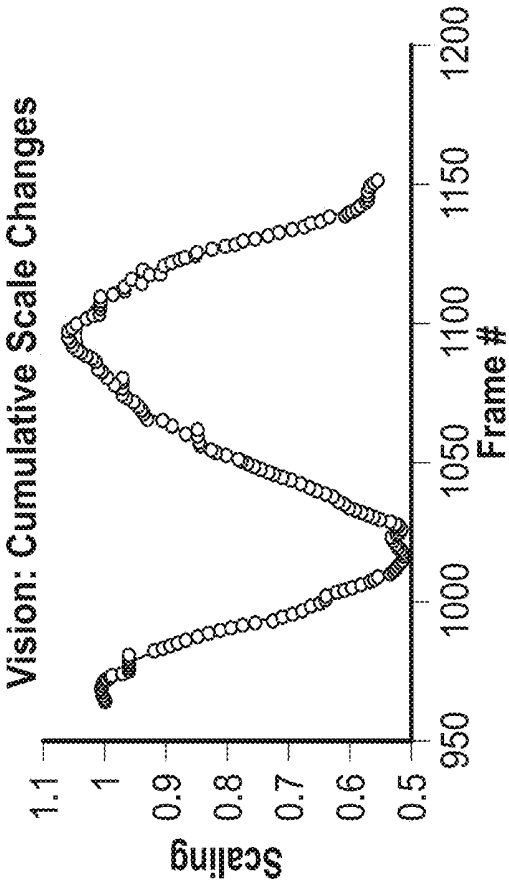


FIG. 15B

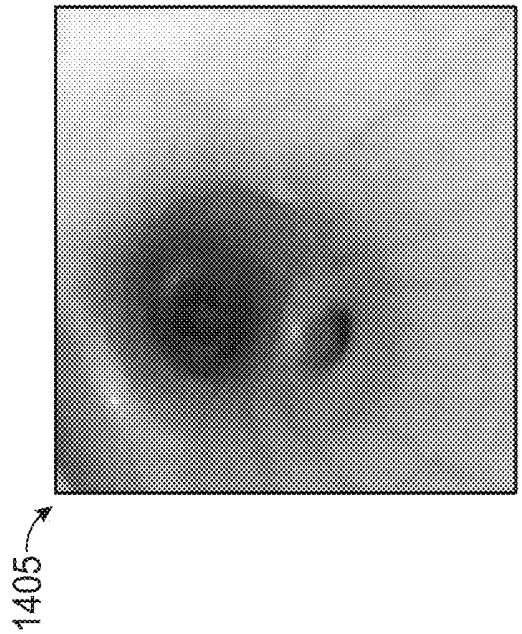


FIG. 14A

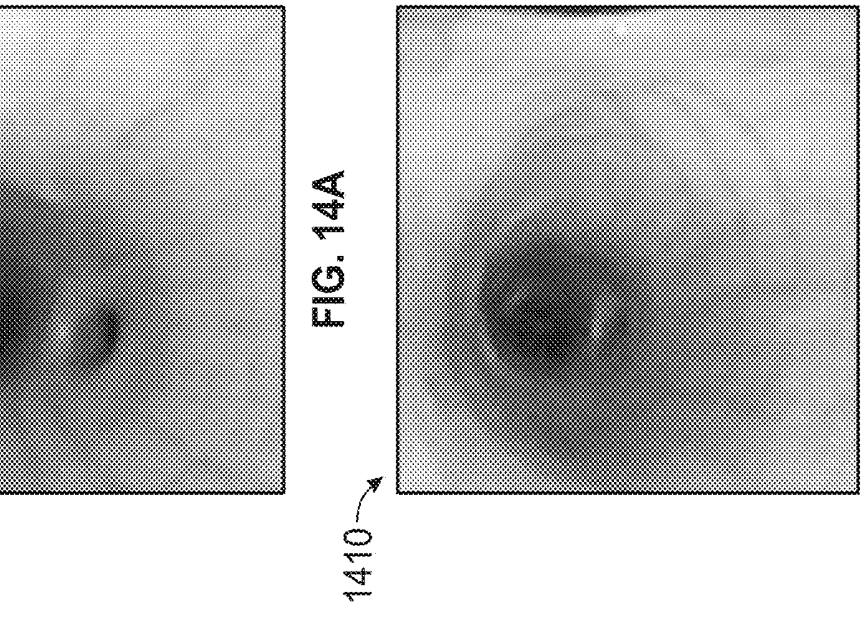


FIG. 14B

ROBOTIC SYSTEMS AND METHODS FOR NAVIGATION OF LUMINAL NETWORK THAT DETECT PHYSIOLOGICAL NOISE

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] This application claims the benefit of U.S. Provisional Application No. 62/678,520, filed May 31, 2018, which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The systems and methods disclosed herein are directed to surgical robotics, and more particularly to endoluminal navigation.

BACKGROUND

[0003] Bronchoscopy is a medical procedure that allows a physician to examine the inside conditions of a patient's lung airways, such as bronchi and bronchioles. The lung airways carry air from the trachea, or windpipe, to the lungs. During the medical procedure, a thin, flexible tubular tool, known as a bronchoscope, may be inserted into the patient's mouth and passed down the patient's throat into his/her lung airways, and patients are generally anesthetized in order to relax their throats and lung cavities for surgical examinations and operations during the medical procedure.

[0004] In the related art, a bronchoscope can include a light source and a small camera that allows a physician to inspect a patient's windpipe and airways, and a rigid tube may be used in conjunction with the bronchoscope for surgical purposes, e.g., when there is a significant amount of bleeding in the lungs of the patient or when a large object obstructs the throat of the patient. When the rigid tube is used, the patient is often anesthetized. Robotic bronchoscopes provide tremendous advantages in navigation through tubular networks. They can ease use and allow therapies and biopsies to be administered conveniently even during the bronchoscopy stage.

[0005] Apart from mechanical devices or platforms, e.g., robotic bronchoscopes described above, various methods and software models may be used to help with the surgical operations. As an example, a computerized tomography (CT) scan of the patient's lungs is often performed during pre-operation of a surgical examination. Data from the CT scan may be used to generate a three-dimensional (3D) model of airways of the patient's lungs, and the generated 3D model enables a physician to access a visual reference that may be useful during the operative procedure of the surgical examination.

[0006] However, previous techniques for navigation of tubular networks still have challenges, even when employing medical devices (e.g., robotic bronchoscopes) and when using existing methods (e.g., performing CT scans and generating 3D models). As one example, motion estimation of a medical device (e.g., a bronchoscope tool) inside a patient's body may not be accurate based on location and orientation change of the device, and as a result the device's position may not be accurately or correctly localized inside the patient's body in real time. Inaccurate location information for such an instrument may provide misleading information to the physician that uses the 3D model as a visual reference during medical operation procedures.

[0007] Thus, there is a need for improved techniques for navigating through a network of tubular structures.

SUMMARY

[0008] In one aspect, there is provided a medical robotic system, comprising a set of one or more processors; and at least one computer-readable memory in communication with the set of processors and having stored thereon computer-executable instructions to cause the set of processors to: receive first image data from an image sensor located on an instrument, the instrument configured to be driven through a luminal network of a patient, detect a set of one or more points of interest the first image data, identify a set of first locations respectively corresponding to the set of points in the first image data, receive second image data from the image sensor, detect the set of one or more points in the second image data, identify a set of second locations respectively corresponding to the set of points in the second image data, and based on the set of first locations and the set of second locations, detect a change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument.

[0009] In another aspect, there is provided a non-transitory computer readable storage medium having stored thereon instructions that, when executed, cause at least one computing device to: receive first image data from an image sensor located on an instrument, the instrument configured to be driven through a luminal network of a patient; detect a set of one or more points of interest the first image data; identify a set of first locations respectively corresponding to the set of points in the first image data; receive second image data from the image sensor; detect the set of one or more points in the second image data; identify a set of second locations respectively corresponding to the set of points in the second image data; and based on the set of first locations and the set of second locations, detect a change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument.

[0010] In yet another aspect, there is provided a method for detecting a change of location of an instrument, comprising: receiving first image data from an image sensor located on the instrument, the instrument configured to be driven through a luminal network of a patient; detecting a set of one or more points of interest the first image data; identifying a set of first locations respectively corresponding to the set of points in the first image data; receiving second image data from the image sensor; detecting the set of one or more points in the second image data; identifying a set of second locations respectively corresponding to the set of points in the second image data; and based on the set of first locations and the set of second locations, detecting the change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] 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.

[0012] FIG. **1**A shows an example surgical robotic system, according to one embodiment.

[0013] FIGS. 1B-1F show various perspective views of a robotic platform coupled to the surgical robotic system shown in FIG. 1A, according to one embodiment.

[0014] FIG. 2 shows an example command console for the example surgical robotic system, according to one embodiment.

[0015] FIG. 3A shows an isometric view of an example independent drive mechanism of the instrument device manipulator (IDM) shown in FIG. 1A, according to one embodiment.

[0016] FIG. 3B shows a conceptual diagram that shows how forces may be measured by a strain gauge of the independent drive mechanism shown in FIG. 3A, according to one embodiment.

[0017] FIG. 4A shows a top view of an example endoscope, according to one embodiment.

[0018] FIG. 4B shows an example endoscope tip of the endoscope shown in FIG. 4A, according to one embodiment.

[0019] FIG. 5 shows an example schematic setup of an EM tracking system included in a surgical robotic system, according to one embodiment.

[0020] FIGS. 6A-6B show an example anatomical lumen and an example 3D model of the anatomical lumen, according to one embodiment.

[0021] FIG. 7 shows a computer-generated 3D model representing an anatomical space, according to one embodiment.

[0022] FIGS. 8A-8D show example graphs illustrating on-the-fly registration of an EM system to a 3D model of a path through a tubular network, according to one embodiment.

[0023] FIGS. 8E-8F show effect of an example registration of the EM system to a 3D model of a branched tubular network, according to one embodiment.

[0024] FIG. 9A shows a high-level overview of an example block diagram of a navigation configuration system, according to one embodiment.

[0025] FIG. 9B shows an example block diagram of the navigation module shown in FIG. 9A, according to one embodiment.

[0026] FIG. 9C shows example block diagram of the estimated state data store included in the state estimator, according to one embodiment.

[0027] FIG. 10A shows an example block diagram of the motion estimation module in accordance with aspects of this disclosure.

[0028] FIG. 10B shows an example block diagram of the object detection module, according to one example.

[0029] FIG. 10C shows an example block diagram of the object mapping module, according to one embodiment.

[0030] FIG. 10D shows an example block diagram of the topological reasoning module, according to one embodiment.

[0031] FIGS. 11A-11B, show an example object-to-lumen mapping performed by the object mapping module, according to one embodiment.

[0032] FIG. 12 is a flowchart illustrating an example method operable by a robotic system, or component(s) thereof, for detecting physiological noise in accordance with aspects of this disclosure.

[0033] FIG. 13A illustrates example image data captured by an image sensor at a first point in time in accordance with aspects of this disclosure.

[0034] FIG. 13B illustrates another example of image data captured by an image sensor at a second point in time, after the first point in time, in accordance with aspects of this disclosure.

[0035] FIG. 13C illustrates an example of the change in location of example pixels between the image data frames illustrated in FIGS. 13A-13B in accordance with aspects of this disclosure.

[0036] FIG. 13D illustrates another example of the change in location of example pixels between the image data frames illustrated in FIGS. 13A-13B in accordance with aspects of this disclosure.

[0037] FIGS. 14A-14B illustrate an example of two image data frames within a sequence of image data frames for which the scale change value may be accumulated in accordance with aspects of this disclosure.

[0038] FIGS. 15A-15B are graphs which illustrate the changes to an accumulated scale change value over a sequence of image data frames in accordance with aspects of this disclosure.

[0039] Reference will now be made in detail to several embodiments, examples of which are illustrated in the accompanying figures. It is noted that wherever practicable similar or like reference numbers may be used in the figures and may indicate similar or like functionality. The figures depict embodiments of the described system (or method) for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles described herein.

DETAILED DESCRIPTION

I. Surgical Robotic System

[0040] FIG. 1A shows an example surgical robotic system **100**, according to one embodiment. The surgical robotic system **100** includes a base **101** coupled to one or more robotic arms, e.g., robotic arm **102**. The base **101** is communicatively coupled to a command console, which is further described with reference to FIG. **2** in Section II. Command Console. The base **101** can be positioned such that the robotic arm **102** has access to perform a surgical procedure on a patient, while a user such as a physician may control the surgical robotic system **100** from the comfort of the command console. In some embodiments, the base **101** may be coupled to a surgical operating table or bed for supporting the patient. Though not shown in FIG. **1** for purposes of clarity, the base **101** may include subsystems such as control electronics, pneumatics, power sources, optical sources, and the like. The robotic arm **102** includes multiple arm segments **110** coupled at joints **111**, which provides the robotic arm **102** multiple degrees of freedom, e.g., seven degrees of freedom corresponding to seven arm segments. The base **101** may contain a source of power **112**, pneumatic pressure **113**, and control and sensor electronics **114**—including components such as a central processing unit, data bus, control circuitry, and memory—and related actuators such as motors to move the robotic arm **102**. The electronics **114** in the base **101** may also process and transmit control signals communicated from the command console.

[0041] In some embodiments, the base **101** includes wheels **115** to transport the surgical robotic system **100**.

Mobility of the surgical robotic system **100** helps accommodate space constraints in a surgical operating room as well as facilitate appropriate positioning and movement of surgical equipment. Further, the mobility allows the robotic arms **102** to be configured such that the robotic arms **102** do not interfere with the patient, physician, anesthesiologist, or any other equipment. During procedures, a user may control the robotic arms **102** using control devices such as the command console.

[0042] In some embodiments, the robotic arm **102** includes set up joints that use a combination of brakes and counter-balances to maintain a position of the robotic arm **102**. The counter-balances may include gas springs or coil springs. The brakes, e.g., fail safe brakes, may be include mechanical and/or electrical components. Further, the robotic arms **102** may be gravity-assisted passive support type robotic arms.

[0043] Each robotic arm **102** may be coupled to an instrument device manipulator (IDM) **117** using a mechanism changer interface (MCI) **116**. The IDM **117** can be removed and replaced with a different type of IDM, for example, a first type of IDM manipulates an endoscope, while a second type of IDM manipulates a laparoscope. The MCI **116** includes connectors to transfer pneumatic pressure, electrical power, electrical signals, and optical signals from the robotic arm **102** to the IDM **117**. The MCI **116** can be a set screw or base plate connector. The IDM **117** manipulates surgical instruments such as the endoscope **118** using techniques including direct drive, harmonic drive, geared drives, belts and pulleys, magnetic drives, and the like. The MCI **116** is interchangeable based on the type of IDM **117** and can be customized for a certain type of surgical procedure. The robotic **102** arm can include a joint level torque sensing and a wrist at a distal end, such as the KUKA AG® LBR5 robotic arm.

[0044] The endoscope **118** is a tubular and flexible surgical instrument that is inserted into the anatomy of a patient to capture images of the anatomy (e.g., body tissue). In particular, the endoscope **118** includes one or more imaging devices (e.g., cameras or other types of optical sensors) that capture the images. The imaging devices may include one or more optical components such as an optical fiber, fiber array, or lens. The optical components move along with the tip of the endoscope **118** such that movement of the tip of the endoscope **118** results in changes to the images captured by the imaging devices. The endoscope **118** is further described with reference to FIGS. **3**A-**4**B in Section IV. Endoscope.

[0045] Robotic arms **102** of the surgical robotic system **100** manipulate the endoscope **118** using elongate movement members. The elongate movement members may include pull wires, also referred to as pull or push wires, cables, fibers, or flexible shafts. For example, the robotic arms **102** actuate multiple pull wires coupled to the endoscope **118** to deflect the tip of the endoscope **118**. The pull wires may include both metallic and non-metallic materials such as stainless steel, Kevlar, tungsten, carbon fiber, and the like. The endoscope **118** may exhibit nonlinear behavior in response to forces applied by the elongate movement members. The nonlinear behavior may be based on stiffness and compressibility of the endoscope **118**, as well as variability in slack or stiffness between different elongate movement members.

[0046] FIGS. **1**B-**1**F show various perspective views of the surgical robotic system **100** coupled to a robotic platform **150** (or surgical bed), according to various embodiments. Specifically, FIG. **1**B shows a side view of the surgical robotic system **100** with the robotic arms **102** manipulating the endoscopic **118** to insert the endoscopic inside a patient's body, and the patient is lying on the robotic platform **150**. FIG. **1**C shows a top view of the surgical robotic system **100** and the robotic platform **150**, and the endoscopic **118** manipulated by the robotic arms is inserted inside the patient's body. FIG. **1**D shows a perspective view of the surgical robotic system **100** and the robotic platform **150**, and the endoscopic **118** is controlled to be positioned horizontally parallel with the robotic platform. FIG. **1**E shows another perspective view of the surgical robotic system **100** and the robotic platform **150**, and the endoscopic **118** is controlled to be positioned relatively perpendicular to the robotic platform. In more detail, in FIG. **1**E, the angle between the horizontal surface of the robotic platform **150** and the endoscopic **118** is 75 degree. FIG. **1**F shows the perspective view of the surgical robotic system **100** and the robotic platform **150** shown in FIG. **1**E, and in more detail, the angle between the endoscopic **118** and the virtual line **160** connecting one end **180** of the endoscopic and the robotic arm **102** that is positioned relatively farther away from the robotic platform is 90 degree.

II. Command Console

[0047] FIG. **2** shows an example command console **200** for the example surgical robotic system **100**, according to one embodiment. The command console **200** includes a console base **201**, display modules **202**, e.g., monitors, and control modules, e.g., a keyboard **203** and joystick **204**. In some embodiments, one or more of the command console **200** functionality may be integrated into a base **101** of the surgical robotic system **100** or another system communicatively coupled to the surgical robotic system **100**. A user **205**, e.g., a physician, remotely controls the surgical robotic system **100** from an ergonomic position using the command console **200**.

[0048] The console base **201** may include a central processing unit, a memory unit, a data bus, and associated data communication ports that are responsible for interpreting and processing signals such as camera imagery and tracking sensor data, e.g., from the endoscope **118** shown in FIG. **1**. In some embodiments, both the console base **201** and the base **101** perform signal processing for load-balancing. The console base **201** may also process commands and instructions provided by the user **205** through the control modules **203** and **204**. In addition to the keyboard **203** and joystick **204** shown in FIG. **2**, the control modules may include other devices, for example, computer mice, trackpads, trackballs, control pads, video game controllers, and sensors (e.g., motion sensors or cameras) that capture hand gestures and finger gestures.

[0049] The user **205** can control a surgical instrument such as the endoscope **118** using the command console **200** in a velocity mode or position control mode. In velocity mode, the user **205** directly controls pitch and yaw motion of a distal end of the endoscope **118** based on direct manual control using the control modules. For example, movement on the joystick **204** may be mapped to yaw and pitch movement in the distal end of the endoscope **118**. The joystick **204** can provide haptic feedback to the user **205**. For example, the joystick **204** vibrates to indicate that the endoscope **118** cannot further translate or rotate in a certain

direction. The command console **200** can also provide visual feedback (e.g., pop-up messages) and/or audio feedback (e.g., beeping) to indicate that the endoscope **118** has reached maximum translation or rotation.

[0050] In position control mode, the command console **200** uses a three-dimensional (3D) map of a patient and pre-determined computer models of the patient to control a surgical instrument, e.g., the endoscope **118**. The command console **200** provides control signals to robotic arms **102** of the surgical robotic system **100** to manipulate the endoscope **118** to a target location. Due to the reliance on the 3D map, position control mode requires accurate mapping of the anatomy of the patient.

[0051] In some embodiments, users **205** can manually manipulate robotic arms **102** of the surgical robotic system **100** without using the command console **200**. During setup in a surgical operating room, the users **205** may move the robotic arms **102**, endoscopes **118**, and other surgical equipment to access a patient. The surgical robotic system **100** may rely on force feedback and inertia control from the users **205** to determine appropriate configuration of the robotic arms **102** and equipment.

[0052] The display modules **202** may include electronic monitors, virtual reality viewing devices, e.g., goggles or glasses, and/or other means of display devices. In some embodiments, the display modules **202** are integrated with the control modules, for example, as a tablet device with a touchscreen. Further, the user **205** can both view data and input commands to the surgical robotic system **100** using the integrated display modules **202** and control modules.

[0053] The display modules **202** can display 3D images using a stereoscopic device, e.g., a visor or goggle. The 3D images provide an "endo view" (i.e., endoscopic view), which is a computer 3D model illustrating the anatomy of a patient. The "endo view" provides a virtual environment of the patient's interior and an expected location of an endoscope **118** inside the patient. A user **205** compares the "endo view" model to actual images captured by a camera to help mentally orient and confirm that the endoscope **118** is in the correct—or approximately correct—location within the patient. The "endo view" provides information about anatomical structures, e.g., the shape of an intestine or colon of the patient, around the distal end of the endoscope **118**. The display modules **202** can simultaneously display the 3D model and computerized tomography (CT) scans of the anatomy the around distal end of the endoscope **118**. Further, the display modules **202** may overlay the already determined navigation paths of the endoscope **118** on the 3D model and scans/images generated based on preoperative model data (e.g., CT scans).

[0054] In some embodiments, a model of the endoscope **118** is displayed with the 3D models to help indicate a status of a surgical procedure. For example, the CT scans identify a lesion in the anatomy where a biopsy may be necessary. During operation, the display modules **202** may show a reference image captured by the endoscope **118** corresponding to the current location of the endoscope **118**. The display modules **202** may automatically display different views of the model of the endoscope **118** depending on user settings and a particular surgical procedure. For example, the display modules **202** show an overhead fluoroscopic view of the endoscope **118** during a navigation step as the endoscope **118** approaches an operative region of a patient.

III. Instrument Device Manipulator

[0055] FIG. **3**A shows an isometric view of an example independent drive mechanism of the IDM **117** shown in FIG. **1**, according to one embodiment. The independent drive mechanism can tighten or loosen the pull wires **321**, **322**, **323**, and **324** (e.g., independently from each other) of an endoscope by rotating the output shafts **305**, **306**, **307**, and **308** of the IDM **117**, respectively. Just as the output shafts **305**, **306**, **307**, and **308** transfer force down pull wires **321**, **322**, **323**, and **324**, respectively, through angular motion, the pull wires **321**, **322**, **323**, and **324** transfer force back to the output shafts. The IDM **117** and/or the surgical robotic system **100** can measure the transferred force using a sensor, e.g., a strain gauge further described below.

[0056] FIG. **3**B shows a conceptual diagram that shows how forces may be measured by a strain gauge **334** of the independent drive mechanism shown in FIG. **3**A, according to one embodiment. A force **331** may direct away from the output shaft **305** coupled to the motor mount **333** of the motor **337**. Accordingly, the force **331** results in horizontal displacement of the motor mount **333**. Further, the strain gauge **334** horizontally coupled to the motor mount **333** experiences strain in the direction of the force **331**. The strain may be measured as a ratio of the horizontal displacement of the tip **335** of strain gauge **334** to the overall horizontal width **336** of the strain gauge **334**.

[0057] In some embodiments, the IDM **117** includes additional sensors, e.g., inclinometers or accelerometers, to determine an orientation of the IDM **117**. Based on measurements from the additional sensors and/or the strain gauge **334**, the surgical robotic system **100** can calibrate readings from the strain gauge **334** to account for gravitational load effects. For example, if the IDM **117** is oriented on a horizontal side of the IDM **117**, the weight of certain components of the IDM **117** may cause a strain on the motor mount **333**. Accordingly, without accounting for gravitational load effects, the strain gauge **334** may measure strain that did not result from strain on the output shafts.

IV. Endoscope

[0058] FIG. **4**A shows a top view of an example endoscope **118**, according to one embodiment. The endoscope **118** includes a leader **415** tubular component nested or partially nested inside and longitudinally-aligned with a sheath **411** tubular component. The sheath **411** includes a proximal sheath section **412** and distal sheath section **413**. The leader **415** has a smaller outer diameter than the sheath **411** and includes a proximal leader section **416** and distal leader section **417**. The sheath base **414** and the leader base **418** actuate the distal sheath section **413** and the distal leader section **417**, respectively, for example, based on control signals from a user of a surgical robotic system **100**. The sheath base **414** and the leader base **418** are, e.g., part of the IDM **117** shown in FIG. **1**.

[0059] Both the sheath base **414** and the leader base **418** include drive mechanisms (e.g., the independent drive mechanism further described with reference to FIG. **3**A-B in Section III. Instrument Device Manipulator) to control pull wires coupled to the sheath **411** and leader **415**. For example, the sheath base **414** generates tensile loads on pull wires coupled to the sheath **411** to deflect the distal sheath section **413**. Similarly, the leader base **418** generates tensile loads on pull wires coupled to the leader **415** to deflect the distal

leader section **417**. Both the sheath base **414** and leader base **418** may also include couplings for the routing of pneumatic pressure, electrical power, electrical signals, or optical signals from IDMs to the sheath **411** and leader **414**, respectively. A pull wire may include a steel coil pipe along the length of the pull wire within the sheath **411** or the leader **415**, which transfers axial compression back to the origin of the load, e.g., the sheath base **414** or the leader base **418**, respectively.

[0060] The endoscope **118** can navigate the anatomy of a patient with ease due to the multiple degrees of freedom provided by pull wires coupled to the sheath **411** and the leader **415**. For example, four or more pull wires may be used in either the sheath **411** and/or the leader **415**, providing eight or more degrees of freedom. In other embodiments, up to three pull wires may be used, providing up to six degrees of freedom. The sheath **411** and leader **415** may be rotated up to 360 degrees along a longitudinal axis **406**, providing more degrees of motion. The combination of rotational angles and multiple degrees of freedom provides a user of the surgical robotic system **100** with a user friendly and instinctive control of the endoscope **118**.

[0061] FIG. **4**B illustrates an example endoscope tip **430** of the endoscope **118** shown in FIG. **4**A, according to one embodiment. In FIG. **4**B, the endoscope tip **430** includes an imaging device **431** (e.g., a camera), illumination sources **432**, and ends of EM coils **434**. The illumination sources **432** provide light to illuminate an interior portion of an anatomical space. The provided light allows the imaging device **431** to record images of that space, which can then be transmitted to a computer system such as command console **200** for processing as described herein. Electromagnetic (EM) coils **434** located on the tip **430** may be used with an EM tracking system to detect the position and orientation of the endoscope tip **430** while it is disposed within an anatomical system. In some embodiments, the coils may be angled to provide sensitivity to EM fields along different axes, giving the ability to measure a full 6 degrees of freedom: three positional and three angular. In other embodiments, only a single coil may be disposed within the endoscope tip **430**, with its axis oriented along the endoscope shaft of the endoscope **118**; due to the rotational symmetry of such a system, it is insensitive to roll about its axis, so only 5 degrees of freedom may be detected in such a case. The endoscope tip **430** further comprises a working channel **436** through which surgical instruments, such as biopsy needles, may be inserted along the endoscope shaft, allowing access to the area near the endoscope tip.

V. Registration Transform of EM System to 3D Model

V. A. Schematic Setup of an EM Tracking System

[0062] FIG. **5** shows an example schematic setup of an EM tracking system **505** included in a surgical robotic system **500**, according to one embodiment. In FIG. **5**, multiple robot components (e.g., window field generator, reference sensors as described below) are included in the EM tracking system **505**. The robotic surgical system **500** includes a surgical bed **511** to hold a patient's body. Beneath the bed **511** is the window field generator (WFG) **512** configured to sequentially activate a set of EM coils (e.g., the EM coils **434** shown in FIG. **4**B). The WFG **512** generates an alternating current (AC) magnetic field over a wide volume; for example, in some cases it may create an AC field in a volume of about 0.5×0.5×0.5 m.

[0063] Additional fields may be applied by further field generators to aid in tracking instruments within the body. For example, a planar field generator (PFG) may be attached to a system arm adjacent to the patient and oriented to provide an EM field at an angle. Reference sensors **513** may be placed on the patient's body to provide local EM fields to further increase tracking accuracy. Each of the reference sensors **513** may be attached by cables **514** to a command module **515**. The cables **514** are connected to the command module **515** through interface units **516** which handle communications with their respective devices as well as providing power. The interface unit **516** is coupled to a system control unit (SCU) **517** which acts as an overall interface controller for the various entities mentioned above. The SCU **517** also drives the field generators (e.g., WFG **512**), as well as collecting sensor data from the interface units **516**, from which it calculates the position and orientation of sensors within the body. The SCU **517** may be coupled to a personal computer (PC) **518** to allow user access and control.

[0064] The command module **515** is also connected to the various IDMs **519** coupled to the surgical robotic system **500** as described herein. The IDMs **519** are typically coupled to a single surgical robotic system (e.g., the surgical robotic system **500**) and are used to control and receive data from their respective connected robotic components; for example, robotic endoscope tools or robotic arms. As described above, as an example, the IDMs **519** are coupled to an endoscopic tool (not shown here) of the surgical robotic system **500**

[0065] The command module **515** receives data passed from the endoscopic tool. The type of received data depends on the corresponding type of instrument attached. For example, example received data includes sensor data (e.g., image data, EM data), robot data (e.g., endoscopic and 1DM physical motion data), control data, and/or video data. To better handle video data, a field-programmable gate array (FPGA) **520** may be configured to handle image processing. Comparing data obtained from the various sensors, devices, and field generators allows the SCU **517** to precisely track the movements of different components of the surgical robotic system **500**, and for example, positions and orientations of these components.

[0066] In order to track a sensor through the patient's anatomy, the EM tracking system **505** may require a process known as "registration," where the system finds the geometric transformation that aligns a single object between different coordinate systems. For instance, a specific anatomical site on a patient has two different representations in the 3D model coordinates and in the EM sensor coordinates. To be able to establish consistency and common language between these two different coordinate systems, the EM tracking system **505** needs to find the transformation that links these two representations, i.e., registration. For example, the position of the EM tracker relative to the position of the EM field generator may be mapped to a 3D coordinate system to isolate a location in a corresponding 3D model.

V. B. 3D Model Representation

[0067] FIGS. **6**A-**6**B show an example anatomical lumen **600** and an example 3D model **620** of the anatomical lumen, according to one embodiment. More specifically, FIGS.

6A-6B illustrate the relationships of centerline coordinates, diameter measurements and anatomical spaces between the actual anatomical lumen **600** and its 3D model **620**. In FIG. **6**A, the anatomical lumen **600** is roughly tracked longitudinally by centerline coordinates **601**, **602**, **603**, **604**, **605**, and **606** where each centerline coordinate roughly approximates the center of the tomographic slice of the lumen. The centerline coordinates are connected and visualized by a centerline **607**. The volume of the lumen can be further visualized by measuring the diameter of the lumen at each centerline coordinate, e.g., coordinates **608**, **609**, **610**, **611**, **612**, and **613** represent the measurements of the lumen **600** corresponding to coordinates **601**, **602**, **603**, **604**, **605**, and **606**.

[0068] FIG. **6**B shows the example 3D model **620** of the anatomical lumen **600** shown in FIG. **6**A, according to one embodiment. In FIG. **6**B, the anatomical lumen **600** is visualized in 3D space by first locating the centerline coordinates **601**, **602**, **603**, **604**, **605**, and **606** in 3D space based on the centerline **607**. As one example, at each centerline coordinate, the lumen diameter is visualized as a 2D circular space (e.g., the 2D circular space **630**) with diameters **608**, **609**, **610**, **611**, **612**, and **613**. By connecting those 2D circular spaces to form a 3D space, the anatomical lumen **600** is approximated and visualized as the 3D model **620**. More accurate approximations may be determined by increasing the resolution of the centerline coordinates and measurements, i.e., increasing the density of centerline coordinates and measurements for a given lumen or subsection. Centerline coordinates may also include markers to indicate point of interest for the physician, including lesions.

[0069] In some embodiments, a pre-operative software package is also used to analyze and derive a navigation path based on the generated 3D model of the anatomical space. For example, the software package may derive a shortest navigation path to a single lesion (marked by a centerline coordinate) or to several lesions. This navigation path may be presented to the operator intra-operatively either in two-dimensions or three-dimensions depending on the operator's preference. In certain implementations, the navigation path (or at a portion thereof) may be pre-operatively selected by the operator. The path selection may include identification of one or more target locations (also simply referred to as a "target") within the patient's anatomy.

[0070] FIG. **7** shows a computer-generated 3D model **700** representing an anatomical space, according to one embodiment. As discussed above in FIGS. **6**A-**6**B, the 3D model **700** may be generated using a centerline **701** that was obtained by reviewing CT scans that were generated preoperatively. In some embodiments, computer software may be able to map a navigation path **702** within the tubular network to access an operative site **703** (or other target) within the 3D model **700**. In some embodiments, the operative site **703** may be linked to an individual centerline coordinate **704**, which allows a computer algorithm to topologically search the centerline coordinates of the 3D model **700** for the optimum path **702** within the tubular network. In certain embodiments, the topological search for the path **702** may be constrained by certain operator selected parameters, such as the location of one or more targets, one or more waypoints, etc.

[0071] In some embodiments, the distal end of the endoscopic tool within the patient's anatomy is tracked, and the tracked location of the endoscopic tool within the patient's anatomy is mapped and placed within a computer model, which enhances the navigational capabilities of the tubular network. In order to track the distal working end of the endoscopic tool, i.e., location and orientation of the working end, a number of approaches may be employed, either individually or in combination.

[0072] In a sensor-based approach to localization, a sensor, such as an EM tracker, may be coupled to the distal working end of the endoscopic tool to provide a real-time indication of the progression of the endoscopic tool. In EM-based tracking, an EM tracker, embedded in the endoscopic tool, measures the variation in the electromagnetic field created by one or more EM transmitters. The transmitters (or field generators), may be placed close to the patient (e.g., as part of the surgical bed) to create a low intensity magnetic field. This induces small-currents in sensor coils in the EM tracker, which are correlated to the distance and angle between the sensor and the generator. The electrical signal may then be digitized by an interface unit (on-chip or PCB) and sent via cables/wiring back to the system cart and then to the command module. The data may then be processed to interpret the current data and calculate the precise location and orientation of the sensor relative to the transmitters. Multiple sensors may be used at different locations in the endoscopic tool, for instance in leader and sheath in order to calculate the individual positions of those components. Accordingly, based on readings from an artificially-generated EM field, the EM tracker may detect changes in field strength as it moves through the patient's anatomy.

V. C. On-the-Fly EM Registration

[0073] FIGS. **8**A-**8**D show example graphs **810**-**840** illustrating on-the-fly registration of an EM system to a 3D model of a path through a tubular network, according to one embodiment. The navigation configuration system described herein allows for on-the-fly registration of the EM coordinates to the 3D model coordinates without the need for independent registration prior to an endoscopic procedure. In more detail, FIG. **8**A shows that the coordinate systems of the EM tracking system and the 3D model are initially not registered to each other, and the graph **810** in FIG. **8**A shows the registered (or expected) location of an endoscope tip **801** moving along a planned navigation path **802** through a branched tubular network (not shown here), and the registered location of the instrument tip **801** as well as the planned path **802** are derived from the 3D model. The actual position of the tip is repeatedly measured by the EM tracking system **505**, resulting in multiple measured location data points **803** based on EM data. As shown in FIG. **8**A, the data points **803** derived from EM tracking are initially located far from the registered location of the endoscope tip **801** expected from the 3D model, reflecting the lack of registration between the EM coordinates and the 3D model coordinates. There may be several reasons for this, for example, even if the endoscope tip is being moved relatively smoothly through the tubular network, there may still be some visible scatter in the EM measurement, due to breathing movement of the lungs of the patient.

[0074] The points on the 3D model may also be determined and adjusted based on correlation between the 3D model itself, image data received from optical sensors (e.g., cameras) and robot data from robot commands. The 3D transformation between these points and collected EM data

points will determine the initial registration of the EM coordinate system to the 3D model coordinate system.

[0075] FIG. **8**B shows a graph **820** at a later temporal stage compared with the graph **810**, according to one embodiment. More specifically, the graph **820** shows the expected location of the endoscope tip **801** expected from the 3D model has been moved farther along the preplanned navigation path **802**, as illustrated by the shift from the original expected position of the instrument tip **801** shown in FIG. **8**A along the path to the position shown in FIG. **8**B. During the EM tracking between generation of the graph **810** and generation of graph **820**, additional data points **803** have been recorded by the EM tracking system but the registration has not yet been updated based on the newly collected EM data. As a result, the data points **803** in FIG. **8**B are clustered along a visible path **814**, but that path differs in location and orientation from the planned navigation path **802** the endoscope tip is being directed by the operator to travel along. Eventually, once sufficient data (e.g., EM data) is accumulated, compared with using only the 3D model or only the EM data, a relatively more accurate estimate can be derived from the transform needed to register the EM coordinates to those of the 3D model. The determination of sufficient data may be made by threshold criteria such as total data accumulated or number of changes of direction. For example, in a branched tubular network such as a bronchial tube network, it may be judged that sufficient data have been accumulated after arriving at two branch points.

[0076] FIG. **8**C shows a graph **830** shortly after the navigation configuration system has accumulated a sufficient amount of data to estimate the registration transform from EM to 3D model coordinates, according to one embodiment. The data points **803** in FIG. **8**C have now shifted from their previous position as shown in FIG. **8**B as a result of the registration transform. As shown in FIG. **8**C, the data points **803** derived from EM data is now falling along the planned navigation path **802** derived from the 3D model, and each data point among the data points **803** is now reflecting a measurement of the expected position of endoscope tip **801** in the coordinate system of the 3D model. In some embodiments, as further data are collected, the registration transform may be updated to increase accuracy. In some cases, the data used to determine the registration transformation may be a subset of data chosen by a moving window, so that the registration may change over time, which gives the ability to account for changes in the relative coordinates of the EM and 3D models—for example, due to movement of the patient.

[0077] FIG. **8**D shows an example graph **840** in which the expected location of the endoscope tip **801** has reached the end of the planned navigation path **802**, arriving at the target location in the tubular network, according to one embodiment. As shown in FIG. **8**D, the recorded EM data points **803** is now generally tracks along the planned navigation path **802**, which represents the tracking of the endoscope tip throughout the procedure. Each data point reflects a transformed location due to the updated registration of the EM tracking system to the 3D model.

[0078] In some embodiments, each of the graphs shown in FIGS. **8**A-**8**D can be shown sequentially on a display visible to a user as the endoscope tip is advanced in the tubular network. In some embodiments, the processor can be configured with instructions from the navigation configuration system such that the model shown on the display remains substantially fixed when the measured data points are registered to the display by shifting of the measured path shown on the display in order to allow the user to maintain a fixed frame of reference and to remain visually oriented on the model and on the planned path shown on the display.

[0079] FIGS. **8**E-**8**F show the effect of an example registration of the EM system to a 3D model of a branched tubular network, according to one embodiment. In FIGS. **8**E-**8**F, 3D graphs showing electromagnetic tracking data **852** and a model of a patient's bronchial system **854** are illustrated without (shown in FIG. **8**E) and with (shown in FIG. **8**F) a registration transform. In FIG. **8**E, without registration, tracking data **860** have a shape that corresponds to a path through the bronchial system **854**, but that shape is subjected to an arbitrary offset and rotation. In FIG. **8**F, by applying the registration, the tracking data **852** are shifted and rotated, so that they correspond to a path through the bronchial system **854**.

VI. Navigation Configuration System

VI. A. High-Level Overview of Navigation Configuration System

[0080] FIGS. **9**A-**9**C show example block diagrams of a navigation configuration system **900**, according to one embodiment. More specifically, FIG. **9**A shows a high-level overview of an example block diagram of the navigation configuration system **900**, according to one embodiment. In FIG. **9**A, the navigation configuration system **900** includes multiple input data stores, a navigation module **905** that receives various types of input data from the multiple input data stores, and an output navigation data store **990** that receives output navigation data from the navigation module. The block diagram of the navigation configuration system **900** shown in FIG. **9**A is merely one example, and in alternative embodiments not shown, the navigation configuration system **900** can include different and/or addition entities. Likewise, functions performed by various entities of the system **900** may differ according to different embodiments. The navigation configuration system **900** may be similar to the navigational system described in U.S. Patent Publication No. 2017/0084027, published on Mar. 23, 2017, the entirety of which is incorporated herein by reference.

[0081] The input data, as used herein, refers to raw data gathered from and/or processed by input devices (e.g., command module, optical sensor, EM sensor, IDM) for generating estimated state information for the endo scope as well as output navigation data. The multiple input data stores **910**-**940** include an image data store **910**, an EM data store **920**, a robot data store **930**, and a 3D model data store **940**. Each type of the input data stores **910**-**940** stores the name-indicated type of data for access and use by a navigation module **905**. Image data may include one or more image frames captured by the imaging device at the instrument tip, as well as information such as frame rates or timestamps that allow a determination of the time elapsed between pairs of frames. Robot data may include data related to physical movement of the medical instrument or part of the medical instrument (e.g., the instrument tip or sheath) within the tubular network. Example robot data includes command data instructing the instrument tip to reach a specific anatomical site and/or change its orientation (e.g., with a specific pitch, roll, yaw, insertion, and retraction for one or both of a leader and a sheath) within the tubular

network, insertion data representing insertion movement of the part of the medical instrument (e.g., the instrument tip or sheath), IDM data, and mechanical data representing mechanical movement of an elongate member of the medical instrument, for example motion of one or more pull wires, tendons or shafts of the endoscope that drive the actual movement of the medial instrument within the tubular network. EM data may be collected by EM sensors and/or the EM tracking system as described above. 3D model data may be derived from 2D CT scans as described above.

[0082] The output navigation data store **990** receives and stores output navigation data provided by the navigation module **905**. Output navigation data indicates information to assist in directing the medical instrument through the tubular network to arrive at a particular destination within the tubular network, and is based on estimated state information for the medical instrument at each instant time, the estimated state information including the location and orientation of the medical instrument within the tubular network. In one embodiment, as the medical instrument moves inside the tubular network, the output navigation data indicating updates of movement and location/orientation information of the medical instrument is provided in real time, which better assists its navigation through the tubular network.

[0083] To determine the output navigation data, the navigation module **905** locates (or determines) the estimated state of the medical instrument within a tubular network. As shown in FIG. **9**A, the navigation module **905** further includes various algorithm modules, such as an EM-based algorithm module **950**, an image-based algorithm module **960**, and a robot-based algorithm module **970**, that each may consume mainly certain types of input data and contribute a different type of data to a state estimator **980**. As illustrated in FIG. **9**A, the different kinds of data output by these modules, labeled EM-based data, the image-based data, and the robot-based data, may be generally referred to as "intermediate data" for sake of explanation. The detailed composition of each algorithm module and of the state estimator **980** is more fully described below.

VI. B. Navigation Module

[0084] FIG. **9**B shows an example block diagram of the navigation module **905** shown in FIG. **9**A, according to one embodiment. As introduced above, the navigation module **905** further includes a state estimator **980** as well as multiple algorithm modules that employ different algorithms for navigating through a tubular network. For clarity of description, the state estimator **980** is described first, followed by the description of the various modules that exchange data with the state estimator **980**.

VI. B. 1 State Estimator

[0085] The state estimator **980** included in the navigation module **905** receives various intermediate data and provides the estimated state of the instrument tip as a function of time, where the estimated state indicates the estimated location and orientation information of the instrument tip within the tubular network. The estimated state data are stored in the estimated data store **985** that is included in the state estimator **980**.

[0086] FIG. **9**C shows an example block diagram of the estimated state data store **985** included in the state estimator **980**, according to one embodiment. The estimated state data store **985** may include a bifurcation data store **1086**, a position data store **1087**, a depth data store **1088**, and an orientation data store **1089**, however this particular breakdown of data storage is merely one example, and in alternative embodiments not shown, different and/or additional data stores can be included in the estimated state data store **985**.

[0087] The various stores introduced above represent estimated state data in a variety of ways. Specifically, bifurcation data refers to the location of the medical instrument with respect to the set of branches (e.g., bifurcation, trifurcation or a division into more than three branches) within the tubular network. For example, the bifurcation data can be set of branch choices elected by the instrument as it traverses through the tubular network, based on a larger set of available branches as provided, for example, by the 3D model which maps the entirety of the tubular network. The bifurcation data can further include information in front of the location of the instrument tip, such as branches (bifurcations) that the instrument tip is near but has not yet traversed through, but which may have been detected, for example, based on the tip's current position information relative to the 3D model, or based on images captured of the upcoming bifurcations.

[0088] Position data indicates three-dimensional position of some part of the medical instrument within the tubular network or some part of the tubular network itself. Position data can be in the form of absolute locations or relative locations relative to, for example, the 3D model of the tubular network. As one example, position data can include an indication of the position of the location of the instrument being within a specific branch. The identification of the specific branch may also be stored as a segment identification (ID) which uniquely identifies the specific segment of the model in which the instrument tip is located.

[0089] Depth data indicates depth information of the instrument tip within the tubular network. Example depth data includes the total insertion (absolute) depth of the medical instrument into the patient as well as the (relative) depth within an identified branch (e.g., the segment identified by the position data store **1087**). Depth data may be determined based on position data regarding both the tubular network and medical instrument.

[0090] Orientation data indicates orientation information of the instrument tip, and may include overall roll, pitch, and yaw in relation to the 3D model as well as pitch, roll, raw within an identified branch.

[0091] Turning back to FIG. **9**B, the state estimator **980** provides the estimated state data back to the algorithm modules for generating more accurate intermediate data, which the state estimator uses to generate improved and/or updated estimated states, and so on forming a feedback loop. For example, as shown in FIG. **9**B, the EM-based algorithm module **950** receives prior EM-based estimated state data, also referred to as data associated with timestamp "t−1." The state estimator **980** uses this data to generate "estimated state data (prior)" that is associated with timestamp "t−1." The state estimator **980** then provides the data back to the EM-based algorithm module. The "estimated state data (prior)" may be based on a combination of different types of intermediate data (e.g., robotic data, image data) that is associated with timestamp "t−1" as generated and received from different algorithm modules. Next, the EM-based algorithm module **950** runs its algorithms using the estimated

state data (prior) to output to the state estimator **980** improved and updated EM-based estimated state data, which is represented by "EM-based estimated state data (current)" here and associated with timestamp t. This process continues to repeat for future timestamps as well.

[0092] As the state estimator **980** may use several different kinds of intermediate data to arrive at its estimates of the state of the medical instrument within the tubular network, the state estimator **980** is configured to account for the various different kinds of errors and uncertainty in both measurement and analysis that each type of underlying data (robotic, EM, image) and each type of algorithm module might create or carry through into the intermediate data used for consideration in determining the estimated state. To address these, two concepts are discussed, that of a probability distribution and that of confidence value.

[0093] The "probability" of the "probability distribution", as used herein, refers to a likelihood of an estimation of a possible location and/or orientation of the medical instrument being correct. For example, different probabilities may be calculated by one of the algorithm modules indicating the relative likelihood that the medical instrument is in one of several different possible branches within the tubular network. In one embodiment, the type of probability distribution (e.g., discrete distribution or continuous distribution) is chosen to match features of an estimated state (e.g., type of the estimated state, for example continuous position information vs. discrete branch choice). As one example, estimated states for identifying which segment the medical instrument is in for a trifurcation may be represented by a discrete probability distribution, and may include three discrete values of 20%, 30% and 50% representing chance as being in the location inside each of the three branches as determined by one of the algorithm modules. As another example, the estimated state may include a roll angle of the medical instrument of 40±5 degrees and a segment depth of the instrument tip within a branch may be is 4±1 mm, each represented by a Gaussian distribution which is a type of continuous probability distribution. Different methods or modalities can be used to generate the probabilities, which will vary by algorithm module as more fully described below with reference to later figures.

[0094] In contrast, the "confidence value," as used herein, reflects a measure of confidence in the estimation of the state provided by one of the algorithms based one or more factors. For the EM-based algorithms, factors such as distortion to EM Field, inaccuracy in EM registration, shift or movement of the patient, and respiration of the patient may affect the confidence in estimation of the state. Particularly, the confidence value in estimation of the state provided by the EM-based algorithms may depend on the particular respiration cycle of the patient, movement of the patient or the EM field generators, and the location within the anatomy where the instrument tip locates. For the image-based algorithms, examples factors that may affect the confidence value in estimation of the state include illumination condition for the location within the anatomy where the images are captured, presence of fluid, tissue, or other obstructions against or in front of the optical sensor capturing the images, respiration of the patient, condition of the tubular network of the patient itself (e.g., lung) such as the general fluid inside the tubular network and occlusion of the tubular network, and specific operating techniques used in, e.g., navigating or image capturing.

[0095] For example one factor may be that a particular algorithm has differing levels of accuracy at different depths in a patient's lungs, such that relatively close to the airway opening, a particular algorithm may have a high confidence in its estimations of medical instrument location and orientation, but the further into the bottom of the lung the medical instrument travels that confidence value may drop. Generally, the confidence value is based on one or more systemic factors relating to the process by which a result is determined, whereas probability is a relative measure that arises when trying to determine the correct result from multiple possibilities with a single algorithm based on underlying data.

[0096] As one example, a mathematical equation for calculating results of an estimated state represented by a discrete probability distribution (e.g., branch/segment identification for a trifurcation with three values of an estimated state involved) can be as follows:

$$S_1 = C_{EM} * P_{1,EM} + C_{Image} * P_{1,Image} + C_{Robot} * P_{1,Robot};$$

$$S_2 = C_{EM} * P_{2,EM} + C_{Image} * P_{2,Image} + C_{Robot} * P_{2,Robot};$$

$$S_3 = C_{EM} * P_{3,EM} + C_{Image} * P_{3,Image} + C_{Robot} * P_{3,Robot}.$$

[0097] In the example mathematical equation above, $S_i (i=1,2,3)$ represents possible example values of an estimated state in a case where 3 possible segments are identified or present in the 3D model, C_{EM}, C_{Image}, and C_{Robot} represents confidence value corresponding to EM-based algorithm, image-based algorithm, and robot-based algorithm and $P_{i,EM}$, $P_{i,Image}$, and $P_{i,Robot}$ represents the probabilities for segment i.

[0098] To better illustrate the concepts of probability distributions and confidence value associated with estimate states, a detailed example is provided here. In this example, a user is trying to identify segment where an instrument tip is located in a certain trifurcation within a central airway (the predicted region) of the tubular network, and three algorithms modules are used including EM-based algorithm, image-based algorithm, and robot-based algorithm. In this example, a probability distribution corresponding to the EM-based algorithm may be 20% in the first branch, 30% in the second branch, and 50% in the third (last) branch, and the confidence value applied to this EM-based algorithm and the central airway is 80%. For the same example, a probability distribution corresponding to the image-based algorithm may be 40%, 20%, 40% for the first, second, and third branch, and the confidence value applied to this image-based algorithm is 30%; while a probability distribution corresponding to the robot-based algorithm may be 10%, 60%, 30% for the first, second, and third branch, and the confidence value applied to this image-based algorithm is 20%. The difference of confidence values applied to the EM-based algorithm and the image-based algorithm indicates that the EM-based algorithm may be a better choice for segment identification in the central airway, compared with the image-based algorithm. An example mathematical calculation of a final estimated state can be:

[0099] for the first branch: 20%*80%+40%*30%+10%*20%=30%; for the second branch: 30%*80%+20%*30%+60%*20%=42%; and for the third branch: 50%*80%+40%*30%+30%*20%=58%.

[0100] In this example, the output estimated state for the instrument tip can be the result values (e.g., the resulting

30%, 42% and 58%), or derivative value from these result values such as the determination that the instrument tip is in the third branch.

[0101] As above the estimated state may be represented in a number of different ways. For example, the estimated state may further include an absolute depth from airway to location of the tip of the instrument, as well as a set of data representing the set of branches traversed by the instrument within the tubular network, the set being a subset of the entire set of branches provided by the 3D model of the patient's lungs, for example. The application of probability distribution and confidence value on estimated states allows improved accuracy of estimation of location and/or orientation of the instrument tip within the tubular network.

VI. B. 2 Algorithm Modules

[0102] As shown in FIG. **9**B, the algorithm modules include an EM-based algorithm module **950**, an image-based algorithm module **960**, and a robot-based algorithm module **970**. The algorithm modules shown in FIG. **9**B is merely one example, and in alternative embodiments, different and/additional algorithm modules involving different and/or additional navigation algorithms can also be included in the navigation module **905**.

VI. B. 2. i. Image-Based Algorithm Module

[0103] Turning back to FIG. **9**B, the image-based algorithm module **960** uses image data to determine the estimated state of the instrument within the tubular network. The image-based algorithm module **960** further includes one or more different types of image-based algorithm modules that employ different image-based algorithms. As shown in FIG. **9**B, one example including an object-based algorithm module **962** is shown. In alternative embodiments not shown, other types of image-based algorithms may be employed and corresponding algorithm modules may be included in the image-based algorithm module **960**. In addition to determining the estimated state of the instrument, the image-based algorithm module **960** may also detect a change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument and provide an indication of the detected change in location to the state estimator **980**. Further detail regarding aspects of the detection of the change in location of the instrument will be provided below in connection with FIG. **11**.

[0104] The object-based algorithm module **962** detects and analyzes objects present in the field of view of the image data, such as branch openings or particles, to determine estimated state. In one embodiment, it includes an object detection module **963**, and object mapping module **964**, a topological reasoning module **965**, and a motion estimation module **966**. In some embodiments, it may or may not be necessary to apply the different modules **963**, **964**, **965** and **966** in a fixed sequential order, and when actually executing a process of object-based algorithm described by the object-based algorithm module **962**, the order of employing each module within the module **962** is a different order than shown in FIG. **9**B.

[0105] Turning to FIG. **10**A, the motion estimation module **963** receives as inputs image data from the image data store **910**, estimated state data (prior) (specifically bifurcation data), from the estimated state data store **985**as well as the 3D model data from the 3D model data store **940**. Based on the received image data, the motion estimation module **963** measures a movement of the medical instrument between multiple image frames based on the received image data. Example techniques used include optical flow and image registration techniques, among others. This measurement determines a differential movement, such as forward-backward motion or roll motion, of the instrument tip in its own local frame of reference. This movement can be combined with the prior estimated state input to calculate a new estimated state. In particular, a forward (or backward) movement can translate into an increase (or decrease) in depth relative to a prior estimated state. Similarly, a differential roll translates into a change in roll angle relative to a prior estimated state. These measurements allow an estimation of movement through the tubular network. As above, these estimations may be represented as a probability distribution (e.g., a roll angle of the medical instrument of 40±5 degrees represented by a Gaussian distribution). The output estimated state is stored in the estimated state data store **985**.

[0106] In one embodiment, in a case where the estimated state and bifurcation data for a particular instant in time indicate that the instrument tip is at or near a branch point, this movement measurement may include an identification of an estimated new branch that the instrument tip is estimated to be entering or have entered. For example, if the bifurcation data indicates that the endoscope tip is at a branch point, pitch and yaw movements can be measured to determine changes in pointing angle, and the new estimated angle can be compared with the expected angles of different branches in the 3D model of the tubular network. A determination can then be made of which branch the endoscope is facing towards when it is moved into a new branch. Estimated state data reflecting each of these estimates of new position, orientation, and/or branch entry are output to the state estimator **980**.

[0107] FIG. **10**B shows an example block diagram of the object detection module **964**, according to one example. The object detection module **964** receives as inputs image data (e.g., image frames), and outputs object data to an object data store **1063** as well as estimated state data to the estimated state data store **985**. Object data indicates information about what objects were identified, as well as positions, orientations, and sizes of objects represented as probabilities.

[0108] Specifically, the object detection module **964** detects, within an image, one or more objects and one or more points of interest of the object(s) that may indicate branch points in a tubular network, and then determines their position, size, and orientation. The objects detected by the object detection module **964** may also be referred to as "points of interest," which may include, for example, one or more identifiable pixels within an image. In certain embodiments, the points of interest may comprise a set of one or more pixels which can be detected over a sequence of one or more images. In some implementations, the detected object may comprise one of more points of interest (e.g., image features) detected using image processing techniques of the related art, such as speeded up robust features (SURF) and scale-invariant feature transform (SIFT). However, any technique which can reliably detect and track one or more pixels through a series of images can be used to detect the points of interest which can be used in the image processing techniques described herein.

[0109] In certain implementations, objects may be calculated or represented in the object detection module **964** as

being two-dimensional shapes, such as circles/ovals/ellipses for detected branch points. This corresponds to the fact that the image data used to capture the objects are images from the camera on the instrument tip pointed usually along an axis substantially parallel to the direction of the segment in which the instrument is located. As a consequence, objects such as branches in the tubular network appear as simple shapes such as ellipses in the images. In one embodiment, in a given image within a tubular network, each branch will typically appear as a dark, approximately elliptical region, and these regions may be detected automatically by a processor, using region-detection algorithms such as maximally stable extremal regions (MSER) as objects. These regions may then be fit to define an object (e.g., ellipse), with appropriate free parameters such as ellipse center, major and minor axes, and angle within the image. The roll measurement and the identified matching between model lumens and lumens in the image are also output to the state estimator **980**, as well as topological reasoning module **966**. An example of identified objects superimposed on an image of a bronchial network, along with a link joining their centers, is described with reference to FIGS. **11**A-**11**B.

[0110] In one embodiment, an "airway" can also be identified as an object present in the image data. The object detection module **964** may use light reflective intensity combined with other techniques to identify airways.

[0111] The object detection module **964** may further track detected objects or points of interest across a set of sequential image frames. The object tracking may be used to detect which branch has been entered from among a set of possible branches in the tubular network. Alternatively or in addition, the tracking of objects may be used to detect a change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument as described in greater detail below. Tracking the relative positions of the objects within the image frames may also be used to determine a local, absolute measurement of roll angle within a branched network.

[0112] FIG. **10**C shows an example block diagram of the object mapping module **965**, according to one embodiment. The object mapping module **965** receives as inputs 3D model data from the 3D model data store **940**, object data (e.g., detected objects such as shapes representing possible branches in the tubular network) from the object data store **1063**, and estimated state data (prior) from the estimated state data store **985**.

[0113] Based on the received input data, the object mapping module **965** outputs object mapping data to an object mapping data store **1065** as well as image-based estimated state data (current) to the estimated state data store **985**. As one example, the object mapping data indicates mapping information between physical branches (lumens) shown in image data (based on the detected objects) and virtual branch information generated by 3D model. The estimated state data (current) generated by module **965** includes identification of each branch of the tubular network visible within the image as well as an estimate of the roll of the endoscope tip relative to the 3D model. As above, the estimated state data (current) can be represented as a probability distribution. The identification of the visible lumens may include coordinates in x and y of each identified lumen center within the image, for example based on object sizes correlated with the 3D model virtual image data, as well as an association of each identified lumen location with a particular branch of the tubular network.

[0114] In some embodiments, since the 3D model is generated prior to the endoscopic procedure, the virtual images of the tubular network may be pre-computed to speed up processing. In alternative embodiments not shown, the tubular network may be represented by a structure such as a tree diagram of lumen midlines, with each such midline describing a 3D path, so that an expected position of local branch centers as seen from any arbitrary perspective may be compared to the identified actual locations of branch centers based on EM data and/or robot data.

[0115] FIGS. **11**A-**11**B, show an example object-to-lumen mapping performed by the object mapping module **965**, according to one embodiment. More specifically, FIG. **11**A shows two example identified objects **1101** and **1102** superimposed on an image of a bronchial network **1105** along with a link **1103** connecting centers of the two objects, according to one embodiment. In the illustrated example, the identified objects **1101** and **1102** are ellipse-shaped.

[0116] FIG. **11**B shows a matching between airway lumens in an actual image **1110** of a real bronchial network and a corresponding virtual image **1120** from a 3D model of that same network, according to one embodiment. In the actual image **1110**, ellipses are identified corresponding to two different branches, located with identified centers **1111** and **1112**, which, in one embodiment, indicates centerline coordinates of the branches as described above in FIGS. **6**A-**6**B. The 3D model virtual image **1120** is a simulated representation of the real bronchial network shown in the actual image **1110**, and the estimated centers **1121** and **1122** of the endoscope tip as determined by the state estimator **980** are shown corresponding to the positions of the identified centers **1111** and **1112**.

[0117] If both images **1110** and **1120** are presented to a user via a user interface, the 3D model image **1120** may be rotated or translated to increase the closeness of fit between actual image **1110** and virtual image **1120**, and the amount of roll needed for the rotation or translation can be output as a correction to the current estimated state (e.g., roll of the instrument tip).

[0118] In one embodiment, the probability applied to a possible estimated state as generated by the object mapping module **965** is based on the closeness of fit between the identified centers **1111** and **1112** detected in the actual image **1110** and estimated centers **1121** and **1121** in the 3D model image **1120**, and as one example, the probability of being in the lumen with identified center **1112** drops as the distance between the estimated center **1122** and identified center **1112** increases.

[0119] FIG. **10**D shows an example block diagram of the topological reasoning module **966**, according to one embodiment. The topological reasoning module **966** receives as input image data from the 3D model data from the 3D model data store **940**, object mapping data from the object mapping data store **1065**, and estimated state data (prior) from the estimated state data store **985**.

[0120] Based on the received data, the topological reasoning module **966** determines which branch the endoscope tip is facing towards, thereby generating a prediction of which branch will be entered if the endoscope is moved forward. As above, the determination may be represented as a probability distribution. In one embodiment, when the instrument tip is moving forward, the topological reasoning mod-

ule **966** determines that a new branch of the tubular network has been entered and identifies which branch the tip has moved into. The determination of which branch is being faced and which segment is entered may be made, for example, by comparing the relative sizes and locations of different identified objects (e.g., ellipses). As one example, as a particular lumen branch is entered, a corresponding detected object will grow larger in successive image frames, and will also become more centered in those frames. If this is behavior is identified for one of the objects, the topological reasoning module **966** assigns an increasingly large probability to a corresponding estimated state as the endoscope tip moves towards the lumen associated with that object. Other branches are assigned correspondingly lower probabilities, until finally their object shapes disappear from images entirely. In one embodiment, the probability of the medical instrument being in those branches depends only on the probability that the branches were misidentified by the object mapping module **964**. The output of the topological reasoning module **966** is image-based estimated state data representing estimated probabilities of being in each of a set of possible branches within the branched network.

VII. Image-Based Detection of Physiological Noise

[0121] Pulmonologists can prevent intra-operative trauma by basing their decisions and actions on the respiratory cycle of the patient. One example of such an action is insertion of a biopsy tool to collect tissue samples, for example via bronchoscopy. At or near the periphery of the lung the airways may be narrow, and the circumference of the airways changes depending on the respiratory phase of the lung. The diameter of an airway expands as a patient inhales in the inspiration phase of the respiratory cycles and constricts as the patient exhales during the expiration phase of the cycle. During a procedure, a pulmonologist can observe the patient to determine whether they are in the inspiration phase or the expiration phase in order to decide whether a particular tool or endoscope of fixed diameter can enter the airway. An airway can close around a tool during expiration without causing trauma, however forcing a tool through a constricted airway during the expiration phase can cause critical trauma, for example by puncturing a blood vessel.

[0122] The aforementioned problems, among others, are addressed in certain embodiments by the luminal network navigation systems and techniques described herein. Some embodiments of the disclosed luminal network navigation systems and techniques relate to incorporating respiratory frequency and/or magnitude into a navigation framework to implement patient safety measures (e.g., instrument control techniques, user interface alerts, notifications, and the like).

[0123] A patient's respiratory cycle may also affect the accuracy of the detection of the position and/or orientation of an instrument inserted into the patient's airways. Thus, some embodiments of the disclosed bronchoscopy navigation systems and techniques relate to identifying, and/or compensating for, motion caused by patient respiration in order to provide a more accurate identification of the position of an instrument within patient airways. For example, an instrument positioned within patient airways can be provided with an EM sensor. The navigation system can filter instrument position information from the EM sensor to remove signal noise due to cyclic motion of the respiratory passages caused by respiration. A frequency of the cyclic respiratory motion can be obtained from data from one or more additional sensors. In some implementations, inspiration and expiration cycles can be determined based on data from additional EM sensor(s), accelerometer(s), and/or acoustic respiratory sensor(s) placed on the body of the patient in one example. In some implementations, the frequency can be obtained from other types of sensors or systems, for example respiratory cycle information from a ventilator used to control patient breathing, or respiratory cycle information extracted from automated analysis of images received from an optical sensor positioned to observe the patient.

[0124] Under certain circumstances, the filtering of the patient's respiration from the position information received from the EM sensor may not be sufficient to determine a sufficiently accurate estimate of the position of the instrument. For example, when additional EM sensor(s) are placed on the exterior of a patient's body, the EM sensors may detect the motion due to respiration in a transverse direction. That is, the EM sensor may track the overall expansion and contraction of the patient's airway via the movement of the EM sensors placed on the body of the patient.

[0125] Depending on the location of the instrument within the patient's airway, the patient's respiration may also have another effect on the location of the instrument. That is, the length of the path traversed by the instrument within the luminal network may expand and contract along with the respiratory cycle. Since the length of the instrument may not appreciably change during the procedure, the relative position of the instrument with respect to the luminal network may change as the overall length of luminal network defined by the path taken by the instrument in the luminal network expands and contracts. From the reference point of the distal end of the instrument, this may appear as though the instrument is being advanced and retraced within the luminal network even though the instrument is not being actively driven. In certain circumstances, the instrument may be substantially stationary with respect to the reference point of the platform even while from the reference point of the distal end of the instrument, the instrument is being advanced and retraced. In this case, the location of the instrument determined based on the EM sensor may indicate that the instrument is substantially stationary, the location of the instrument with respect to the reference frame of the luminal network may be changing in accordance with the patient's respiratory cycle.

[0126] Thus, certain aspects of this disclosure may relate to the detection of movement of the instrument with respect to the reference frame of the luminal network (e.g., movement of the luminal network around the instrument) due to a patient's respiration (or other physiological motion). Once detected, the robotic system may provide a user interface alert to indicate that there may be a certain amount of uncompensated error in the displayed location of the instrument.

VII. A. Overview of Image-Based Detection of Physiological Noise

[0127] FIG. **12** is a flowchart illustrating an example method operable by a robotic system, or component(s) thereof, for detecting physiological noise in accordance with aspects of this disclosure. For example, the steps of method **1200** illustrated in FIG. **12** may be performed by processor(s) and/or other component(s) of a medical robotic system (e.g., surgical robotic system **500**) or associated system(s)

(e.g., the image-based algorithm module **960** of the navigation configuration system **900**). For convenience, the method **1200** is described as performed by the navigation configuration system, also referred to simply as the "system" in connection with the description of the method **1200**.

[0128] The method **1200** begins at block **1201**. At block **1205**, the system may receive first image data from an image sensor located on an instrument, the instrument configured to be driven through a luminal network of a patient. In example embodiments, the instrument may comprise a bronchoscope configured to be driven through a patient's airways. In these embodiments, the system may be configured to detect respiratory motion of the instrument based at least in part on the images received from the image sensor.

[0129] At block **1210**, the system may detect a set of one or more points of interest the first image data. As discussed above, the points of interest may be any distinguishable data across multiple image data, such as, for example, one or more identifiable pixels within the image or one or more objects detected in the image data. In certain embodiments, the points of interest may comprise a set of one or more pixels which can be detected over a sequence of one or more images. In some implementations, the detected object may comprise one of more distinguishable objects detected using image processing techniques of the related art, such as SURF and SIFT. However, any technique which can reliably detect and track one or more pixels through a series of images can be used to detect the points of interest which can be used in the image processing techniques described herein.

[0130] At block **1215**, the system may identify a set of first locations respectively corresponding to the set of points in the first image data. In embodiments where the set of points correspond to identifiable pixels within the image, the set of locations may correspond to the row and/or column values of the pixels within the image. Thus, the first set of locations may comprise the X- and Y-coordinates for each of the pixels in the set of points.

[0131] At block **1220**, the system may receive second image data from the image sensor. The second image may be an image received from the image sensor at a point in time occurring after the time at which the first image was captured by the image sensor.

[0132] At block **1225**, the system may detect the set of one or more points in the second image data. The set of points detected in the second image may correspond to the set of points detected in the first image. The detection of the same set of points between multiple images will be described in greater detail below in connection with FIGS. **13**A-**13**C.

[0133] At block **1230**, the system may identify a set of second locations respectively corresponding to the set of points in the second image data. In some situations, when the physiological noise is affecting the relative position of the instrument with respect to the luminal network, the set of locations of the points of interest in the second image may be different from the set of locations of the points of interest in the first image. For example, as the instrument is advanced into the luminal network (e.g., due to contraction of the length of the luminal network), an object appearing in the images captured by the image sensor may appear as though it is approaching the image sensor. Thus, by tracking the location of the object (e.g., by tracking the points of interest), the system may be able to estimate motion of the instrument with respect to the luminal network.

[0134] At block **1235**, the system may, based on the set of first locations and the set of second locations, detect a change of location of the luminal network around the instrument caused by movement of the luminal network relative to the instrument. As described above, movement of the location of the tracked points of interest may be indicative of movement of the luminal network with respect to the instrument. Specific embodiments related to the detection of the change of location caused by movement of the luminal network will be described below in connection with FIGS. **14**A-**15**B. The method **1200** ends at block **1240**.

VII. B. Example of Tracking Points of Interest Between a Series of Image Data Frames

[0135] FIG. **13**A illustrates example image data captured by an image sensor at a first point in time in accordance with aspects of this disclosure. FIG. **13**B illustrates another example of image data captured by an image sensor at a second point in time, after the first point in time, in accordance with aspects of this disclosure. Depending on the embodiment, the first image data and the second image data may be successive images in a series of image data frames captured by the image sensor or may be separated in time with at least one additional image data frame interposed therebetween. FIG. **13**C illustrates an example of the change in location of example pixels between the image data frames illustrated in FIGS. **13**A-**13**B in accordance with aspects of this disclosure. FIG. **13**D illustrates another example of the change in location of example pixels between the image data frames illustrated in FIGS. **13**A-**13**B in accordance with aspects of this disclosure.

[0136] The image data frames illustrated in FIGS. **13**A-**13**B are simplified to show certain aspects of the detected image data which may be involved in the tracking of the locations of points of interest between a series of image data frames. In certain embodiments, the image data captured by an image sensor of an instrument may include an array of pixels having a greater or lesser number of pixels than illustrated. For example, the image sensor may be configured to capture 200×200 pixel image data frames in certain implementations.

[0137] FIG. **13**A illustrates first image data **1300**A including two points of interest **1310**A and **1320**A. The limited number of points of interest **1310**A and **1320**A is simplified merely for descriptive purposes and, in other embodiments, a larger number of points of interest **1310**A and **1320**A may be detected and tracked in the first image data **1300**A. Further, in the FIG. **13**A example, the points of interest **1310**A and **1320**A may correspond to individual pixels within the first image data **1300**A. However, as discussed above, in other embodiments the points of interest **1310**A and **1320**A may correspond to objects identified by the object detection module **964** or points of interest detected using image processing techniques such as SURF and/or SIFT.

[0138] In the second image data **1300**B of FIG. **13**B, the system may detect the same points of interest **1310**B and **1320**B which were identified in the first image data **1300**A. However, the points of interest **1310**B and **1320**B may have moved to new locations within the second image data **1300**B in the time elapsed between the capturing of the first and second image data **1300**A and **1300**B. The movement of the points of interest **1310**B and **1320**B from the first image data **1300**A to their respective locations in the second image data

1300B may be based on the relative movement of the corresponding portions of the luminal network with respect to the location of the image sensor. When the instrument is stationary with respect to the robotic system (e.g., when no robotic commands are being provided to drive the instrument), the system may be able to infer that movement of the points of interest 1310B and 1320B, and thus instrument within the luminal network, is due physiological noise. In a bronchoscopy example, the physiological noise may correspond to the length of the luminal network expanding and contracting along the path taken by the instrument due to respiration of the patient. Additionally or alternatively, the change in the diameter of the airway due to respiration may also be tracked by changes in the locations of the points of interest. Examples of physiological noise which may be detected by the image methodologies disclosed herein include respiration of the patient and a heart rate of the patient.

[0139] The locations of the points of interest in FIGS. 13A-14B may include the 2D locations of the points within the first image data and the second image data. Thus, the locations of the points of interest may include the X- and Y-coordinates for each of the points. In other embodiments, the system may track the location of the points in 3D space (not illustrated) based on the image data 1300A and 1300B. In these embodiments, the system may extract depth information for the from the each of the image data 1300A and 1300B and represent the location of the points in 3D information indicative of the respective locations of the points.

[0140] FIG. 13C illustrates the locations of the points of interest at each of the first point in time and the second point in time overlaid on the same image data frame. As shown in FIG. 13C, a first point of interest 1310A and 1310B moved from the first image data 1300A to different location in the second image data 1300B. The movement of the first point of interest is illustrated by the vector 1315. Similarly, a second point of interest 1320A and 1320B has moved between the first and second image data 1300A and 1300B as illustrated by the vector 1325.

[0141] In more general terms, the system may track a set of points of interest over a series of image data frames received from an image sensor positions on the instrument. The system may determine a "scale change" between two successive image data frames in the series. FIG. 13D illustrates another example of the locations of the points of interest at each of the first point in time and the second point in time overlaid on the same image data to illustrate the relative distances between the points of interest. As shown in FIG. 13D, a first point of interest 1310A and 1310B moved from the first image data 1300A to different location in the second image data 1300B. The system may determine a determine a first distance 1330 between the first point 1310A and the second point 1320A in the first image data based on the locations of the first point 1310A and the second point 1320A in the first image data 1300A. The system may also determine a second distance 1335 between the first point 1310B and the second point 1320B in the second image data 1300B based on the locations of the first point 1310B and the second point 1320B in the first image data 1300B. In some implementations, the first and second distances 1330 and 1335 distance may be determined by the Euclidean distance between the respective points.

[0142] The system may use the first distance 1330 and the second distance 1335 to detect the change of location of the instrument within the luminal network. For example, in one embodiment, the system may determine a scale change estimate based on the first distance 1330 and the second distance 1335. In one implementation, the scale change estimate may be based on the difference between the first distance 1330 and the second distance 1335.

[0143] Although only two points of interest are illustrated in FIGS. 13A-13D, the system may track a set of at least three points of interest over the series of image data frames. When the number of points in the set of points of interest is less than the number of pixels in the image data, the set of points may be considered a "sparse" set of points. In other embodiments, the number of points in the set of points of interest tracked by the system may be a "dense" set of points, where the number of tracked points is equal to the number of pixels in the image data. The system may group the points in the set of points a plurality of pairs of points. This may include each combination of pairs of points for the entire set of points or may include a subset of the possible pairs of points for the set of points.

[0144] The system may determine a scale change value between the two image data frames based on the scale estimates determined for the pairs of points. In certain embodiments, the scale change value may be representative of the scale change between the two image data frames based on all or a subset of the tracked pairs of points. In one embodiment, the system may determine the scale change value as a median value of the scale change estimates. In another embodiment, the system may determine the scale change value as an average value of the scale change estimates. Those skilled in the art will recognize that other techniques or methodologies may be used to generate a scale change value based on the set of scale change estimates.

VII. C. Example of Tracking a Cumulative Scale Change Over a Series of Image Data Frames

[0145] The system may accumulate a scale change value over a sequence of image data frames, and there by track the scale change over more than two image data frames. In certain implementations, the system may accumulate the scale change value my multiplying the scale change values between successive pairs of image data frames in the sequence of image data frames. FIGS. 14A-14B illustrate an example of two image data frames within a sequence of image data frames for which the scale change value may be accumulated in accordance with aspects of this disclosure. FIGS. 15A-15B are graphs which illustrate the changes to an accumulated scale change value over a sequence of image data frames in accordance with aspects of this disclosure.

[0146] With reference to FIGS. 14A-15B, a sequence of image data is illustrated over a numbered sequence of image data frames, where FIG. 15A includes image data from frame #930 to frame #1125 and FIG. 15B includes image data from frame #965 to frame #1155. FIG. 14A includes image data 1405 from frame #1125 while FIG. 14B includes image data 1410 from frame #1155.

[0147] Each of FIGS. 15A-15B illustrates cumulative scale values determined in accordance with aspects of this disclosure. For example, the values at each frame in the graphs may be calculated by multiplying a currently determined scale change value between two image data frames with the accumulated scale change value determined for the

previous frame. As is shown the graphs, the cumulative scale change values are period when periodic physiological noise is affecting the position of the image sensor (and thus the distal end of the instrument). The system may track cumulative changes to the scale change value in the sequence of image data received from the image sensor over a first time period and determine the frequency of the physiological noise based on the cumulative scale change values over a period of time. In one embodiment, the system may transform the tracked scale change value into a frequency domain (e.g., using a Fourier or other transform). The system may further identify at least one harmonic in the tracked scale change value in frequency domain. In certain embodiments, the system may identify the first harmonic in the tracked scale change value in frequency domain as an estimated frequency of the physiological noise.

[0148] The frequency determined from the cumulative scale change values may be utilized as an estimate of the frequency of physiological noise. However, physiological noise may not always have a large enough effect on the location of the instrument with respect to the luminal network that the physiological noise will introduce error in the localization of the instrument (e.g., as determined by the navigation configuration system **900**). Thus, in certain embodiments, the system may compare the estimated frequency of the physiological noise to a separately estimated frequency of the physiological noise.

[0149] In one embodiment, the system may determine a first physiological movement frequency of the patient based on a sequence of image data frames received from the image sensor. The system may further determine a second physiological movement frequency of the patient based on the data received from one or more location sensors (e.g., an EM sensor, a shape-sensing fiber, robot command data, and a radiation-based image sensors). Examples of systems and techniques for determining a physiological movement frequency of a patient based on data received from one or more location sensors is described in U.S. Patent Application Pub. No. 2018/0279852, filed on Mar. 29, 2018, the entirety of which is incorporated herein by reference.

[0150] The system may then determine whether the difference between the first physiological movement frequency based on the sequence of image data and the second physiological movement frequency based on the location sensor data is less than a threshold difference. When the difference between the first and second physiological movement frequencies is less than the threshold difference, the system may determine that the frequency of the scale changes in the sequence of image data frames is due to a physiological noise source. In certain embodiments, the system may provide an indication of the detected change of location of the instrument within the luminal network to a display in response to determining that the frequency of the scale changes in the sequence of image data frames is due to a physiological noise source.

[0151] In contrast, when the difference between the first and second physiological movement frequencies is not less than the threshold difference, the system may not have sufficient confidence to determine that the movement in the luminal network with respect to the instrument will affect the accuracy of the in the localization of the instrument (e.g., as determined by the navigation configuration system **900**). In other words, when the frequency of the scale changes in the sequence of image data does not sufficiently match the physiological frequency measured using a separate technique, the system may infer that the location of the instrument sufficiently stable with respect to the luminal network so as to not introduce errors into the localization of the instrument.

VII. D. Example of Backtracking of Points of Interest

[0152] Depending on the particular image processing technique used to identify the points of interest (e.g., SURF, SIFT, etc.), the order in which two frames of image data are processed may affect the identification of the locations of the points of interest within the image data. For example, referring to FIGS. **13**A-**13**B, in one example, the system may identify pixels **1310**B and **1320**B in image data frame **1300**B by tracking a change in the location of pixels **1310**A and **1320**A from frame **1300**A. However, under certain conditions, in reversing this process by backtracking pixels **1310**B and **1320**B from image data frame **1300**B to image data frame **1300**A, the system may identify different pixels from the original pixels **1310**A and **1320**A. When pixels identified during a backtracking process are not the same as the original pixels **1310**A and **1320**A, the identified pixels may not be sufficiently robust to determine a scale change estimate.

[0153] Accordingly, the system may identify a set of backtracked locations of the set of points in first image data via backtracking the set of points from second image data to the first image data and compare the set of backtracked locations to the original set of locations of the set of points identified from the first image data. The system may identify a sub-set of the points from the set of points for which the backtracked locations are not within a threshold distance of the set of first locations (e.g., the locations of the backtracked pixels do not sufficiently match the originally determined locations of the pixels used for forward tracking). The system may remove the sub-set of points from the set of points and determine the scale change estimate without the removed sub-set of points. This may improve the accuracy and robustness of the point tracking over a series of image data frames.

VII. D. Example of Detecting Physiological Noise During Dynamic Instrument Movement

[0154] While certain aspects of this disclosure may be performed while the instrument is stationary (e.g., while no robot commands are provided to move the instrument), it may also be desirable to detect physiological noise during dynamic instrument movement (e.g., while driving the instrument within the luminal network). During such dynamic instrument movement, the change between two image data frames (e.g., received at a first time and a second time), may be the result of a combination of instrument movement and physiological noise. Accordingly, to detect the physiological noise during dynamic movement of the instrument, the instrument movement motion should be decoupled from the physiological noise in the motion detected by the image-based algorithm module **970**. In certain embodiments, the system can perform motion decoupling in 3D space by using the 3D movement of the instrument received from positioning sensors (e.g., EM-based state data, robot-based state data, EM and/or optical shape sensing state data, etc.). The system can employ certain image processing techniques including image-based

3D motion estimation (e.g., structure from motion) to determine the relative 3D motion between the instrument and the luminal network.

[0155] In one example implementation, the system may determine a location sensor-based 3D instrument movement between two points in time (e.g., between t_0 and t_1) based on data received from locations sensors. The 3D instrument movement data may be represented by three spatial degrees-of-freedom (DoF), for example $\{x_z,y_z,z_z\}$, and three rotational DoF, for example, $\{\theta_s^x,\theta_s^y,\theta_s^z\}$. The system may also determine an image sensor-based 3D instrument movement between the two points in time represented by the same six DoF measurements as in the location sensor-based 3D instrument movement.

[0156] The system may determine a 3D instrument movement estimate representative of physiological movement by determining the difference between the location sensor-based 3D instrument movement and the image sensor-based 3D instrument movement. The system may then accumulate the 3D instrument movement estimate representative of physiological movement over a sequence of image data and location sensor measurements over a given time period, from which a frequency and amplitude associated with the physiological noise can be extracted (e.g., using one or more of the above-defined techniques including harmonic analysis).

VII. E. Example of Detecting an Instrument Transitioning Between Junctions Due to Physiological Noise

[0157] There may be uncertainty in the determined location of an instrument introduced due to physiological noise when the instrument is located near a junction in a luminal network (e.g., when a current segment branches into two or more child segments). That is, if the instrument is not located near a junction, even though the instrument may have a change in depth within a current segment due to the physiological noise, the instrument may remain within the current segment without transitioning into another segment. However, if the instrument is located near a junction, the movement of the instrument due to physiological noise may be sufficient to move the instrument from one segment into another segment. Thus, it may be desirable to provide an indication to the user that the system is unable to accurately determine whether the instrument has crossed over the junction into a new segment of the luminal network.

[0158] In certain embodiments, the system can detect junction transition by identifying and analyzing the airways from image data received from an image sensor. For example, the system tracks the locations of detected airways between two image data frames (e.g., received at a first time t_0 and a second time t_1). The system may, in certain embodiments, determine that the instrument has transitioned through a junction in response to at least one of the following conditions being satisfied: 1) all of the estimated airways overlap with the detected airways in the image data at time t_1, but there exists one or more detected airways in the image data at time t_1 that do not have an overlap with the estimated airways; 2) all the detected airways in in the image data at time t_1 overlap with the estimated airways, but there exists one or more estimated airways do not have an overlap with the detected airways the image data at time t_0; and 3) there exists one or more detected airways that do not overlap with the estimated airways and there exists one or more estimated airways do not overlap with the detected airways. As such, embodiments may track the location and sizes of prior airways and compare them to the locations and sizes of airways detected in current image data. The presences of one or more of the above listed conditions and the detected of movement of the anatomy relative to the instrument may be used by the system to detect a transition between junctions.

VIII. Implementing Systems and Terminology

[0159] Implementations disclosed herein provide systems, methods and apparatuses for detecting physiological noise during navigation of a luminal network.

[0160] 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.

[0161] The path-based navigational 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 can 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 may comprise RAM, ROM, EEPROM, flash memory, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to store desired program code in the form of instructions or data structures and that can 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.

[0162] 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.

[0163] 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.

[0164] 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."

[0165] 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.

What is claimed is:

1. A medical robotic system, comprising:

a set of one or more processors; and

at least one computer-readable memory in communication with the set of processors and having stored thereon computer-executable instructions to cause the set of processors to:

receive first image data from an image sensor located on an instrument, the instrument configured to be driven through a luminal network of a patient,

detect a set of one or more points of interest the first image data,

identify a set of first locations respectively corresponding to the set of points in the first image data,

receive second image data from the image sensor,

detect the set of one or more points in the second image data,

identify a set of second locations respectively corresponding to the set of points in the second image data, and

based on the set of first locations and the set of second locations, detect a change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument.

2. The system of claim **1**, wherein:

the set of first locations and the set of second locations respectively define two-dimensional (2D) locations of the points within the first image data and the second image data.

3. The system of claim **2**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

group the set of points into a plurality of pairs of points, a first pair of points comprising a first point and a second point,

determine a first distance between the first point and the second point in the first image data based on the set of first locations, and

determine a second distance between the first point and the second point in the second image data based on the set of second locations,

wherein detecting the change of location of the instrument within the luminal network is further based on the first distance and the second distance.

4. The system of claim **3**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

determine a first scale change estimate for the first pair of points based on the first distance and the second distance, and

determine a scale change value representative of the scale change between the first image data and the second image data based on the scale change estimate,

wherein detecting the change of location of the instrument within the luminal network is further based on the scale change value.

5. The system of claim **4**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

determine a set of scale change estimates respectively corresponding to the pairs of points, and

determine the scale change value based on a median value of the set of scale change estimates or an average value of the set of scale change estimates.

6. The system of claim **1**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

track cumulative changes to a scale change value representative of a scale change in image data received from the image sensor over a first time period,

transform the tracked scale change value into a frequency domain, and

identify at least one harmonic in the tracked scale change value in frequency domain,

wherein detecting the change of location of the instrument within the luminal network is further based on the at least one harmonic.

7. The system of claim **1**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

determine a location of the instrument based on data received from one or more location sensors,

determine a first physiological movement frequency of the patient based on the set of first locations and the set of second locations, wherein detecting the change of location of the instrument within the luminal network is further based on the first physiological movement frequency, and

provide an indication of the detected change of location of the instrument within the luminal network to a display.

8. The system of claim **7**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

determine a second physiological movement frequency of the patient based on the data received from the one or more location sensors, and

determine that a difference between the first physiological movement frequency and the second physiological movement frequency is less than a threshold difference,

wherein detecting the change of location of the instrument within the luminal network is further in response to determining that the difference between the first physiological movement frequency and the second physiological movement frequency is less than the threshold difference.

9. The system of claim **7**, wherein the one or more location sensors comprise at least one of: an electromagnetic

(EM) sensor, a shape-sensing fiber, robot command data, and a radiation-based image sensor.

10. The system of claim **7**, wherein the physiological movement comprises at least one of a respiration of the patient or a heart rate of the patient.

11. The system of claim **1**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

identify a set of backtracked locations of the set of points in the first image data via backtracking the set of points from the second image data to the first image data,

compare the set of backtracked locations to the set of first locations,

identify a sub-set of points in the set of points for which the backtracked locations are not within a threshold distance of the set of first locations, and

remove the sub-set of points from the set of points.

12. The system of claim **1**, wherein the first set of locations and the second set of locations comprise two-dimensional (2D) information indicative of the respective locations of the points with respect to a coordinate system of the first image data and the second image data.

13. The system of claim **1**, wherein the memory further has stored thereon computer-executable instructions to cause the set of processors to:

extract depth information for the set of points from the first image data, and

extract depth information for the set of points from the second image data,

wherein the first set of locations and the second set of locations comprise three-dimensional (3D) information indicative of the respective locations of the points determined based on depth information extracted from each of the first image data and second image data.

14. A non-transitory computer readable storage medium having stored thereon instructions that, when executed, cause at least one computing device to:

receive first image data from an image sensor located on an instrument, the instrument configured to be driven through a luminal network of a patient;

detect a set of one or more points of interest the first image data;

identify a set of first locations respectively corresponding to the set of points in the first image data;

receive second image data from the image sensor;

detect the set of one or more points in the second image data;

identify a set of second locations respectively corresponding to the set of points in the second image data; and

based on the set of first locations and the set of second locations, detect a change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument.

15. The non-transitory computer readable storage medium of claim **14**, wherein:

the set of first locations and the set of second locations respectively define two-dimensional (2D) locations of the points within the first image data and the second image data.

16. The non-transitory computer readable storage medium of claim **15**, wherein the non-transitory computer readable storage medium further has stored thereon instructions that, when executed, cause the at least one computing device to:

group the set of points into a plurality of pairs of points, a first pair of points comprising a first point and a second point;

determine a first distance between the first point and the second point in the first image data based on the set of first locations; and

determine a second distance between the first point and the second point in the second image data based on the set of second locations,

wherein detecting the change of location of the instrument within the luminal network is further based on the first distance and the second distance.

17. The non-transitory computer readable storage medium of claim **16**, wherein the non-transitory computer readable storage medium further has stored thereon instructions that, when executed, cause the at least one computing device to:

determine a first scale change estimate for the first pair of points based on the first distance and the second distance; and

determine a scale change value representative of the scale change between the first image data and the second image data based on the scale change estimate,

wherein detecting the change of location of the instrument within the luminal network is further based on the scale change value.

18. The non-transitory computer readable storage medium of claim **17**, wherein the non-transitory computer readable storage medium further has stored thereon instructions that, when executed, cause the at least one computing device to:

determine a set of scale change estimates respectively corresponding to the pairs of points; and

determine the scale change value based on a median value of the set of scale change estimates or an average value of the set of scale change estimates.

19. The non-transitory computer readable storage medium of claim **14**, wherein the non-transitory computer readable storage medium further has stored thereon instructions that, when executed, cause the at least one computing device to:

track cumulative changes to a scale change value representative of a scale change in image data received from the image sensor over a first time period;

transform the tracked scale change value into a frequency domain; and

identify at least one harmonic in the tracked scale change value in frequency domain,

wherein detecting the change of location of the instrument within the luminal network is further based on the at least one harmonic.

20. The non-transitory computer readable storage medium of claim **14**, wherein the non-transitory computer readable storage medium further has stored thereon instructions that, when executed, cause the at least one computing device to:

determine a location of the instrument based on data received from one or more location sensors;

determine a first physiological movement frequency of the patient based on the set of first locations and the set of second locations, wherein detecting the change of location of the instrument within the luminal network is further based on the first physiological movement frequency; and

provide an indication of the detected change of location of the instrument within the luminal network to a display.

21. The non-transitory computer readable storage medium of claim **20**, wherein the non-transitory computer readable

storage medium further has stored thereon instructions that, when executed, cause the at least one computing device to:

determine a second physiological movement frequency of the patient based on the data received from the one or more location sensors; and

determine that a difference between the first physiological movement frequency and the second physiological movement frequency is less than a threshold difference,

wherein detecting the change of location of the instrument within the luminal network is further in response to determining that the difference between the first physiological movement frequency and the second physiological movement frequency is less than the threshold difference.

22. The non-transitory computer readable storage medium of claim **20**, wherein the physiological movement comprises at least one of a respiration of the patient or a heart rate of the patient.

23. The non-transitory computer readable storage medium of claim **14**, wherein the non-transitory computer readable storage medium further has stored thereon instructions that, when executed, cause the at least one computing device to:

extract depth information for the set of points from the first image data; and

extract depth information for the set of points from the second image data,

wherein the first set of locations and the second set of locations comprise three-dimensional (3D) information indicative of the respective locations of the points determined based on depth information extracted from each of the first image data and second image data.

24. A method for detecting a change of location of an instrument, comprising:

receiving first image data from an image sensor located on the instrument, the instrument configured to be driven through a luminal network of a patient;

detecting a set of one or more points of interest the first image data;

identifying a set of first locations respectively corresponding to the set of points in the first image data;

receiving second image data from the image sensor;

detecting the set of one or more points in the second image data;

identifying a set of second locations respectively corresponding to the set of points in the second image data; and

based on the set of first locations and the set of second locations, detecting the change of location of the instrument within the luminal network caused by movement of the luminal network relative to the instrument.

25. The method of claim **24**, wherein:

the set of first locations and the set of second locations respectively define two-dimensional (2D) locations of the points within the first image data and the second image data.

26. The method of claim **25**, further comprising:

grouping the set of points into a plurality of pairs of points, a first pair of points comprising a first point and a second point;

determining a first distance between the first point and the second point in the first image data based on the set of first locations; and

determining a second distance between the first point and the second point in the second image data based on the set of second locations,

wherein detecting the change of location of the instrument within the luminal network is further based on the first distance and the second distance.

27. The method of claim **26**, further comprising:

determining a first scale change estimate for the first pair of points based on the first distance and the second distance; and

determining a scale change value representative of the scale change between the first image data and the second image data based on the scale change estimate,

wherein detecting the change of location of the instrument within the luminal network is further based on the scale change value.

28. The method of claim **27**, further comprising:

determining a set of scale change estimates respectively corresponding to the pairs of points; and

determining the scale change value based on a median value of the set of scale change estimates or an average value of the set of scale change estimates.

29. The method of claim **24**, further comprising:

tracking cumulative changes to a scale change value representative of a scale change in image data received from the image sensor over a first time period;

transforming the tracked scale change value into a frequency domain; and

identifying at least one harmonic in the tracked scale change value in frequency domain,

wherein detecting the change of location of the instrument within the luminal network is further based on the at least one harmonic.

30. The method of claim **24**, further comprising:

determining a location of the instrument based on data received from one or more location sensors;

determining a first physiological movement frequency of the patient based on the set of first locations and the set of second locations, wherein detecting the change of location of the instrument within the luminal network is further based on the first physiological movement frequency; and

providing an indication of the detected change of location of the instrument within the luminal network to a display.

* * * * *

专利名称(译)	用于检测生理噪声的腔网络导航的机器人系统和方法		
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[标]发明人	YE MENGLONG UMMALANENI RITWIK RAFII TARI HEDYEH NOONAN DAVID PAUL		
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IPC分类号	A61B1/00 G06T7/73 G06T7/55 G06T7/262 G06T7/246 A61B1/005 A61B34/00 A61B5/06 A61B1/267 A61B5/00		
CPC分类号	A61B5/7285 G06T7/55 A61B2034/742 G06T2207/30061 A61B1/0057 A61B1/2676 G06T7/248 A61B1/00048 G06T7/262 A61B5/062 G06T7/74 A61B1/00149 A61B34/74 A61B1/00009 G06T2207/10068 A61B1/00006 A61B1/0016 A61B1/0055 A61B1/018 A61B1/05 A61B1/0676 A61B1/0684 A61B34/20 A61B34/30 A61B34/37 A61B34/70 A61B34/76 A61B2034/2051 A61B2034/301 A61B2034/303 A61B2034/744 A61B2090/364 G06T7/246 G06T7/73		
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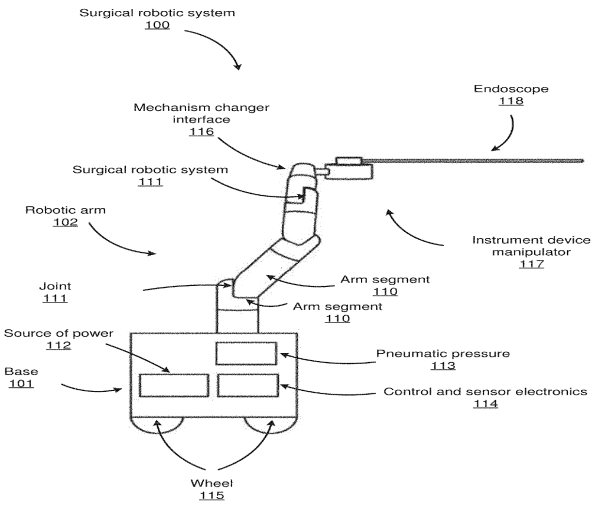
摘要(译)

提供用于检测生理噪声的用于管腔网络导航的机器人系统和方法。 在一个方面，该系统包括一个或多个处理器的集合，其被配置为从位于仪器上的图像传感器接收第一和第二图像数据，检测第一图像数据的一个或多个兴趣点的集合，并识别一个集合。 第一位置和第二位置的集合分别对应于第一和第二图像数据中的点集合。 处理器组还被配置为基于第一位置组和第二位置组，检测基于管腔网络相对于仪器的运动引起的仪器在管腔网络内的位置变化。 第一位置和第二位置集合。