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Catheters with control modes for interchangeable probes

Abstract

A medical system including a catheter, a sheath, and a control system. The catheter includes a lumen, a distal steerable segment, and a distal tip. The sheath is disposed within the lumen of the catheter and the sheath is extendable from the distal tip of the catheter. The control system is coupled to the catheter and includes a memory operable to store desired position coordinates and a plurality of modes including a stiffening mode in which the control system actively maintains the distal tip at the desired position coordinates.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This patent application is a continuation of U.S. patent application Ser. No. 16/283,039, filed Feb. 22, 2019, which is a continuation of U.S. patent application Ser. No. 13/274,198, filed Oct. 14, 2011, both of which are incorporated by reference herein in their entireties. U.S. patent application Ser. No. 13/274,198 is related to and incorporates by reference the following patent applications: U.S. patent application Ser. No. 13/274,208; U.S. patent application Ser. No. 13/274,229; U.S. Pat. App. No. 13/274,237, all filed on Oct. 14, 2011, which are also incorporated by reference herein in their entireties.

BACKGROUND

(1) Medical devices that navigate body lumens need to be physically small enough to fit within the lumen. Lung catheters, for example, which may be used to perform minimally invasive lung biopsies or other medical procedures, may need to follow airways that decrease in size as the catheter navigates branching passages. To reach a target location in a lung, a catheter may need to follow passages having diameters as small as 3 mm or less. Manufacturing a catheter that includes the mechanical structures suitable for remote or robotic operation and that has a diameter that is sufficiently small to navigate such small lumens can be challenging. In particular, one desirable configuration for remotely operated catheter would provide a tool mounted on a flexible distal tip; tendons or pull wires that extend down the length of the catheter to an

external drive system that pulls on the tendons to actuate the tool or distal tip; lumens for suction and/or irrigation; a vision system for viewing of the target location; and sensors to identify the location of the instrument relative to a patient's body. Accommodating all of the desired features and elements of a lung catheter or other device having a diameter about 3 mm or less can be difficult.

SUMMARY

(2) In accordance with an aspect of the invention, a catheter control system has a control mode (sometimes referred to herein as a holding mode) that actively maintains the catheter in a working configuration desired for a medical procedure. This holding mode facilitates use of the catheter system with interchangeable probes. In particular, a vision probe can be deployed in the catheter while the catheter navigates to a work site, to view the work site, or to assist in identifying the desired working configuration for the catheter during performance of a medical task. The catheter control system can then switch into the holding mode, and the vision system can be removed. A medical probe can then be deployed through the catheter in place of the removed vision probe, and the control system maintains the working configuration and allows performance of a medical task without the vision probe, while the desired working configuration is fixed and held. In one implementation, the control system actively keeps the catheter in the desired working configuration while the medical probe is inserted through the catheter, reaches the work site, and performs a medical function. In an alternative implementation, the control system returns the catheter to the recorded working configuration before the medical function is performed. Since the catheter only needs to accommodate the vision or medical probe and not both, the diameter of the catheter may be smaller than might otherwise be possible for a convention system that provides similar functionality.

(3) In accordance with another aspect of the invention, a feedback control method and system for a robotically controlled flexible device implements multiple different modes of closed-loop device actuation or stiffening for different applications and usage scenarios. The different stiffening modes can cause the device to respond in a desired way in case of externally applied forces, for example, tissue reaction forces as the device navigates through a clinical space or as the device interacts with tissue as part of a medical procedure. Details concerning feedback control methods and systems for robotically controlled flexible devices may be found in U.S. patent application Ser. No. 12/780,417 (filed May 14, 2010; disclosing “Drive Force Control in Medical Instrument Providing Position Measurements”) and in U.S. patent application Ser. No. 12/945,734 (filed Nov. 12, 2010; disclosing “Tension Control in Actuation of Multijoint Medical Instrument”), both of which are incorporated herein by reference.

(4) In one embodiment, a flexible device such as a catheter uses real-time feedback from a sensor system in generation of signals for actuators attached to tendons that are used to articulate a distal portion of the device. For example, a catheter may include a flexible section at its distal tip that can bend in two directions (pitch and yaw). A fiber-optic shape sensor can measure the bending of the flexible section and return measurement data indicating the position and orientation of the distal tip relative to a base of the shape sensed. The position of the base may be determined, for example, using electromagnetic sensors that provide measurements of a position and orientation of the base relative to an external reference that may be attached to a patient. Multiple actuation tendons (e.g., pull wires or cables) attach to the distal tip and run along the length of the catheter to the actuators. Control logic that controls the actuators to pull the tendons and hence move the distal tip in any pitch/yaw direction can operate in different modes for different purposes. In particular, for a holding mode, the control logic can use the sensor data and fixed information on a target shape of the catheter to compute control signals for the actuators.

(5) The control logic for a robotic catheter or other flexible system may have multiple modes of operation including one or more of the following: 1.) A position stiffness mode in which the control system controls actuators to minimize a difference between desired and measured positions of the distal tip of the catheter or probe; 2.) An orientation stiffness mode in which the control system controls the actuators to minimize a difference between desired and measured pointing directions of the distal tip; 3.) A target position stiffness mode in which the control system uses a combination of the measured tip position and pointing direction to control the distal tip to always point towards a specified target point; and 4.) A target axial motion stiffness mode in which the control system uses a combination of the measured tip position and pointing direction, together with sensor measurements from other parts of the device, and controls actuators to ensure that the distal tip is positioned on a specific line in space and has a pointing direction also along that line. The selection of which of the available modes the control system uses can be made through user selection, according to the type of probe being used (e.g. forceps, camera, laser, brush, or needle), or according to the

action the catheter is performing (e.g., navigating or performing a biopsy). Any of these modes can be used to hold the catheter for a medical procedure by fixing the desired location, direction, target point, or line.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1 shows a robotic catheter system in accordance with an embodiment of the invention having multiple control modes.
- (2) FIG. 2 shows an embodiment of an actuated distal tip that can be employed in the system of FIG. 1.
- (3) FIGS. 3A and 3B show cross-sectional views of proximal and distal sections of a catheter in accordance with an embodiment of the invention.
- (4) FIG. 4 shows a cross-sectional view of a vision probe that may be deployed in the catheter of FIGS. 3A and 3B and swapped out for use of medical probes in the catheter shown in FIGS. 3A and 3B.
- (5) FIG. 5 is a flow diagram of a process for using the catheter system with a removable vision system and multiple control modes.
- (6) FIG. 6 is a flow diagram of a catheter control process in a steering mode.
- (7) Use of the same reference symbols in different figures indicates similar or identical items.

DETAILED DESCRIPTION

(8) A catheter system can employ a vision probe that is interchangeable with one or more medical probes or tools. The vision probe can be removed and replaced with a medical probe used in a medical procedure. The interchanging of the vision and medical probes may permit the catheter system to have a smaller diameter and thus navigate smaller passages than would a similar system that simultaneously accommodates both vision and medical systems. Alternatively, interchanging probes allow more space for vision and medical systems having greater functionality than might a catheter that must simultaneously accommodate both vision and medical systems.

(9) One method for using a catheter system includes steering a catheter along a body lumen for at least part of the path to a work site for a medical procedure. A vision system may then be deployed in the catheter during the steering and/or used to view the work site reached when navigation is complete. The vision system can also be used to help identify a desired working configuration for the catheter and when manipulating the catheter into the desired working configuration. The control system of the catheter can then record the working configuration and may be placed in a “holding” mode in which the pose of the catheter relative to a patient is monitored and the catheter is actuated to actively maintain or return to the recorded working configuration. The control system may provide different types of control modes, which may be useful for different types of medical probes or different types of medical procedures. For example, if the medical probe includes a laser, a combination of the location and orientation of the distal tip of the catheter can be controlled so that the distal tip remains targeted on a specific location in the patient. An alternative holding mode can maintain the location of the distal tip of the catheter while permitting the orientation of the distal tip to change or maintain a distal tip along a line.

(10) FIG. 1 schematically illustrates a catheter system **100** in accordance with one embodiment of the invention. In the illustrated embodiment, catheter system **100** includes a catheter **110**, a drive interface **120**, control logic **140**, an operator interface **150**, and a sensor system **160**.

(11) Catheter **110** is a generally flexible device having one or more lumens including a main lumen that can accommodate interchangeable probes such as described further below. Flexible catheters can be made using a braided structure such as a woven wire tube with inner or outer layers of a flexible or low friction material such as polytetrafluoroethylene (PTFE). In one embodiment, catheter **110** includes a bundle of lumens or tubes held together by a braided jacket and a reflowed (i.e., fused by melting) jacket of a material such as Polyether Block Amide (Pebax). An additional tip section (e.g., a metal structure such as shown in FIG. 2 and described further below) can be attached at the distal end of catheter **110**. Alternatively, an extrusion of a material such as Pebax can similarly be used to form multiple lumens in catheter **110**. Catheter **110** particularly includes a main lumen for interchangeable probe systems and smaller lumens for pull wires and sensor lines. In the illustrated embodiment, catheter **110** has a proximal section **112** attached to drive interface **120** and a distal section **114** that extends from the proximal section **112**. Pull wires extend from drive system **120** through proximal section **112** and distal section **114** and connect to a steerable distal steerable segment **116**.

(12) The overall length of catheter **110** may be about 60 to 80 cm or longer with distal section **114** being about 15 cm long and steerable segment **116** being about 4 to 5 cm long. In accordance with an aspect of the invention, distal section **114** has a smaller diameter than does proximal section **112** and thus can navigate smaller natural lumens or passages. During a medical procedure, at least a portion of proximal section **112** and all of distal section **114** may be inserted along a natural lumen such as an airway of a patient. The smaller diameter of distal section **114** permits use of distal section **114** in lumens that may be too small for proximal section **112**, but the larger diameter of distal section **114** facilitates inclusion of more or larger structures or devices such as electromagnetic (EM) sensors **162** that may not fit in distal section **114**.

(13) Steerable segment **116** is remotely controllable and particularly has a pitch and a yaw that can be controlled using pull wires. Steerable segment **116** may include all or part of distal section **114** and may be simply implemented as a multi-lumen tube of flexible material such as Pebax. In general, steerable segment **116** is more flexible than the remainder of catheter **110**, which assists in isolating actuation or bending to steerable segment **116** when drive interface **120** pulls on actuating tendons. Catheter **110** can also employ additional features or structures such as use of Bowden cables for actuating tendons to prevent actuation from bending proximal section **112** (or bending any portion the section of **114** other than steerable segment **116**) of catheter **110**. FIG. 2 shows one specific embodiment in which steerable segment **116** is made from a tube **210** that in catheter **110** of FIG. 1 contains multiple tubes defining a main lumen for a probe system and smaller lumens for actuation tendons **230** and a shape sensor not shown in FIG. 2. In the illustrated embodiment, tendons **230** are placed 90° apart surrounding lumen **312** to facilitate steering catheter **110** in pitch and yaw directions defined by the locations of tendons **230**. A reflowed jacket, which is not shown in FIG. 2 to better illustrate the internal structure of steerable segment **116**, may also cover tube **210**. As shown in FIG. 2, tube **210** is cut or formed to create a series of flexures **220**. Tendons **230** connect to a distal tip **215** of steerable segment **116** and extend back to a drive interface **120**. Tendons **230** can be wires, cables, Bowden cables, hypotubes, or any other structures that are able to transfer force from drive interface **120** to distal tip **215** and limit bending of proximal section **112** when drive interface **120** pulls on tendons **230**. In operation, pulling harder on any one of tendons **230** tends to cause steerable segment **116** to bend in the direction of that tendon **230**. To accommodate repeated bending, tube **210** may be made of a material such as Nitinol, which is a metal alloy that can be repeatedly bent with little or no damage.

(14) Drive interfaces **120** of FIG. 1, which pulls on tendons **230** to actuate distal steerable segment **116**, includes a mechanical system or transmission **124** that converts the movement of actuators **122**, e.g., electric motors, into movements of (or tensions in) tendons **230** that run through catheter **110** and connect to distal steerable segment **116**. (Push rods could conceivably be used in catheter **110** instead of pull wires but may not provide a desirable level of flexibility.) The movement and pose of distal steerable segment **116** can thus be controlled through selection of drive signals for actuators **122** in drive interface **120**. In addition to manipulating tendons **230**, drive interface **120** may also be able to control other movement of catheter **110** such as range of motion in an insertion direction and rotation or roll of the proximal end of catheter **110**, which may also be powered through actuators **122** and transmission **124**. Backend mechanisms or transmissions that are known for flexible-shaft instruments could in general be used or modified for drive interface **120**. For example, some known drive systems for flexible instruments are described in U.S. Pat. App. Pub. No. 2010/0331820, entitled “Compliant Surgical Device,” which is hereby incorporated by reference in its entirety. Drive interface **120** in addition to actuating catheter **110** should allow removal and replacements of probes in catheter **110**, so that the drive structure should be out of the way during such operations.

(15) A dock **126** in drive interface **120** can provide a mechanical coupling between drive interface **120** and catheter **110** and link actuation tendons to transmission **124**. Dock **126** may additionally contain electronics for receiving and relaying sensor signals from portions of sensor system **160** in catheter **110** and an electronic or mechanical system for identifying the probe or the type of probe deployed in catheter **110**.

(16) Control logic **140** controls the actuators in drive interface **120** to selectively pull on the tendons as needed to actuate and steer distal steerable segment **116**. In general, control logic **140** operates in response to commands from a user, e.g., a surgeon or other medical personnel using operator interface **150**, and in response to measurement signals from sensor system **160**. However, in holding modes as described further below, control logic **140** operates in response to measurement signals from sensor system **160** to maintain or acquire a previously identified working configuration. Control logic **140** may be implemented using a

general purpose computer with suitable software, firmware, and/or interface hardware to interpret signals from operator interface **150** and sensor system **160** and to generate control signals for drive interface **120**.

(17) In the illustrated embodiment, control logic **140** includes multiple modules **141**, **142**, **143**, and **144** that implement different processes for controlling the actuation of catheter **110**. In particular, modules **141**, **142**, **143**, and **144** respectively implement a position stiffening mode, an orientation stiffening mode, a target position mode, and a target axial mode, which are described further below. A module **146** selects which control process will be used and may base the selection on user input, the type or status of the probe deployed in catheter **110**, and the task being performed. Control logic **140** also includes memory storing parameters **148** of a working configuration of distal steerable segment **116** that is desired for a task, and each of the modules **141**, **142**, **143**, and **144** can use their different control processes to actively maintain or hold the desired working configuration.

(18) Operator interface **150** may include standard input/output hardware such as a display, a keyboard, a mouse, a joystick, or other pointing device or similar I/O hardware that may be customized or optimized for a surgical environment. In general, operator interface **150** provides information to the user and receives instructions from the user. For example, operator interface **150** may indicate the status of system **100** and provide the user with data including images and measurements made by system **100**. One type of instruction that the user may provide through operator interface **150**, e.g., using a joystick or similar controller, indicates the desired movement or position of distal steerable segment **116**, and using such input, control logic **140** can generate control signals for actuators in drive interface **120**. Other instructions from the user can select an operating mode of control logic **140**.

(19) Sensor system **160** generally measures a pose of distal steerable segment **116**. In the illustrated embodiment, sensor system **160** includes EM sensors **162** and a shape sensor **164**. EM sensors **162** include one or more conductive coils that may be subjected to an externally generated electromagnetic field. Each coil of EM sensors **162** then produces an induced electrical signal having characteristics that depend on the position and orientation of the coil relative to the externally generated electromagnetic field. In an exemplary embodiment, EM sensors **162** are configured and positioned to measure six degrees of freedom, e.g., three position coordinates X, Y, and Z and three orientation angles indicating pitch, yaw, and roll of a base point. The base point in system **100** is at or near the end of proximal section **112** and the start of distal section **114** of catheter **110**. Shape sensor **164** in the exemplary embodiment of the invention includes a fiber grating that permits determination of the shape of a portion of catheter **110** extending from the base point, e.g., the shape of distal section **114** or distal steerable segment **116**. Such shape sensors using fiber gratings are further described in U.S. Pat. No. 7,720,322, entitled "Fiber Optic Shape Sensor," which is hereby incorporated by reference in its entirety. An advantage of the illustrated type of sensor system **160** is that EM sensors **162** can provide measurements relative to the externally generated electrical field, which can be calibrated relative to a patient's body. Thus, system **160** can use EM sensors **162** to reliably measure the position and orientation of a base point for shape sensor **164**, and shape sensor **164** need only provide shape measurement for a relatively short distance. Additionally, distal section **114** only contains shape sensor **164** and may have a diameter that is smaller than the diameter of proximal section **112**. More generally, sensor system **160** need only be able to measure the pose of distal steerable segment **116**, and other types of sensors could be employed.

(20) FIGS. 3A and 3B respectively show cross-sections of the proximal and distal sections **112** and **114** of catheter **110** in one embodiment of the invention. FIG. 3A shows an embodiment of catheter **110** having a body **310** that includes a main lumen **312** for a vision or medical probe, lumens **314** containing tendons **230**, lumens **316** containing EM sensors **162** or associated signal wires, and a lumen **318** containing a fiber shape sensor **164**. Main lumen **312**, wire lumens **314**, and a shape sensor lumen **318** extend into distal section **114** as shown in FIG. 3B, but lumens **316** for EM sensors **162** are not needed in distal section **114** because EM sensors **162** are only in proximal section **112**. Accordingly, distal section **114** can be smaller than proximal section **112**. In an exemplary embodiment, body **310** in proximal section **112** has an outer diameter of about 4 mm (e.g., in a range from 3 to 6 mm) and provides main lumen **312** with a diameter of about 2 mm (e.g., in a range from 1 to 3 mm) and in distal section **114** has an outer diameter of about 3 mm (e.g., in a range from 2 to 4 mm) while maintaining the diameter of main lumen **312** at about 2 mm. A smooth taper (as shown in FIG. 1) or an abrupt step in body **310** can be used at the transition from the larger diameter of proximal section **112** to the smaller diameter of distal section **116**.

(21) The specific dimensions described in above are primarily for a catheter that accommodates probes

having a diameter of about 2 mm, which is a standard size for existing medical tools such as lung biopsy probes. However, alternative embodiments of the invention could be made larger or smaller to accommodate medical probes with a larger or smaller diameter, e.g., 1 mm diameter probes. A particular advantage of such embodiments is that a high level of functionality is provided in a catheter with relative small outer diameter when compared to the size of probe used in the catheter.

(22) FIGS. 3A and 3B also show a sheath **360** that may be employed between catheter body **310** and a probe in main lumen **312**. In one embodiment of catheter **110**, sheath **360** is movable relative to body **310** can be extended beyond the end of distal steerable segment **116**. This may be advantageous in some medical procedures because sheath **360** is even smaller than distal section **114** and therefore may fit into smaller natural lumens or passages. For example, if catheter **110** reaches a branching of lumens that are too small to accommodate distal steerable segment **116**, distal steerable segment **116** may be pointed in the direction of the desired branch, so that sheath **360** can be pushed beyond the end of distal steerable segment **116** and into that branch. Sheath **360** could thus reliably guide a medical probe into the desired branch. However, sheath **360** is passive in that it is not directly actuated or steerable. In contrast, distal section **116** accommodates pull wires **230** that connect to distal steerable segment **116** and can be manipulated to steer or pose distal steerable segment **116**. In some medical applications, the active control of distal steerable segment **116** is desirable or necessary during a medical procedure, and passive sheath **360** may not be used in some embodiments of the invention.

(23) Main lumen **312** is sized to accommodate a variety of medical probes. One specific probe is a vision probe **400** such as illustrated in FIG. 4. Vision probe **400** has a flexible body **410** with an outer diameter (e.g., about 2 mm) that fits within the main lumen of catheter **110** and with multiple inner lumens that contain the structures of vision probe **400**. Body **410** may be formed using an extruded flexible material such as Pebax, which allows creation of multiple lumens. In the illustrated embodiment, the structure of vision probe **400** includes a CMOS camera **420**, which is at the distal end of the probe and connected through one or more signal wires (not shown) that extend along the length of vision probe **400**, e.g., to provide a video signal to control logic **140** or operator interface **150** as shown in FIG. 1. Vision probe **400** also includes illumination fibers **430** that provide light for imaging within a body lumen and fluid ports **326** for suction and irrigation that may be useful, for example, for rinsing of a lens of camera **420**. Additionally, vision probe **400** may include an electromagnetic sensor (not shown) embedded just proximally to camera **420** to provide additional pose information about the tip of vision probe **400**.

(24) Vision probe **400** is adapted to be inserted or removed from catheter **110** while catheter **110** is in use for a medical procedure. Accordingly, vision probe **400** is generally free to move relative to catheter **110**. While movement relative to catheter **110** is necessary or desirable during insertion or removal of vision probe **400**, the orientation of a vision probe **400** (and some medical probes) may need to be known for optimal or easier use. For example, a user viewing video from vision probe **400** and operating a controller similar to a joystick to steer catheter **110** generally expects the directions of movement of the controller to correspond to the response of distal steerable segment **116** and the resulting change in the image from vision probe **400**. Operator interface **150** needs (or at least can use) information on the orientation of vision probe **400** relative to tendons **230** in order to provide a consistency in directions used in the user interface. In accordance with an aspect of the invention, a keying system (not shown) can fix vision probe **400** into a known orientation relative to catheter **110** and tendons **230**. The keying system may, for example, include a spring, fixed protrusion, or latch on vision probe **400** or distal steerable segment **116** and a complementary notch or feature in distal steerable segment **116** or vision probe **400**.

(25) Vision probe **400** is only one example of a probe system that may be deployed in catheter **110** or guided through catheter **110** to a work site. Other probe systems that may be used include, but are not limited to, biopsy forceps, biopsy needles, biopsy brushes, ablation lasers, and radial ultrasound probes. In general, catheter **110** can be used with existing manual medical probes that are commercially available from medical companies such as Olympus Europa Holding GmbH.

(26) The catheter system **100** of FIG. 1 can be used in procedures that swap a vision probe and a medical probe. FIG. 5 is a flow diagram of one embodiment of a process **500** for using the catheter system **100** of FIG. 1. In process **500**, vision probe **400** is deployed in catheter **110** in step **510**, and catheter **110** is inserted along a path including a natural lumen of a patient. For example, for a lung biopsy, distal steerable segment **116** of catheter **110** may be introduced through the mouth of a patient into the respiratory tract of the patient. Vision probe **400** when fully deployed in catheter **110** may fit into a keying structure that keeps

vision probe **400** in a desired orientation at or even extending beyond distal steerable segment **116** to provide a good forward view from the distal steerable segment **116** of catheter **110**. As noted above, distal steerable segment **116** of catheter **110** is steerable, and vision probe **320** can provide video of the respiratory tract that helps a user when navigating catheter **110** toward a target work site. However, use of vision probe **400** during navigation is not strictly necessary since navigation of catheter **110** may be possible using measurements of sensor system **160** or some other system with or without vision probe **400** being deployed or used in catheter **110**. The path followed to the work site may be entirely within natural lumens such as the airways of the respiratory track or may pierce and pass through tissue at one or more points.

(27) When steerable segment **116** reaches the target work site, vision probe **400** can be used to view the work site as in step **530** and to pose steerable segment **116** for performance of a task at the target work site as in step **540**. Posing of steerable segment **116** may use images or visual information from vision probe **400** and measurements from sensor system **160** to characterize the work site and determine the desired working configuration. The desired working configuration may also depend on the type of tool that will be used or the next medical task. For example, reaching a desired working configuration of catheter **110** may bring the distal tip of steerable segment **116** into contact with tissue to be treated, sampled, or removed with a medical tool that replaces vision probe **400** in catheter **110**. Another type of working configuration may point steerable segment **116** at target tissue to be removed using an ablation laser. For example, tissue could be targeted in one or more 2D camera views while vision probe **400** is still in place in catheter **110**, or target tissue can be located on a virtual view of the work site using pre-operative 3D imaging data together with the position sensing relative to patient anatomy. Still another type of working configuration may define a line for the insertion of a needle or other medical tool into tissue, and the working configuration includes poses in which the distal tip of steerable segment **116** is along the target line. In general, the desired working configuration defines constraints on the position or the orientation of the distal tip of steerable segment **116**, and the shape of more proximal sections of catheter **110** is not similarly constrained and may vary as necessary to accommodate the patient.

(28) Step **550** stores in memory of the control logic parameters that identify the desired working configuration. For example, the position of a distal tip or target tissue can be defined using three coordinates. A target line for a need can be defined using the coordinates of a point on the line and angles indicating the direction of the line from that point. In general, control logic **120** uses the stored parameters that define the desired working configuration when operating in a holding mode that maintains distal steerable segment **116** of catheter **110** in the desired working configuration as described further below.

(29) Step **560** selects and activates a holding mode of the catheter system after the desired working configuration has been established and recorded. Control logic **140** for catheter **110** of FIG. **1** may have one or more modules **141**, **142**, **143**, and **144** implementing multiple stiffening modes that may be used as holding modes when the desired configuration of steerable segment **116** has fixed constraints. The available control modes may include one or more of the following. 1.) A position stiffness mode compares the position of the distal tip of steerable segment **116** as measured by sensor system **160** to a desired tip position and controls the actuators to minimize the difference in desired and measured tip positions. The position stiffness mode may particularly be suitable for general manipulation tasks in which the user tries to precisely control the position of the tip and for situations where the distal tip contacts tissue. 2.) An orientation stiffness mode compares the measured orientation or pointing direction of the distal tip to a desired pointing direction of the distal tip and controls the actuators to minimize the difference in desired and actual tip pointing direction. This orientation stiffening that may be suitable, e.g., when controlling an imaging device such as vision probe **400** attached steerable segment **116**, in which case the viewing direction is kept as desired, while the exact position of steerable segment **116** may be less important. 3.) A target position stiffness mode uses a combination of the measured tip position and pointing direction to control catheter **110** to always point the distal tip of steerable segment **116** towards a specified target point some distance in front of steerable segment **116**. In case of external disturbances, control logic **140** may control the actuators to implement this target position stiffening behavior, which may be suitable, e.g., when a medical probe inserted though the catheter contains an ablation laser that should always be aimed at a target ablation point in tissue. 4.) A target axial motion stiffness mode uses a combination of the measured tip position and pointing direction to ensure that the distal tip of steerable segment **116** is always on a line in space and has a pointing direction that is also along that line. This mode can be useful, e.g., when inserting a biopsy needle along a specified line into tissue. Tissue reaction forces could cause the flexible

section of catheter **110** to bend while inserting the needle, but this control strategy would ensure that the needle is always along the right line.

(30) The selection of a mode in step **560** could be made through manual selection by the user, based on the type of probe that is being used (e.g., grasper, camera, laser, or needle) in catheter **110**, or based on the activity catheter **110** is performing. For example, when a laser is deployed in catheter **110**, control logic **120** may operate in position stiffness mode when the laser deployed in catheter **110** is off and operate in target position stiffness mode to focus the laser on a desired target when the laser is on. When “holding” is activated, control logic **140** uses the stored parameters of the working configuration (instead of immediate input from operator interface **150**) in generating control signals for drive interface **120**.

(31) The vision probe is removed from the catheter in step **570**, which clears the main lumen of catheter **110** for the step **580** of inserting a medical probe or tool through catheter **110**. For the specific step order shown in FIG. **5**, control logic **140** operates in holding mode and maintains distal steerable segment **116** in the desired working configuration while the vision system is removed (step **570**) and the medical probe is inserted (step **580**). Accordingly, when the medical probe is fully deployed, e.g., reaches the end of distal steerable segment **116**, the medical probe will be in the desired working configuration, and performance of the medical task as in step **590** can be then performed without further need or use of the removed vision probe. Once the medical task is completed, the catheter can be taken out of holding mode or otherwise relaxed so that the medical probe can be removed. The catheter can then be removed from the patient if the medical procedure is complete, or the vision or another probe can be inserted through the catheter if further medical tasks are desired.

(32) In one alternative for the step order of process **500**, catheter **110** may not be in a holding mode while the medical probe is inserted but can be switched to holding mode after the medical probe is fully deployed. Once holding mode is initiated, control logic **140** will control the drive interface **130** to return distal steerable segment **116** to the desired working configuration if distal steerable segment **116** has moved since being posed in the desired working configuration. Thereafter, control logic **140** monitors the pose of distal steerable segment **116** and actively maintains distal steerable segment **116** in the desired working configuration while the medical task is performed in step **590**.

(33) FIG. **6** shows a flow diagram of a process **600** of a holding mode that can be implemented in control logic **140** of FIG. **1**. Process **600** begins in step **610** with receipt of measurement signals from sensor system **160**. The particular measurements required depend on the type of holding mode being implemented, but as an example, the measurements can indicate position coordinates, e.g., rectangular coordinates X , Y , and Z , of the distal tip of steerable segment **116** and orientation angles, e.g., angles $\theta_{\text{sub}.X}$, $\theta_{\text{sub}.Y}$, and $\theta_{\text{sub}.Z}$ of a center axis of the distal tip of steerable segment **116** relative to coordinate axes X , Y , and Z . Other coordinate systems and methods for representing the pose of steerable segment **116** could be used, and measurements of all coordinates and direction angles may not be necessary. However, in an exemplary embodiment, sensor system **160** is capable of measuring six degrees of freedom (DoF) of the distal tip of steerable segment **116** and of providing those measurements to control logic **140** in step **610**.

(34) Control logic **140** in step **620** determines a desired pose of distal steerable segment **116**. For example, control logic **140** can determine desired position coordinates, e.g., X' , Y' , and Z' , of the end of distal steerable segment **116** and desired orientation angles, e.g., angles $\theta'_{\text{sub}.X}$, $\theta'_{\text{sub}.Y}$, and $\theta'_{\text{sub}.Z}$ of the center axis of distal steerable segment **116** relative to coordinate axes X , Y , and Z . The holding modes described above generally provide fewer than six constraints on the desired coordinates. For example, position stiffness operates to constrain three degrees of freedom, the position of the end of distal steerable segment **116** but not the orientation angles. In contrast, orientation stiffness mode constrains one or more orientation angles but not the position of end of distal steerable segment **116**. Target position stiffness mode constrains four degrees of freedom, and axial stiffness mode constrains five degrees of freedom. Control logic **610** can impose further constraints to select one of set of parameters, e.g., X' , Y' , and Z' and angles $\theta'_{\text{sub}.X}$, $\theta'_{\text{sub}.Y}$, and $\theta'_{\text{sub}.Z}$, that provides the desired working configuration. Such further constraints include but are not limited to mechanical constraints required by the capabilities of distal steerable segment **116** and of catheter **110** generally and utilitarian constraints such as minimizing movement of distal steerable segment **116** or providing desired operating characteristics such as smooth, non-oscillating, and predictable movement with controlled stress in catheter **110**. Step **620** possibly includes just keeping a set pose distal steerable segment **116** by finding smallest movement from the measured pose to a pose satisfying the constraints, e.g., finding the point on the target line closest to the measure position for axial

motion stiffness or finding some suitable pose from registered pre-op data that is close to the current pose. (35) Control logic **140** in step **630** uses the desired and/or measured poses to determine corrected control signals that will cause drive interface **120** to move distal steerable segment **116** to the desired pose. For example, the mechanics of catheter **110** and drive interface **120** may permit development of mappings from the desired coordinates X' , Y' , and Z' and angles $\theta'.sub.X$, $\theta'.sub.Y$, and $\theta'.sub.Z$ to actuator control signals that provide the desired pose. Other embodiments may use differences between the measured and desired pose to determine corrected control signals. In general, the control signals may be used not only to control actuators connected through tendons to distal steerable segment **116** but may also control (to some degree) insertion or roll of catheter **110** as a whole.

(36) A branch step **650** completes a feedback loop by causing process **600** to return to measurement step **610** after control system **140** applies new control signals drive interface **120**. The pose of distal tip is thus actively monitored and controlled according to fixed constraints as long as control system **120** remains in the holding mode. It may be noted, however, that some degrees of freedom of distal steerable segment **116** may not require active control. For example, in orientation stiffness mode, feedback control could actively maintain pitch and yaw of distal steerable segment **116**, while the mechanical torsional stiffness of catheter **110** is relied on to hold the roll angle fixed. However, catheter **110** in general may be subject to unpredictable external forces or patient movement that would otherwise cause catheter **110** to move relative to the work site, and active control as in process **600** is needed to maintain or hold the desired working configuration.

(37) Some embodiments or elements of the above invention can be implemented in a computer-readable media, e.g., a non-transient media, such as an optical or magnetic disk, a memory card, or other solid state storage containing instructions that a computing device can execute to perform specific processes that are described herein. Such media may further be or be contained in a server or other device connected to a network such as the Internet that provides for the downloading of data and executable instructions.

(38) Although the invention has been described with reference to particular embodiments, the description is only an example of the invention's application and should not be taken as a limitation. Various adaptations and combinations of features of the embodiments disclosed are within the scope of the invention as defined by the following claims.

Claims

1. A medical system comprising: a catheter comprising a lumen, a distal steerable segment, and a distal tip; a sheath disposed within the lumen of the catheter; and a control system coupled to the catheter, wherein the control system includes: a memory operable to store desired position coordinates; and a plurality of modes including a stiffening mode in which the control system actively maintains the distal tip at the desired position coordinates, wherein the sheath is extendable from the distal tip of the catheter while the control system actively maintains the distal tip at the desired position coordinates in the stiffening mode.
2. The medical system of claim 1, further comprising at least one sensor operable to determine measured position coordinates of the distal tip.
3. The medical system of claim 2, wherein the at least one sensor includes at least one electromagnetic sensor.
4. The medical system of claim 2, wherein during operation in the stiffening mode, the control system is configured to: receive the measured position coordinates of the distal tip; determine a difference between the measured position coordinates and the desired position coordinates; and without user input directing movement of the catheter, move the distal steerable segment to minimize a difference between the measured and desired position coordinates.
5. The medical system of claim 4, wherein during operation in the stiffening mode, the control system constrains three degrees of freedom of the distal tip.
6. The medical system of claim 4, wherein during operation in the stiffening mode, the control system constrains at least four degrees of freedom of the distal tip.
7. The medical system of claim 1, further comprising at least one sensor operable to determine a measured orientation angle of the distal tip.
8. The medical system of claim 7, wherein the at least one sensor includes an optical fiber shape sensor.
9. The medical system of claim 7, wherein the memory is further operable to store a desired orientation

angle of the distal tip, and wherein the control system is further operable to actively maintain the distal tip in the desired orientation angle during operation in the stiffening mode.

10. The medical system of claim 9, wherein during operation in the stiffening mode, the control system is further configured to: receive the measured orientation angle of the distal tip; determine a difference between the measured orientation angle and the desired orientation angle; and rotate the distal steerable segment to minimize a difference between the measured and desired orientation angles.

11. The medical system of claim 9, wherein during operation in the stiffening mode, the control system constrains three or more degrees of freedom of the distal tip.

12. The medical system of claim 1, wherein the plurality of modes further includes a mode in which the control system steers the catheter in response to commands received from an operator interface.

13. The medical system of claim 1, wherein the sheath is sized for extension into a natural passage during operation in the stiffening mode, the natural passage having a diameter less than an outer diameter of the catheter.

14. The medical system of claim 1, wherein the sheath comprises a passive sheath.

15. The medical system of claim 1, wherein the control system is configured to: steer the catheter to point in a direction of a natural passage, wherein the sheath is extendable into the natural passage after the catheter points in the direction of the natural passage.

16. The medical system of claim 1, further comprising at least one removable probe deployable through the lumen and the sheath.

17. The medical system of claim 16, wherein the at least one removable probe comprises a laser.

18. The medical system of claim 16, wherein the at least one removable probe comprises a biopsy needle.

19. The medical system of claim 16, wherein the at least one removable probe comprises a camera.
