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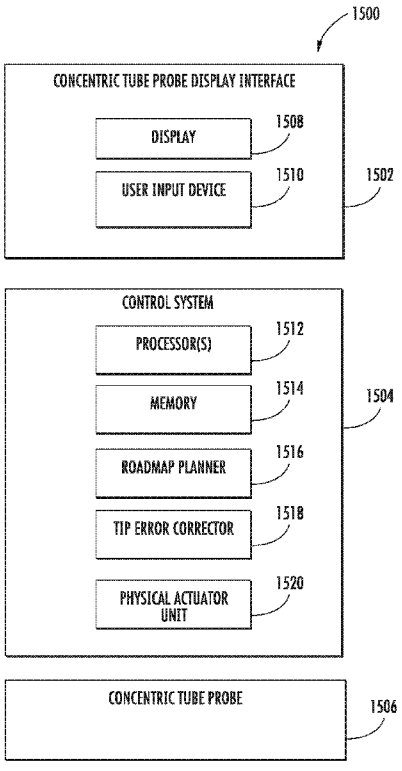

FIG. 8

(57) Abstract: Systems for controlling concentric tube probes are disclosed. In some examples, the system includes a concentric tube position display interface and a control system. The concentric tube display interface includes a display for displaying visual feedback to a user indicating a position (and possibly orientation) of a tip of a concentric tube probe and a user input device for receiving user input from the user designating a goal position (and possibly orientation) for the tip of the concentric tube probe. The control system is configured for interactive-rate motion planning of the concentric tube probe by creating, in real-time or near real-time, a motion plan to move the tip of the concentric tube probe to the goal position (and possibly orientation) while avoiding contact by the concentric tube probe with one or more obstacles and for configuring the concentric tube probe as specified by the motion plan.

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METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR CONTROLLING A CONCENTRIC TUBE PROBE

PRIORITY CLAIM

This application claims the benefit of U.S. Provisional Application Serial No. 62/165,656, filed May 22, 2015, the disclosure of which is incorporated herein by reference in its entirety. This application claims the benefit of U.S. Provisional Application Serial No. 62/165,648, filed May 22, 2015, the disclosure of which is incorporated herein by reference in its entirety.

GOVERNMENT INTEREST

This invention was made with government support under National Institutes of Health under Grant Nos. EB017467 and EB017952 and by the National Science Foundation under Award No. IIS-1149965. The government has certain rights in the invention.

TECHNICAL FIELD

This specification relates generally to systems for interactive-rate motion planning for concentric tube probes.

BACKGROUND

Concentric tube probes may enable new, safer minimally invasive surgical procedures by moving along curved paths to reach difficult-to-reach sites in a patient's anatomy. Operating these devices is challenging due to their complex, unintuitive kinematics and the need to avoid certain structures in the anatomy. Accordingly, there exists a need for interactive-rate motion planning for concentric tube probes.

SUMMARY

A system for controlling a concentric tube probe includes a concentric tube position (and possibly orientation) display interface and a control

system. The concentric tube display interface includes a display for displaying visual feedback to a user indicating a position (and possibly orientation) of a tip of a concentric tube probe and a user input device for receiving user input from the user designating a goal position (and possibly orientation) for the tip of the concentric tube probe. The concentric tube probe can include at least two concentric tubes configured so that translation and rotation of one of the tubes inside another of the tubes creates curvilinear motion of the concentric tube probe. The visual feedback can include position or both position and orientation. Similarly, the goal position can include a goal position or both a goal position and orientation.

The control system is configured for interactive-rate motion planning of the concentric tube probe. The control system can include a system of one or more computers configured for interactive-rate motion planning by virtue of appropriate instructions for the computers stored on one or more computer readable mediums. The control system can include a physical actuation unit for rotating and translating the curved tubes of the concentric tube probe to achieve a configuration specified by the motion plan.

The control system creates, in real-time or near real-time, a motion plan to move the tip of the concentric tube probe to the goal position while avoiding contact by the concentric tube probe with one or more obstacles and for configuring the concentric tube probe as specified by the motion plan. The user input device can continually receive goal positions from the user and the control system can, in response, continually update configurations of the concentric tube probe for collision-free motions to the goal positions. The control system can be configured to cache a plurality of collision-free configurations and motions of the concentric tube probe and the corresponding shapes, positions, and orientations of the concentric tube probe as computed by a kinematic model.

The control system can include a roadmap planner for generating collision-free motions for the concentric tube probe to the goal position by approximating shapes, positions, and orientations of the curved tubes using a kinematic model of the concentric tube probe. The roadmap planner can be configured to, in a preoperative phase, receive a probe specification

specifying the shape of the tubes constituting the concentric tube probe, an obstacle specification specifying a location and shape of each of the one or more obstacles, and an insertion pose of the concentric tube probe. The insertion pose can include both the position and the orientation of the concentric tube probe. The roadmap planner can, in the preoperative phase, output a roadmap including a set of configurations of the concentric tube probe and motions between the configurations, wherein the configurations and motions are verified to be collision-free according to the kinematic model, the probe specification, the obstacle specification, and the insertion pose.

The roadmap planner can generate the roadmap using a rapidly-exploring random graph algorithm and can evaluate, for each of a plurality of candidate configurations and motions of the concentric tube probe, whether the candidate configuration or motion satisfies one or more kinematic constraints of the kinematic model and is collision-free according to the obstacle specification. The roadmap planner can be configured to cache a plurality of collision-free configurations and motions of the concentric tube probe and the corresponding shapes, positions, and orientations of the concentric tube probe as computed by a kinematic model. The roadmap planner can register a probe coordinate frame of the concentric tube probe with a target coordinate frame of the obstacle specification.

The goal position can be in proximity of a patient's lungs, and registering the probe coordinate frame with the target coordinate frame can include determining a current breath phase of the patient and registering the probe coordinate frame to the target coordinate frame using the current breath phase and breath phase data associated with the obstacle specification. The roadmap planner can, during an intraoperative phase, respond to a new user-specified goal position by searching the roadmap using a graph search algorithm to produce a collision-free motion plan for the concentric tube probe from a previous position to the new user-specified goal position.

The control system can include a tip error corrector for sensing the position of the tip of the concentric tube probe and moving the tip closer to

the goal position. The tip error corrector is configured to receive measurements from a tip position sensing system and use inverse kinematics (IK) to move the tip closer to the goal position.

The concentric tube position display interface can be an augmented reality interface. The user input device of the augmented reality interface can be a 3D mouse. Displaying feedback indicating the position of the tip can include displaying a video feed of the concentric tube probe with an overlaid 3D cursor to indicate an intended goal.

The subject matter described in this specification may be implemented in hardware, software, firmware, or combinations of hardware, software and/or firmware. In some examples, the subject matter described in this specification may be implemented using a non-transitory computer readable medium storing computer executable instructions that when executed by one or more processors of a computer cause the computer to perform operations. Computer readable media suitable for implementing the subject matter described in this specification include non-transitory computer-readable media, such as disk memory devices, chip memory devices, programmable logic devices, random access memory (RAM), read only memory (ROM), optical read/write memory, cache memory, magnetic read/write memory, flash memory, and application specific integrated circuits. In addition, a computer readable medium that implements the subject matter described in this specification may be located on a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter described herein will now be explained with references to the accompanying drawings of which:

Figure 1 illustrates a virtual simulation of a concentric tube probe being controlled using a 3D mouse;

Figure 2 illustrates the method and the precomputation phase and the interactive planning phase;

Figure 3 shows an example 3D model of the nasal cavity and skull base that can be used for collision detection during generation of the roadmap of collision-free concentric tube probe motion plans;

Figure 4 illustrates three snapshots of an interactive neurosurgical simulation session;

Figure 5 shows an example concentric tube probe steering between and avoiding two tubular obstacles;

Figure 6 is a schematic overview of the motion planning approach for concentric tube probe teleoperation with automatic obstacle avoidance;

Figure 7 shows an example augmented reality interface;

Figure 8 is a block diagram of an example system for controlling a concentric tube probe.

DETAILED DESCRIPTION

This specification describes systems for controlling concentric tube probes. In some examples, the system includes a concentric tube position display interface and a control system. The concentric tube display interface includes a display for displaying visual feedback to a user indicating a position (and possibly orientation) of a tip of a concentric tube probe and a user input device for receiving user input from the user designating a goal position (and possibly orientation) for the tip of the concentric tube probe. The control system is configured for interactive-rate motion planning of the concentric tube probe by creating, in real-time or near real-time, a motion plan to move the tip of the concentric tube probe to the goal position (and possibly orientation) while avoiding contact by the concentric tube probe with one or more obstacles and for configuring the concentric tube probe as specified by the motion plan.

Introduction

Concentric tube probes, sometimes called concentric tube robots, are tentacle-like robotic devices designed for minimally invasive surgery. Their curving ability and small size allow them to reach anatomical sites inaccessible to traditional, straight surgical instruments. Concentric tube

probes may enable new, safer surgical access to many sites in the human body, including the skull base, the lungs, and the heart.

These robots can be composed of thin, pre-curved, elastic tubes that are nested within one another. The device's maneuverability is enabled via telescopically inserting and rotating each tube, causing the entire device's shape to change. This powerful shape-changing property also poses a major challenge: unintuitive kinematics determined by mechanical interactions between the device's curved elastic tubes. A physician would therefore find it difficult to safely and accurately guide the robot to perform a surgical task by manually rotating and inserting each tube.

We look to computation to enable intuitive guidance by a physician. Collisions with anatomical obstacles can increase risk to the patient and can bend the device unpredictably, impeding effective control. Requiring a physician to enforce collision avoidance when using a position control interface places a significant burden on the physician. Furthermore, even if the physician successfully steers the tip clear of obstacles, reaching for a given tip position can cause a dramatic change in the robot's shape, potentially causing collision of the robot with anatomical obstacles.

This specification describes a motion planning approach for teleoperation of concentric tube probes that frees the physician to focus on controlling the robot's tip, while an integrated motion planner automatically handles obstacle avoidance along the robot's entire shaft. Motion planning can harness these robots' redundant degrees of freedom in order to curve around obstacles and still reach desired tip positions. This specification describes a motion planner that computes collision-free plans for concentric tube probes at interactive rates. We assume a pre-operative image (e.g., CT scan, MRI, ultrasound) is obtained prior to the procedure, as is common for surgery. From these images anatomical obstacles can be segmented. The interactive-rate motion planner can allow a physician to continuously specify a desired tip location for the concentric tube probe using a 3D mouse (e.g., a SensAble Phantom), and the robot can interactively respond by reaching the desired goal position while ensuring that the entire device shaft avoids anatomical obstacles. The approach can also reduce the error between the

commanded goal position and the robot's tip position by using tip position sensing to account for kinematic modeling error.

Achieving interactive-rate motion planning for concentric tube probes is complicated by their kinematics. Accurately evaluating the robot's kinematics is critical for obstacle avoidance. However, accurately estimating the robot's shape requires solving a numerical system that is sufficiently computationally expensive that previous motion planners would be rendered too slow to be used interactively during a procedure that involves obstacle avoidance.

The systems and methods described in this specification achieve interactive rates by creating a motion planner specifically designed for concentric tube probes that mixes precomputation and position control. In the example sampling-based motion planning approach, we begin by precomputing a roadmap of collision-free paths in the robot's configuration space, and then search for paths on this roadmap during the procedure. We can then use a position control method based on iterative inverse kinematics (IK) to reach user-specified positions not exactly represented in the precomputed roadmap. To link the sampling-based and control approaches, the precomputed roadmap can cache shape information that is computationally expensive to compute online, speeding up the iterative IK. This results in a method that can quickly compute collision-free motion plans to a region of interest, and then can use fast position control to locally guide the robot tip closer to the goal position specified by the physician.

Figure 1 illustrates a virtual simulation of a concentric tube probe. The concentric tube probe is being controlled with a 3D mouse (e.g., a SensAble Phantom Desktop), as illustrated in the inset. Figure 3 shows an example 3D model of the nasal cavity and skull base that can be used for collision detection during generation of the roadmap of collision-free concentric tube probe motion plans. Figure 4 illustrates three snapshots of an interactive neurosurgical simulation session. Figure 5 shows an example concentric tube probe steering between and avoiding two tubular obstacles. A fast motion planner enables a teleoperated concentric tube probe to maneuver its tip to points specified by a 3D mouse, as shown in the inset of

Figure 5, while automatically avoiding collisions with obstacles along its shaft.

Overview of Approach

Figure 6 is a schematic overview of the motion planning approach for concentric tube probe teleoperation with automatic obstacle avoidance. Before operation, we require a geometrical specification of the anatomical obstacles that must be avoided by the concentric tube probe during the procedure. The obstacles O can be specified using polygonal meshes and can be obtained by segmenting volumetric medical images (e.g., CT scans) either manually or using automatic segmentation software.

During operation, the user repeatedly specifies a new goal position x_{goal} (possibly including orientation) for the concentric tube probe to reach. The robot immediately responds by moving its tip to reach the latest given goal position while automatically avoiding contact with obstacles. The user specifies the goal positions with a 3D mouse in an augmented reality display that shows a cursor overlaid on a video feed of the surgical site (e.g., from an endoscopic camera). The 3D mouse can specify 3D positions, and in some examples can also specify 3D orientations.

A concentric tube probe can include *N* telescoping tubes. Each tube *i* can be curved in an arbitrary manner. The device is inserted at a point x_{start} along a vector v_{start}.

Each tube may be (1) inserted or retracted from the previous tube, and (2) axially rotated, yielding 2 degrees of freedom per tube. Hence, the robot's configuration is a 2*N* dimensional vector q = $(\theta_i, \beta_i : i = 1, \ldots, N)$ where θ_i is the axial angle at the base of the *i*'th tube and $\beta_i \leq 0$ is the arc-length position of the base of tube *i* behind the robot insertion point (i.e., β = 0 corresponds to x_{start}). The configuration space is $\mathcal{Q} = (S^1)^N \times \mathbb{R}^N$.

For a given configuration $q \in \mathcal{Q}$, we represent the device's shape as a 3D space curve $\mathbf{x}(\mathbf{q}, s) : \mathcal{Q} \times [0, 1] \mapsto \mathbb{R}^3$ where $\mathbf{x}(\mathbf{q}, 0) = \mathbf{x}_{ins}$ and $\mathbf{x}(\mathbf{q}, 1)$ is the robot's tip position.

Each time the user provides a new x_{goal}, the robot's motion planner computes a collision-free sequence of configurations to guide the robot to the vicinity of x_{goal}, and then performs a tip error correction step guided by sensed measurements of the tip position. These steps make up a motion plan Pi, denoted by a sequence of configurations Pi = (q_1, … , q_n), to move the robot from its current configuration q_1 to a new configuration q_n such that:

1) the distance between the robot's tip $x(q_n, 1)$ and the goal x_{goal} is minimized,

2) each configuration q_i of the motion plan Pi is free of contact with obstacles, and

3) each configuration q_i satisfies the robot's kinematic constraints, which includes limits on tube translations.

To enable interactivity, each plan PI should be computed sufficiently fast. Due to the unmodeled effects (e.g., friction and tube tolerances), there may be some difference between mechanics-based model predictions and the robot's actual shape. Thus, we consider the model's predictions to be an estimate x^ of the robot's true shape x. Accurately reaching desired goal positions while ensuring collision avoidance becomes especially challenging when we only have an approximation x^ of the robot's true shape. We describe further below how we select motion plans that encourage collision avoidance and use sensing to correct tip error.

Methods

The motion planning approach for concentric tube probe teleoperation consists of the following components.

- a user interface for specifying desired goal points for the robot to reach.
- an integrated motion planner that computes a path that moves the robot as close as possible to the goal while avoiding collisions. The planner has two parts: a roadmap-based planner that generates collision-free paths to the goal's vicinity, and a tip error correction (TEC) that senses the robot's tip position and moves the robot's tip closer to the goal.

- a physical concentric tube probe actuation unit that executes the commands computed by the motion planner.

The user can specify goal positions (and possibly orientations) for the robot by pointing and clicking with a 3D user input device (e.g. GEOMAGIC TOUCH X), which allows for input of 3D points and, in some examples, can also provide input of 3D orientation. To facilitate selection of goal positions (and possibly orientations), an augmented reality display can show a video feed of the concentric tube probe with an overlaid 3D cursor as the intended goal. We can register the video camera view with the robot's frame of reference. In clinical settings, we expect to use an endoscopic video camera attached to the robot in a manner such that this registration can be pre-calibrated. The user moves the 3D cursor with the handheld stylus of 3D input device, and clicking the stylus triggers the motion planner to move the robot's tip to the specified goal position (and possibly orientation).

Figure 7 shows an example of the augmented reality interface. The curve is the robot's shape as estimated by the kinematic model, which almost exactly corresponds to the actual tubes in the video feed. A translucent sphere can be used to show the 3D cursor, which the user moves with a 3D mouse to select goal positions (and possibly orientations) for the robot tip.

We use a motion planner that can generate collision-free paths (as approximated by the kinematic model) for concentric tube probes at interactive rates. The motion planner achieves its speed by separating planning into two phases: a preoperative phase (or precomputation phase) and an intraoperative phase (or interactive planning phase). Figure 2 illustrates the approach and the two phases.

1) Preoperative Phase: The inputs to the preoperative phase of motion planning are:

- the geometry of anatomical obstacles, which can be represented as 3D polygonal surface meshes.
- physical specifications of the concentric tube probe.
- insertion pose of the concentric tube probe.

The output of the preoperative phase is a discretization of the collision-free subset of the robot's configuration space *Q* in the form of a *roadmap*. The roadmap stores a set of configurations and motions between these configurations that have all been verified to be collision-free, according to the kinematic model x^. The motion connecting two adjacent configurations in the roadmap can be assumed to be linear interpolation. Paths in the roadmap can be represented as sequences of adjacent configurations, which means the roadmap generates piecewise linear motions in configuration space.

The output of the precomputation phase is a precomputed roadmap with cached data that will facilitate interactive planning. We can compute the collision-free roadmap using a *rapidly-exploring random graph*, or RRG. RRG focuses roadmap construction only on regions of the configuration space that are reachable from the robot's insertion pose. RRG also stores multiple alternative paths between configurations, thus allowing us to select paths that meet application-specific criteria.

The RRG algorithm requires a predicate is_collision_free(q) that evaluates whether the robot satisfies kinematic constraints and is collision-free at configuration q. We can compute this predicate by generating a 3D polygonal mesh on-the-fly of the kinematic model x^(q, s) and using a collision detection library to check for collisions between the robot's mesh and the anatomical obstacle meshes. For this work we assume the obstacles are described in the robot's coordinate frame, but in some examples, we will need to register to the preoperative volumetric image coordinate system.

We note that the function is_collision_free(q) is approximate because it uses the kinematic model x^. In order to reduce false negatives in collision detection due to modeling error, we can add padding to the anatomical obstacle representation used in computing is_collision_free(q).

In order to speed up offline roadmap computation and online position control, we store additional information about previous robot shape computations in each node of the roadmap. Computing the robot's shape may require solving for the initial conditions of a boundary value problem. We store the solved initial conditions for each configuration in the roadmap

so that they can be used as initial guesses for future shape computations of nearby configurations.

We must also ensure that the roadmap only includes feasible robot configurations. In order to sample only configurations that satisfy the constraints, we can use rejection sampling. We can continually sample from a set of box constraints that tightly contains the true set of valid configurations and reject those samples that violate the constraints.

2) Intraoperative Phase: In the intraoperative phase, the motion planner performs the following steps each time the user specifies a new desired goal position x_{goal}.

1) Find the configuration q_{near_goal} in the roadmap with the minimum predicted tip distance to the goal.

2) Given that the concentric tube probe is currently at configuration q_{start}, find the configuration q_{near_start} in the roadmap that is nearest to q_{start}.

3) Use a graph search algorithm (e.g., Dijkstra's shortest path algorithm) to find the optimal sequence of configurations PI* on the roadmap from q_{near_start} to q_{near_goal}. We will describe below how we define edge costs.

4) Send PI* to the robot for execution.

The roadmap stores multiple alternative collision-free paths between configurations. In some examples, we selected paths that resulted in smooth robot motion by choosing paths that minimized the total distance traveled by the robot's tip. An example alternative is to prioritize collision avoidance over smooth tip motion. In this case, we can select paths based on a metric that considers the robot's *clearance* from anatomical obstacles. Given a function clear(q) that computes the minimum distance between the robot at configuration q and the anatomical obstacles, we define the cost of the motion connecting configurations q_1 and q_2 as

$$c(\mathbf{q}_1, \mathbf{q}_2) = \|\mathbf{q}_1 - \mathbf{q}_2\| \int_0^1 \frac{1}{\mathrm{clear}(\mathbf{q}_1 + t(\mathbf{q}_2 - \mathbf{q}_1))} dt \quad (1)$$

This function integrates (1/clear(q)) along the linear interpolation between q_1 and q_2. We can use the reciprocal of the clear function because we want to incur higher cost on a path with smaller robot-obstacle clearance. We can use a collision detection library to compute clear.

We can use Dijkstra's shortest path algorithm using the cost function in Eq. 1 in order to return paths on the roadmap that tend to steer farther away from anatomical obstacles. We can cache these motion costs during precomputation of the collision-free roadmap in order to avoid online evaluation of the expensive clear function.

To reduce errors in practice, we can use measurements from a tip position sensing system combined with iterative inverse kinematics (IK) to "step out" of the precomputed roadmap and toward the specified goal point. To step off the roadmap and move the robot's tip from its sensed position to the goal position, we can use the damped least squares (DLS) IK algorithm. If we do not consider kinematic uncertainty, then we could compute the off-roadmap steps using tip error computed from the kinematic model:

$$\Delta q = \text{DLS_IK}(x_{goal} - \hat{x}(q, 1)). \qquad (2)$$

As an example, we incorporate feedback from tip position measurements in order to mitigate the effects of kinematic modeling error. We can take the off-roadmap steps using the tip error measured by the position sensing system:

$$\Delta q = \text{DLS_IK}(x_{goal} - x_{measured}). \qquad (3)$$

We can iteratively sense the position of the robot's tip and adjust the robot's configuration using Eq. 3 until convergence or until we fail to make positive progress toward the goal position. We only perform off-roadmap steps if they are predicted to be collision-free with is_collision_free(q).

Conclusion

This specification describes a teleoperated concentric tube probe with integrated motion planning for automatic obstacle avoidance. This specification describes a motion planning method that can compute collision-free plans for concentric tube probes at interactive rates. The planner's speed enables users to continuously move the robot's tip while the planner ensures obstacle avoidance for the robot's shaft. The method derives its speed and accuracy by combining offline precomputation of a collision-free roadmap with online position control. The use of a 3D mouse combined with an augmented reality interface makes the robot's responses to the user's

inputs more intuitive. In some examples, the user's spatial reasoning of the surgical site can be improved with a stereoscopic display or visual overlay of surgically relevant anatomical structures. Additionally, force feedback can be used to provide the physician with tactile information about the surroundings of the concentric tube probe.

Figure 8 is a block diagram of an example system **1500** for controlling a concentric tube probe. System **1500** includes a concentric tube position (and possibly orientation) display interface **1502**, a control system **1504**, and a concentric tube probe **1506**. Concentric tube display interface **1502** includes a display **1508** for displaying visual feedback to a user indicating a position (and possibly orientation) of a tip of concentric tube probe **1506** and a user input device **1510** for receiving user input from the user designating a goal position (and possibly orientation) for the tip of concentric tube probe **1506**. Concentric tube probe **1506** can include at least two concentric tubes configured so that translation and rotation of any of the tubes creates curvilinear motion of concentric tube probe **1506**. The visual feedback can include position or both position and orientation. Similarly, the goal position can include a goal position or both a goal position and orientation.

Control system **1504** includes one or more processors **1512** and memory **1514** and is configured, by virtue of appropriate programming, for interactive-rate motion planning of concentric tube probe **1506**. Control system **1504** can include a physical actuation unit **1520** for rotating and translating the curved tubes of concentric tube probe **1506** to achieve a configuration specified by the motion plan.

Control system **1504** creates, in real-time or near real-time, a motion plan to move the tip of concentric tube probe **1506** to the goal position while avoiding contact by concentric tube probe **1506** with one or more obstacles and configures concentric tube probe **1506** as specified by the motion plan. User input device **1510** can continually receive goal positions from the user and control system **1504** can, in response, continually update configurations of concentric tube probe **1506** for collision-free motions to the goal positions. Control system **1504** can be configured to cache a plurality of collision-free configurations and motions of concentric tube probe **1506** and the

corresponding shapes, positions, and orientations of concentric tube probe **1506** as computed by a kinematic model.

Control system **1504** can include a roadmap planner **1516** for generating collision-free motions for concentric tube probe **1506** to the goal position by approximating shapes, positions, and orientations of the curved tubes using a kinematic model of concentric tube probe **1506**. Roadmap planner **1516** can be configured to, in a preoperative phase, receive a probe specification specifying the shape of the tubes constituting concentric tube probe **1506**, an obstacle specification specifying a location and shape of each of the one or more obstacles, and an insertion pose of concentric tube probe **1506**. The insertion pose can include both the position and the orientation of concentric tube probe **1506**. Roadmap planner **1516** can, in the preoperative phase, output a roadmap including a set of configurations of concentric tube probe **1506** and motions between the configurations, wherein the configurations and motions are verified to be collision-free according to the kinematic model, the probe specification, the obstacle specification, and the insertion pose.

Roadmap planner **1516** can generate the roadmap using a rapidly-exploring random graph algorithm and can evaluate, for each of a plurality of candidate configurations and motions of concentric tube probe **1506**, whether the candidate configuration or motion satisfies one or more kinematic constraints of the kinematic model and is collision-free according to the obstacle specification. Roadmap planner **1516** can be configured to cache a plurality of collision-free configurations and motions of concentric tube probe **1506** and the corresponding shapes, positions, and orientations of concentric tube probe **1506** as computed by a kinematic model. Roadmap planner **1516** can register a probe coordinate frame of concentric tube probe **1506** with a target coordinate frame of the obstacle specification.

The goal position can be in proximity of a patient's lungs, and registering the probe coordinate frame with the target coordinate frame can include determining a current breath phase of the patient and registering the probe coordinate frame to the target coordinate frame using the current breath phase and breath phase data associated with the obstacle

specification. Roadmap planner **1516** can, during an intraoperative phase, respond to a new user-specified goal position by searching the roadmap using a graph search algorithm to produce a collision-free motion plan for concentric tube probe **1506** from a previous position to the new user-specified goal position.

Control system **1504** can include a tip error corrector **1518** for sensing the position of the tip of concentric tube probe **1506** and moving the tip closer to the goal position. Tip error corrector **1518** is configured to receive measurements from a tip position sensing system and use inverse kinematics (IK) to move the tip closer to the goal position.

Concentric tube probe display interface **1502** can be an augmented reality interface. User input device **1510** can be a 3D mouse. Displaying feedback indicating the position of the tip can include displaying a video feed of concentric tube probe **1506** with an overlaid 3D cursor to indicate an intended goal.

It is understood that various details of the presently disclosed subject matter may be changed without departing from the scope of the presently disclosed subject matter. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

CLAIMS

What is claimed is:

1. A system for controlling a concentric tube probe, the system comprising:

a concentric tube position display interface comprising a display for displaying visual feedback to a user indicating a position and optionally the orientation of a tip of a concentric tube probe and a user input device for receiving user input from the user designating a goal position and optionally orientation for the tip of the concentric tube probe, wherein the concentric tube probe comprises at least two concentric tubes so that translation and rotation of one of the tubes inside another of the tubes creates curvilinear motion of the concentric tube probe; and

a control system for interactive-rate motion planning of the concentric tube probe by creating, in real-time or near real-time, a motion plan to move the tip of the concentric tube probe to the goal position and optionally the goal orientation while avoiding contact by the concentric tube probe with one or more obstacles and for configuring the concentric tube probe as specified by the motion plan.

2. The system of claim 1, wherein the user input device continually receives goal positions and/or orientations from the user and wherein the control system updates configurations of the concentric tube probe for collision-free motions to the goal positions.

3. The system of claim 1, wherein the control system is configured to cache a plurality of collision-free configurations of the concentric tube probe.

4. The system of claim 1, wherein the concentric tube position display interface is an augmented reality interface.

5. The system of claim 1, wherein the control system comprises a roadmap planner for generating collision-free motions for the concentric tube probe to the goal position and/or orientation by approximating shapes, positions, and orientations of the curved tubes using a kinematic model of the concentric tube probe.

6. The system of claim 5, wherein the roadmap planner is configured to, in a preoperative phase, receive a probe specification specifying the shape

of each component tube of the concentric tube probe, an obstacle specification specifying a location and shape of each of the one or more obstacles, and an insertion pose of the concentric tube probe, and wherein the roadmap planner is configured to, in the preoperative phase, output a roadmap comprising a set of configurations of the concentric tube probe and motions between the configurations, wherein the configurations and motions are verified to be collision-free according to the kinematic model, the probe specification, the obstacle specification, and the insertion pose.

7. The system of claim 6, wherein the roadmap planner is configured to generate the roadmap using a rapidly-exploring random graph algorithm and evaluate, for each of a plurality of candidate configurations of the concentric tube probe, whether the candidate configuration satisfies one or more kinematic constraints of the kinematic model and is collision-free according to the obstacle specification.

8. The system of claim 7, wherein the roadmap planner is configured to cache the shapes, positions, and orientations of the concentric tube probe as computed by a kinematic model for the plurality of configurations and motions in the roadmap.

9. The system of claim 5, wherein the roadmap planner is configured to register a probe coordinate frame of the concentric tube probe with a target coordinate frame of the obstacle specification.

10. The system of claim 9, wherein the goal position is in proximity of a patient's lungs, and wherein registering the probe coordinate frame with the target coordinate frame comprises determining a current breath phase of the patient and registering the probe coordinate frame to the target coordinate frame using the current breath phase and breath phase data associated with the obstacle specification.

11. The system of claim 5, wherein the roadmap planner is configured to, during an intraoperative phase, respond to a new user-specified goal position or orientation by searching the roadmap using a graph search algorithm to produce a collision-free motion plan for the concentric tube probe from a previous position and orientation to the new user-specified goal position and/or orientation.

12. The system of claim 1, wherein the control system comprises a tip error corrector for sensing the position and/or orientation of the tip of the concentric tube probe and moving the tip closer to the goal position and/or orientation.

13. The system of claim 12, wherein the tip error corrector is configured to receive measurements from a tip position and/or orientation sensing system and use inverse kinematics (IK) to move the tip closer to the goal position and/or orientation.

14. The system of claim 1, wherein the control system comprises a physical actuation unit for rotating and translating the curved tubes of the concentric tube probe to achieve a configuration specified by the motion plan.

15. The system of claim 1, wherein the user input device comprises a 3D mouse.

16. The system of claim 1, wherein displaying feedback indicating the position and/or orientation of the tip comprises displaying a video feed of the concentric tube probe with an overlaid 3D cursor to indicate an intended goal.

17. A method for controlling a concentric tube probe, the method comprising:

displaying, by a concentric tube position display interface of a system of one or more computers, visual feedback to a user indicating a position and/or orientation of a tip of a concentric tube probe, wherein the concentric tube probe comprises at least two concentric tubes so that translation and rotation of one of the tubes inside another of the tubes creates curvilinear motion of the concentric tube probe;

receiving, by a user input device of the system of one or more computers, user input from the user designating a goal position and/or orientation for the tip of the concentric tube probe;

creating, in real-time or near real-time by the system of one or more computers, a motion plan to move the tip of the concentric tube probe to the goal position and/or orientation while avoiding contact by the concentric tube probe with one or more obstacles; and

configuring, by the system of one or more computers, the concentric tube probe as specified by the motion plan.

18. The method of claim 17, comprising continually receiving goal positions and/or orientations from the user and updating configurations of the concentric tube probe for collision-free motions to the goal positions and/or orientations.

19. The method of claim 17, comprising caching, for a given position and orientation of the tip and the goal position and/or orientation, a plurality of collision-free configurations of the concentric tube probe to reach the goal position and/or orientation.

20. The method of claim 17, wherein displaying visual feedback comprises displaying an augmented reality interface.

21. The method of claim 17, comprising generating collision-free motions for the concentric tube probe to the goal position and/or orientation by approximating shapes, positions, and orientations of the curved tubes using a kinematic model of the concentric tube probe.

22. The method of claim 21, comprising, in a preoperative phase:

receiving a probe specification specifying the shape of the concentric tube probe, an obstacle specification specifying a location of each of the one or more obstacles, and an insertion pose of the concentric tube probe; and

output a roadmap comprising a set of configurations of the concentric tube probe and motions between the configurations, wherein the configurations are verified to be collision-free according to the kinematic model, the probe specification, the obstacle specification, and the insertion pose.

23. The method of claim 22, comprising generating the roadmap using a rapidly-exploring random graph algorithm and evaluating, for each of a plurality of candidate configurations of the concentric tube probe, whether the candidate configuration satisfies one or more kinematic constraints of the kinematic model and is collision-free according to the obstacle specification.

24. The method of claim 21, comprising registering a probe coordinate frame of the concentric tube probe with a target coordinate frame of the obstacle specification.

25. The method of claim 24, wherein the goal position and/or orientation is in proximity of a patient's lungs, and wherein registering the probe coordinate frame with the target coordinate frame comprises determining a current breath phase of the patient and registering the probe coordinate frame to the target coordinate frame using the current breath phase and breath phase data associated with the obstacle specification.

26. The method of claim 21, comprising, during an intraoperative phase, responding to a new user-specified goal position and/or orientation by searching the roadmap using a graph search algorithm to produce a collision-free motion plan for the concentric tube probe from a previous position and orientation to the new user-specified goal position and/or orientation.

27. The method of claim 17, comprising sensing the position and/or orientation of the tip of the concentric tube probe and moving the tip closer to the goal position and/or orientation.

28. The method of claim 27, comprising receiving measurements from a tip position and/or orientation sensing system and using inverse kinematics (IK) to move the tip closer to the goal position and/or orientation.

29. The method of claim 17, wherein the control system comprises a physical actuation unit for rotating and translating the curved tubes of the concentric tube probe to achieve a configuration specified by the motion plan.

30. The method of claim 17, wherein the user input device comprises a 3D mouse.

31. The method of claim 17, wherein displaying feedback indicating the position and/or orientation of the tip comprises displaying a video feed of the concentric tube probe with an overlaid 3D cursor to indicate an intended goal.

32. One or more non-transitory computer readable mediums storing instructions that, when executed by one or more computers, cause the computers to perform operations comprising:

displaying, by a concentric tube position display interface, feedback to a user indicating a position and/or orientation of a tip of a concentric tube

probe, wherein the concentric tube probe comprises at least two concentric tubes so that translation and rotation of one of the tubes inside another of the tubes creates curvilinear motion of the concentric tube probe;

receiving, by a user input device, user input from the user designating a goal position and/or orientation for the tip of the concentric tube probe;

creating, in real-time or near real-time, a motion plan to move the tip of the concentric tube probe to the goal position and/or orientation while avoiding contact by the concentric tube probe with one or more obstacles; and

configuring the concentric tube probe as specified by the motion plan.

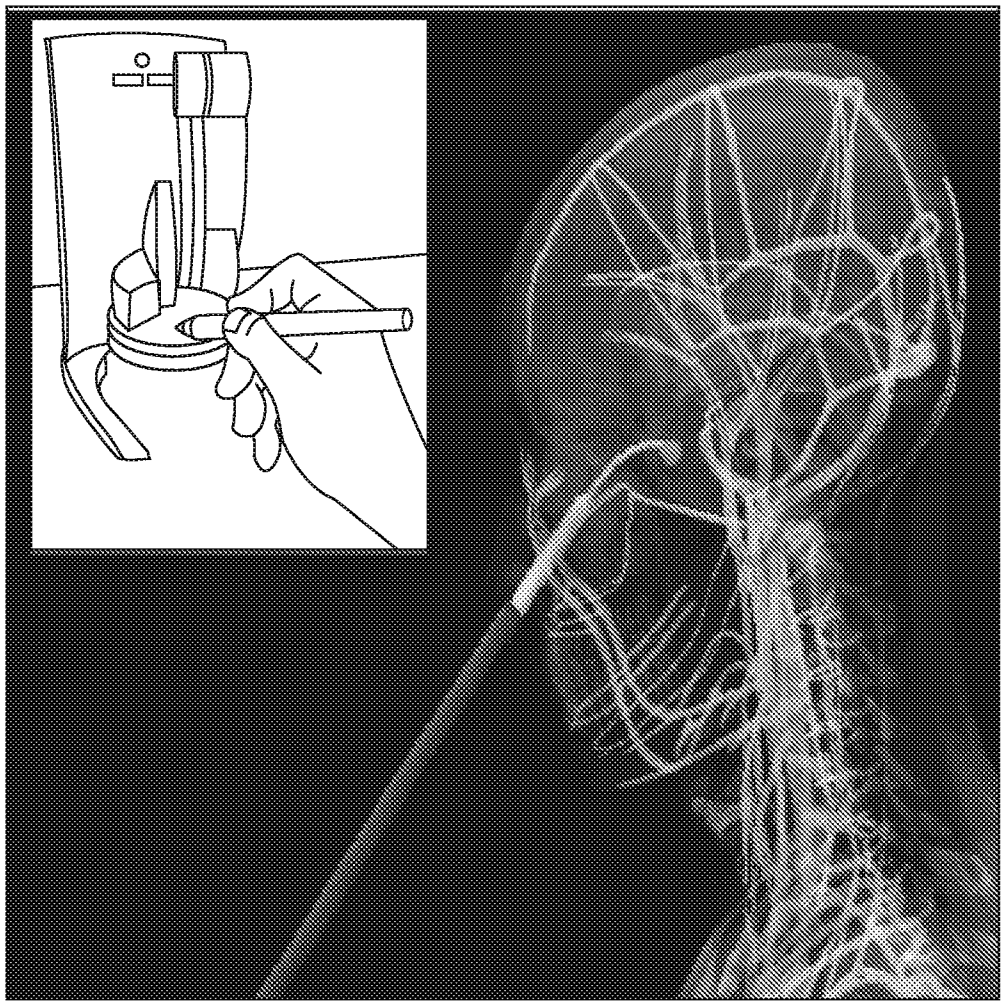

FIG. 1

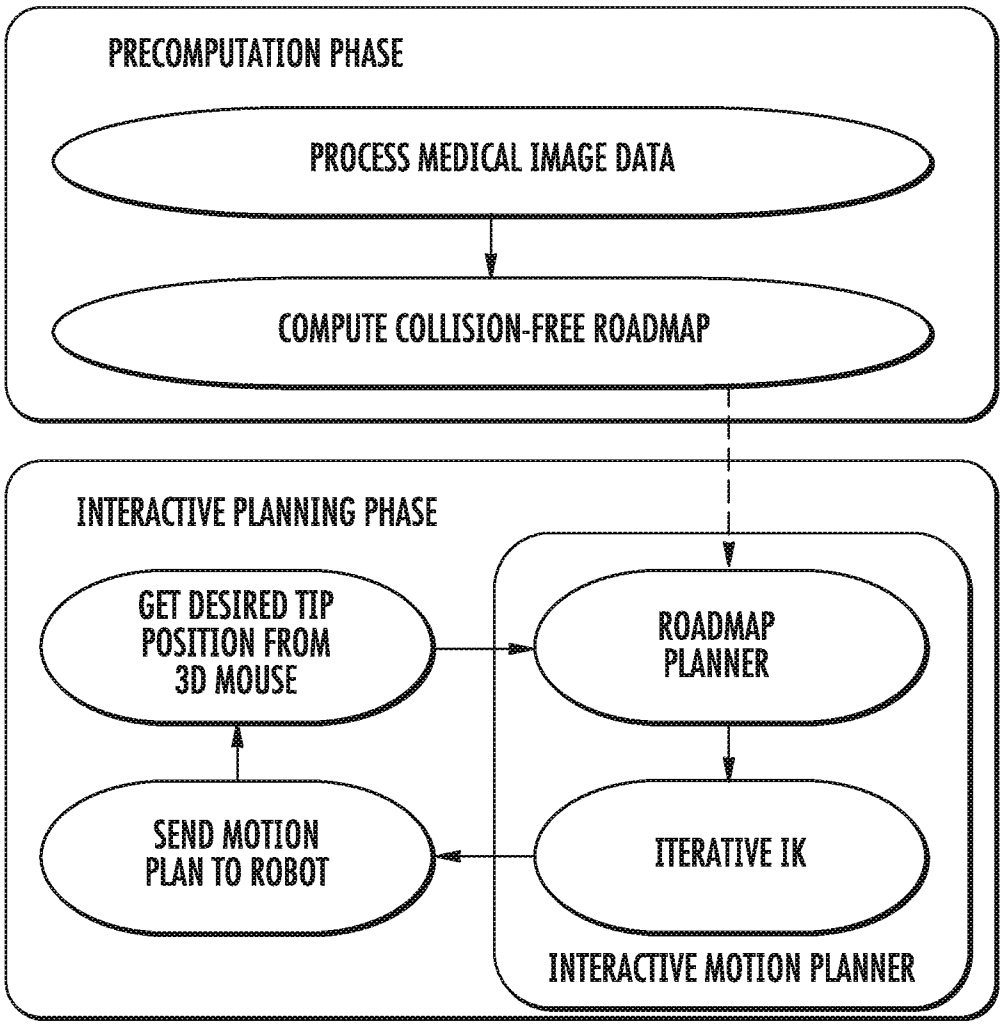
PRECOMPUTATION PHASE
PROCESS MEDICAL IMAGE DATA
COMPUTE COLLISION-FREE ROADMAP
INTERACTIVE PLANNING PHASE
GET DESIRED TIP POSITION FROM 3D MOUSE
ROADMAP PLANNER
SEND MOTION PLAN TO ROBOT
ITERATIVE IK
INTERACTIVE MOTION PLANNER

FIG. 2

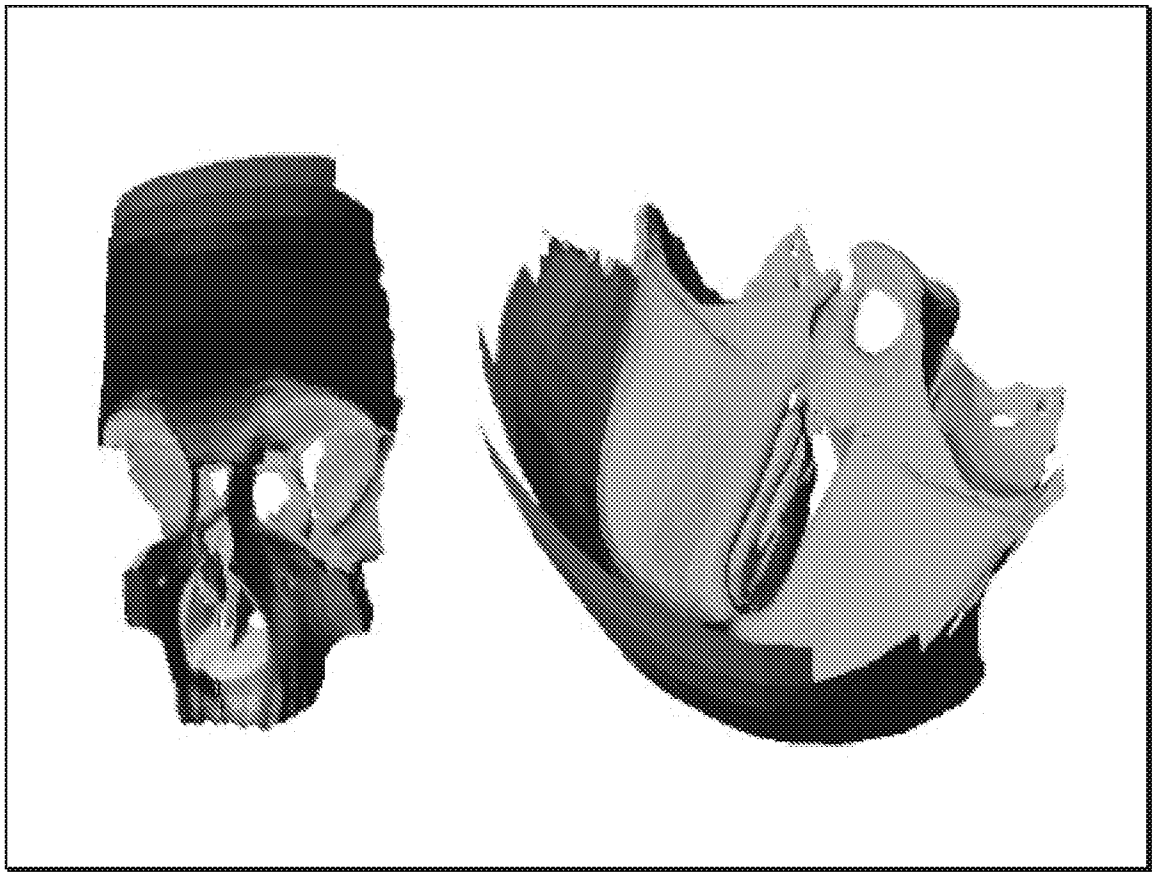

FIG. 3

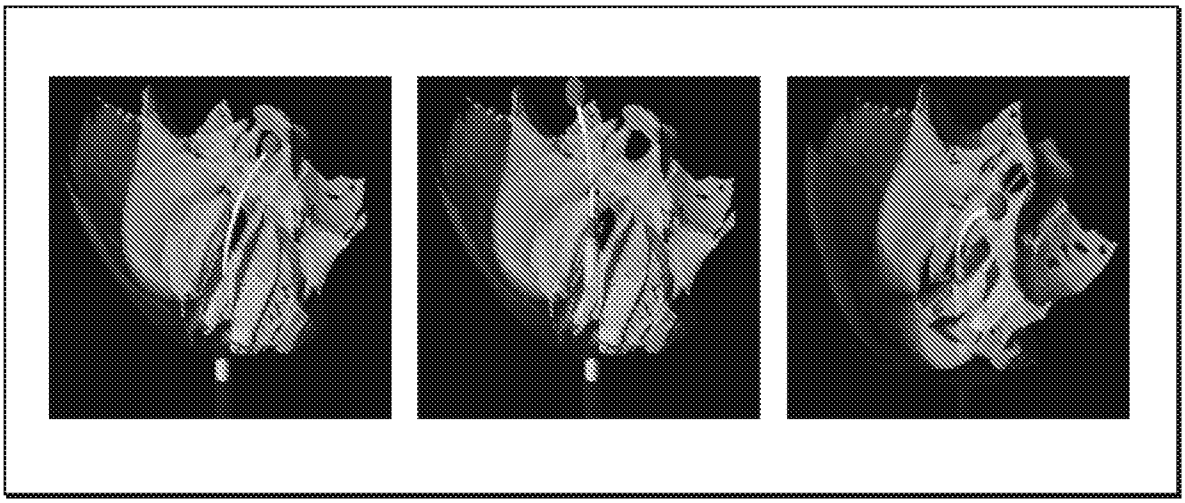

FIG. 4

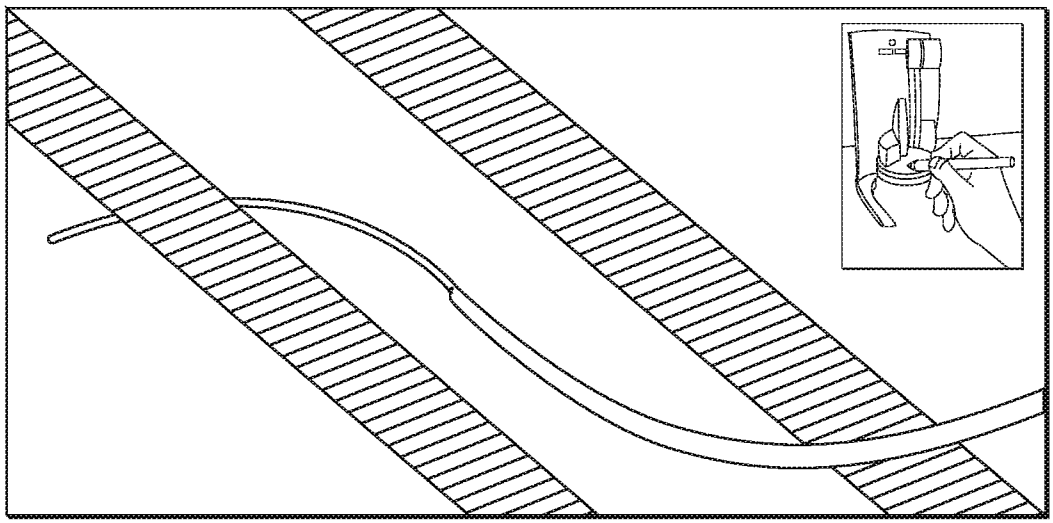

FIG. 5

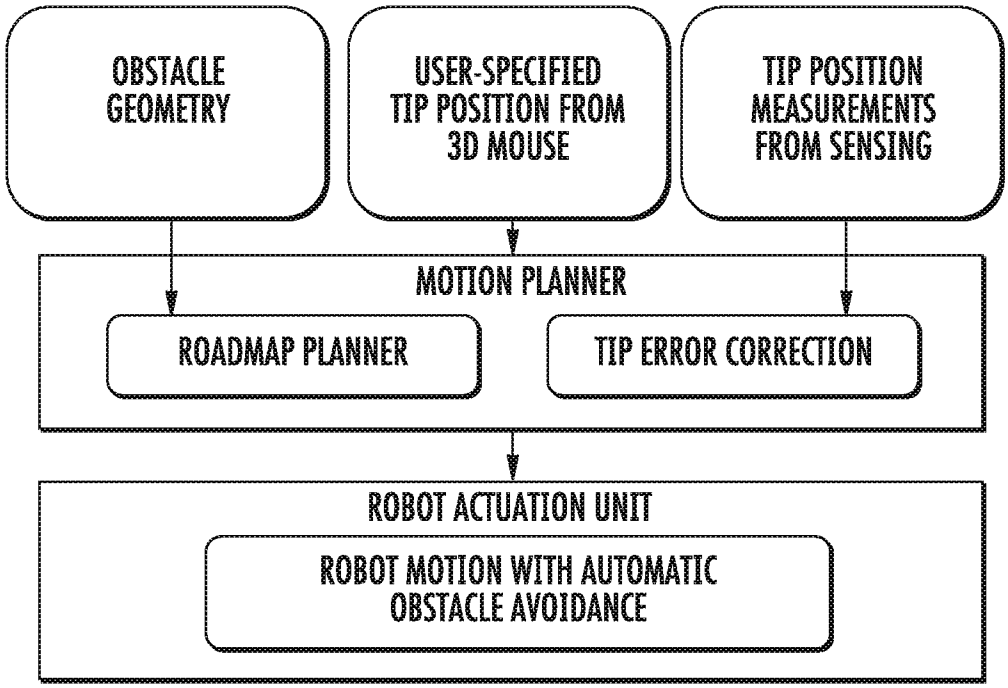
OBSTACLE GEOMETRY
USER-SPECIFIED TIP POSITION FROM 3D MOUSE
TIP POSITION MEASUREMENTS FROM SENSING
MOTION PLANNER
ROADMAP PLANNER
TIP ERROR CORRECTION
ROBOT ACTUATION UNIT
ROBOT MOTION WITH AUTOMATIC OBSTACLE AVOIDANCE

FIG. 6

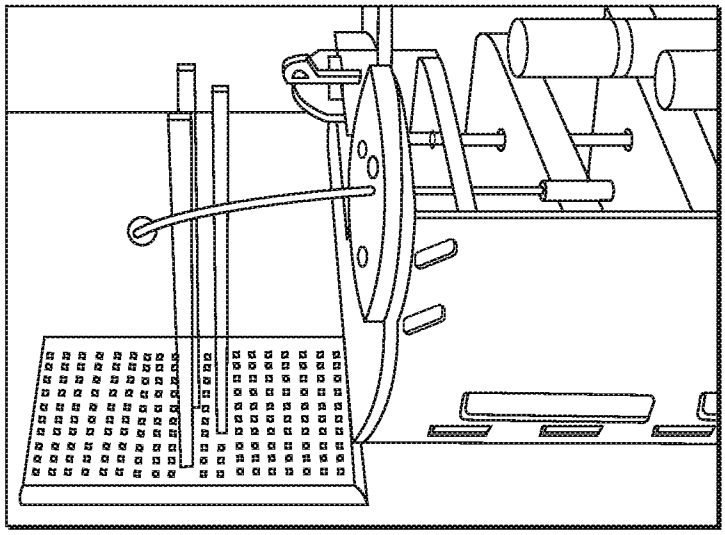

FIG. 7

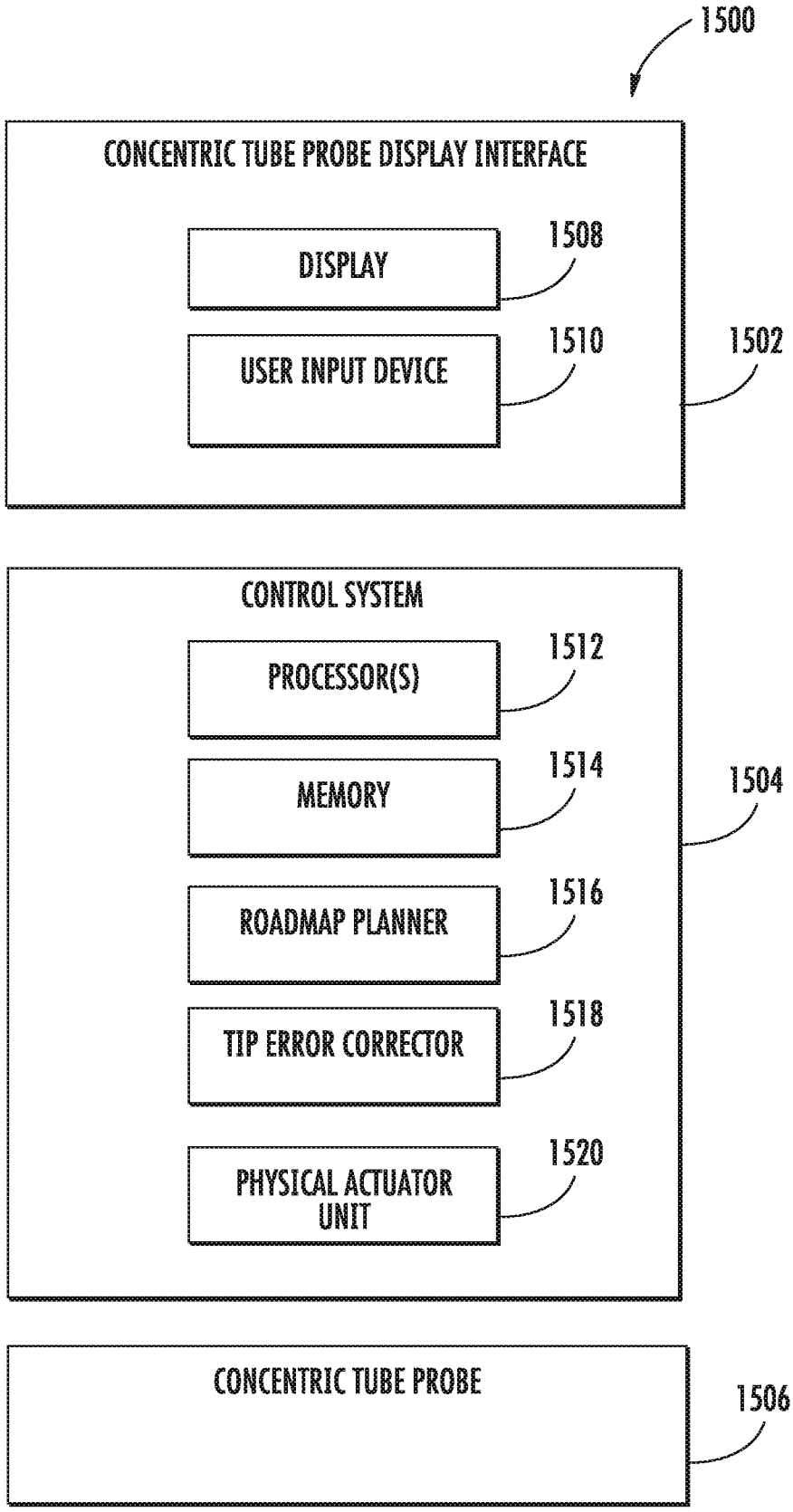
1500
CONCENTRIC TUBE PROBE DISPLAY INTERFACE
DISPLAY
1508
USER INPUT DEVICE
1510
1502
CONTROL SYSTEM
PROCESSOR(S)
1512
MEMORY
1514
1504
ROADMAP PLANNER
1516
TIP ERROR CORRECTOR
1518
PHYSICAL ACTUATOR UNIT
1520
CONCENTRIC TUBE PROBE
1506

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2016/033767

A. CLASSIFICATION OF SUBJECT MATTER

A61B 1/01 *(2006.01)*
A61M 25/08 *(2006.01)*
A61M 25/092 *(2006.01)*
G06T 15/08 *(2011.01)*

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61B 1/00-1/05, G06Q 50/00-50/22, G06F 19/00, G06T 15/08, A61M 25/08, 25/092

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSearch (RUPTO internal), USPTO, PAJ, K-PION, Esp@cenet, Information Retrieval System of FIPS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2015/0080907 A1 (VANDERBILT UNIVERSITY) 19.03.2015, paragraphs [0003], [0011], [0025]-[0029], [0075], fig.1, 11	1-32
Y	LUIS G. TORRES et al. Interactive-rate Motion Planning for Concentric Tube Robots.HHS Public Access, Author manuscript, available in PMC 2015 May 1, section IV-VI, figs. 1, 4	1-32
Y	US 2011/0270040 A1 (KONINKLIJKE PHILIPS ELECTRONICS N.V.) 03.11.2011, abstract	32

☐ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

* Special categories of cited documents:

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 August 2016 (24.08.2016)	01 September 2016 (01.09.2016)

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