



- (51) **International Patent Classification:**
A61B 1/267 (2006.01) *A61B 10/04* (2006.01)
- (21) **International Application Number:** PCT/US2016/033762
- (22) **International Filing Date:** 23 May 2016 (23.05.2016)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
62/165,648 22 May 2015 (22.05.2015) US
62/165,656 22 May 2015 (22.05.2015) US
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- (81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).
- Published:**
- with international search report (Art. 21(3))
 - before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

(54) **Title:** METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR TRANSORAL LUNG ACCESS

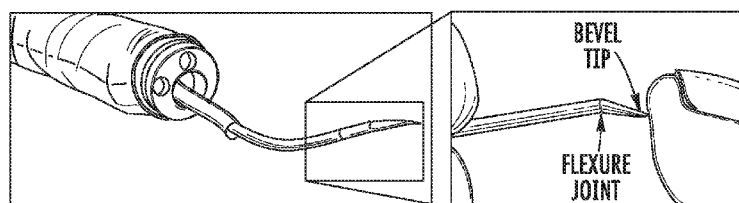


FIG. 1A

FIG. 1B

(57) **Abstract:** Methods, systems, and computer readable media for transoral lung access. In some examples, the system includes a bronchoscope, a concentric tube probe deployable from within the bronchoscope, and a steerable needle nested deployable from within the concentric tube probe. The system can include a control system for deploying the concentric tube probe from the bronchoscope into a lung to a location where a target is within a range of the steerable needle and for deploying the steerable needle from the location to the target.

METHODS, SYSTEMS, AND COMPUTER READABLE MEDIA FOR TRANSORAL LUNG ACCESS

PRIORITY CLAIM

5 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
10 entirety.

GOVERNMENT INTEREST

 This invention was made with government support under National
Institutes of Health Grant No. EB017952 and by the National Science
15 Foundation (NSF) Award Nos. IIS-1149965 and IIS-1054331. The
government has certain rights in the invention.

TECHNICAL FIELD

 This specification relates generally to systems for transoral lung
20 access and for motion planning for a multilumen transoral lung access
system.

BACKGROUND

 Lung cancer is the most deadly form of cancer in part because of the
25 challenges associated with accessing nodules for diagnosis and therapy.
Transoral access is preferred to percutaneous access due to lower risk of
lung collapse and other complications, yet many sites are currently
unreachable transorally, due to limitations in bronchoscope-deployed
instruments. Many sites in the lung, particularly those in the peripheral
30 zones of the lung or distant from the bronchi, cannot currently be accessed
transorally, due to the relatively large diameter and/or lack of sufficient
steerability of current instrumentation. Accordingly, there exists a need for

systems for transoral lung access and for motion planning for a multilumen transoral lung access system.

SUMMARY

5 A system for transoral lung access can include a bronchoscope, a concentric tube probe deployable from within the bronchoscope, and a steerable needle nested deployable from within the concentric tube probe. The system can include a control system for deploying the concentric tube probe from the bronchoscope into a lung to a location where a target is
10 within a range of the steerable needle and for deploying the steerable needle from the location to the target. The concentric tube probe can include one or more curved tubes that can be configured to translate and rotate inside one another to create curvilinear motion. The steerable needle can include a flexible needle shaft, a flexure joint at an end of the flexible needle shaft, and
15 a beveled needle tip that can be attached to the flexure joint.

 The control system can be implemented as a system of one or more computers configured, by virtue of appropriate programming stored as instructions on one or more computer readable media, to deploy the concentric tube probe and the steerable needle. The control system can be
20 configured to insert the steerable needle into tissue and rotate the steerable needle so that the steerable needle travels in a curved trajectory through the tissue.

 The control system can include an actuation unit for rotating and translating concentric tube sections of the concentric tube probe and for
25 rotating and translating the steerable needle. The control system can include a magnetic tracking system and a closed-loop feedback controller for the steerable needle. The control system can include an image guidance system for receiving and displaying an intraoperative image feed and for registering the intraoperative image feed with preoperative data for the lung.
30 The control system can register a coordinate frame of the tip of the concentric tube probe and/or the steerable needle with a lung coordinate frame of the lung using breathing phase data from preoperative data for the lung.

The system can include a puncture system, which can include a sharp wire and an actuation unit. The sharp wire is configured to deploy through the concentric tube probe and create an opening in a bronchial wall of the lung using a spring-loaded mechanism. The actuation unit is configured to
5 deploy the sharp wire and actuate the spring-loaded mechanism to create the opening.

The bronchoscope can include a flexible shaft, zero or more levers, zero or more tendons, and a tendon-driver tip that bends when the tendons are actuated by the levers. The bronchoscope can include a working
10 channel and a thin-walled polytetrafluoroethylene (PTFE) sheath through the working channel, so that the concentric tube probe and the steerable needle can be nested within the PTFE sheath. A coaxial access tube can be inserted through the working channel and over the steerable needle, creating an access channel to the target. An access channel can be created
15 inside the steerable needle. Through an access channel, a biopsy can be collected or a therapeutic agent can be injected or deposited.

A method for motion planning for a multilumen transoral lung access system can be performed by a system of one or more computers. The computers can be configured to perform the method by virtue of appropriate
20 programming stored on one or more computer readable media. The method includes receiving, by one or more computers, input specifying a structure of one or more bronchial tubes, a target location, and one or more anatomical obstacles in a vicinity of the bronchial tubes. The anatomical obstacles can include sensitive tissues, obstructions, and regions in space that the user of
25 the system desires to avoid touching or piercing. The method includes selecting, by the one or more computers, a plurality of candidate starting positions and orientations within the bronchial tubes for a lung access system comprising a bronchoscope, a concentric tube probe nested with the bronchoscope, and a steerable needle nested with the concentric tube
30 probe. The method includes searching, by the one or more computers using a motion planning algorithm, for a trajectory from each of the candidate starting positions and orientations for the steerable needle to traverse from the concentric tube probe to the target while avoiding the anatomical

obstacles, resulting in one or more candidate motion plans, each specifying a starting position and orientation for the lung access system and a trajectory for the concentric tube probe and steerable needle that avoids the anatomical obstacles.

5 The method can include determining a cost for each of the candidate motion plans and selecting a motion plan having a lowest cost among the candidate motion plans. The method can include determining, for each of the candidate motion plans, a metric based on one or more distances between the steerable needle and the anatomic obstacles.

10 The method can include repeating the selecting and searching until reaching an end condition. The method can include using a mechanics-based kinematic model to compute a tip frame for the concentric tube probe for each candidate starting position and orientation. The method can include determining, for each tip frame, whether the target lies outside of a
15 reachable workspace for the steerable needle and rejecting the candidate starting position and orientation for the tip frame if the target lies outside of the reachable workspace for the steerable needle.

 Searching using the motion planning algorithm can include incrementally building a tree of steerable needle states that are reachable
20 from the candidate starting positions and orientations by collision-free paths. Incrementally building the tree can include, at each iteration of a plurality of iterations, sampling a possible state of the steerable needle from a state space of the steerable needle, using a distance function to select a nearest state to the possible state from the tree of steerable needle states, and
25 determining a control input that when applied to the nearest state results in a new state that is nearer to the target than the nearest state.

 The method can include, for each iteration, determining whether a motion between the nearest state and the new state is collision-free, and if so, adding the new state to the tree of steerable needle states. The method
30 can include using a collision library for collision detection between the steerable needle and the anatomical obstacles.

 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:

Figures 1A-C is a diagram illustrating an example system for transoral lung access;

Figure 2 illustrates example components of a three-stage steering system;

Figure 3 shows an example concentric tube probe including a puncture target in a bronchial tube;

Figure 4 shows two views of an example puncture mechanism;

Figures 5A-B illustrate aligning the workspace of an example steerable needle;

Figure 6 illustrates an example setup for system feasibility and accuracy testing;

Figures 7A-B show results of firing the puncture needle;

Figure 8 shows an example motion plan for the multilumen transoral lung access system reaching a lung nodule while avoiding significant blood vessels;

Figure 9 shows an example of a reachable workspace;

Figure 10 is a block diagram of an example system for transoral lung access; and

Figure 11 is a flow diagram of an example method for motion planning
5 for a multilumen transoral lung access system.

DETAILED DESCRIPTION

This specification describes systems for transoral lung access. In some examples, the system includes a bronchoscope, a concentric tube
10 probe deployable from within the bronchoscope, and a steerable needle nested deployable from within the concentric tube probe. The system can include a control system for deploying the concentric tube probe from the bronchoscope into a lung to a location where a target is within the reachable workspace of the steerable needle and for deploying the steerable needle
15 from the location to the target.

Introduction

Figures 1A-B illustrate an example system for transoral lung access. Figure 1A shows a combined bronchoscope, concentric tube probe, steerable needle system. Figure 1B shows a close up view of an example
20 steerable needle's tip. Figure 1C shows the steps in deployment including 1) deploying the bronchoscope, 2) deploying the concentric tube probe to the bronchial wall, puncturing through it, and entering the parenchyma, and 3) steering the needle to the target. Concentric tube probes, also referred to as concentric tube robots, are made from a series of precurved, superelastic
25 tubes that translate and rotate inside one another to create curvilinear motion. The steerable needle can take multiple forms; in this example a bevel-tip steerable needle is used, which harnesses the asymmetry of a wedgelike bevel tip to bend the needle in a controllable manner as it is advanced through tissue. The bevel tip steerable needle can include a
30 flexure joint. The target can be a suspicious nodule or other site in the lung that is to be accessed.

System Overview and Workflow

The example system illustrated in Figures 1A-C aims to expand the capabilities of a transoral approach through the integration of a concentric tube probe and a bevel tip steerable needle with a standard tendon-actuated bronchoscope (Figure 1B). In the system, the physician or system first inserts a bronchoscope to an accessible location en route to the target. A concentric tube probe then deploys through the bronchoscope and pierces through the bronchial wall, providing access to targets located in the lung parenchyma (the tissue surrounding the bronchi). Lastly, a steerable needle deploys through the concentric tube probe and drives through the lung tissue to the target (Figure 1C). This approach can enable access to targets located in the parenchyma of the lung with less risk of pneumothorax compared to percutaneous approaches, since the pleura surrounding the lung is never damaged. An example prototype is shown in Figure 2 and the deployment of the three stages of the device is illustrated in Figure 1C.

Figure 2 illustrates example components of a three-stage steering system. The system includes a magnetic tracking system **202** for feedback, a tendon-actuated flexible bronchoscope **204**, a concentric tube probe **206**, a steerable needle **208**, an actuation unit **210** for controlling the concentric tube probe and steerable needle, and a puncture mechanism **212**.

At a more granular level, an example of the intended insertion workflow is as follows:

- (1) The physician or system deploys the bronchoscope transorally.
- (2) The concentric tube probe deploys through the bronchoscope tool port toward the bronchial wall.
- (3) The bronchial wall is punctured. This can be accomplished using a "puncture needle" that deploys through the concentric tube probe and creates an opening in the bronchial wall. In this example, a sharp nitinol wire deployed via a spring-loaded puncture mechanism was used. The puncture needle is then removed.
- (4) The concentric tube probe aims its tip approximately toward the target.

(5) The steerable needle deploys through the concentric tube probe and is guided to the target.

(6) The physician creates a working channel to the target. In this example, the physician advances a coaxial access tube through the bronchoscope and over the steerable needle, creating an access channel to the target through which a biopsy can be collected or a therapeutic agent can be injected or deposited. As another example, an access channel can be created inside the steerable needle.

In some examples, the concentric tube probe and the steerable needle can be advanced using a control system and closed-loop control. In some examples, bronchoscope deployment can be performed by a robot. The system can be used in conjunction with virtual bronchoscopy to assist the physician with manually navigating the bronchial tree.

The workflow above can be performed under image-guidance. Achieving this requires a preoperative scan of the anatomy which can be used to identify the target and plan the puncture location in the bronchi. The feedback for the closed-loop needle steering control can be provided with electromagnetic tracking, real-time CT, CT Fluoroscopy, MRI, or other sensing modalities. This will require registration between preoperative and intraoperative data, which is already done in current image guided lung systems. The following sections describe in more detail the devices that are deployed from the bronchoscope and enable the system to reach targets located in the parenchyma without puncturing the pleura.

Concentric Tube Probe Subsystem

After the bronchoscope is guided to the desired site in the bronchial tree, the concentric tube probe is deployed through the bronchoscope tool port. The concentric tube probe serves at least three purposes: 1) it guides the needles deployed subsequently from the tip of the bronchoscope to the desired location in the bronchial wall, 2) it can deliver the puncture needle to create an access port in the bronchial wall, and 3) it aligns the initial pose of the steerable needle approximately toward the target so that the target is in the needle's reachable workspace.

The added dexterity of the concentric tube probe coupled with the tendon-actuated bronchoscope helps bring the puncture needle from the bronchoscope tip to the bronchial wall. In order to assist with puncturing the bronchial wall, it is useful to approach the wall in as nearly a perpendicular direction as possible. We use the concentric tube probe to accomplish this (see Figure 3 for an example).

Figure 3 shows an example concentric tube probe including a puncture target and bronchial wall. Depending on the location of the puncture site and desired puncture orientation, the physician may choose to deploy zero, one, or multiple concentric tubes from the bronchoscope to the puncture site.

After reaching the puncture site in the bronchial wall with the concentric tube probe, the puncture needle is deployed through the concentric tube probe. Due to the muscular tissue and cartilage rings that make up the bronchi, an impulse is needed to puncture the wall. In order to deliver this impulse to the puncture needle, in this example a spring-loaded puncture mechanism was designed. The mechanism is shown in Figure 4.

Figure 4 shows two views, (a) and (b), of an example puncture mechanism. The puncture mechanism is used to impart a rapid motion to the puncture needle that creates a port in the bronchial wall. In the puncture mechanism, the lead screw slide compresses a spring until the collar is secured by the release lever. Upon triggering the release lever, the needle holder is propelled forward until it contacts the lead screw slide, controlling the depth of the puncture needle.

Puncture depth can be adjusted by the physician using the depth limiter built into the puncture mechanism (see Figure 4, view (b)). Upon puncturing the bronchial wall, the puncture needle is removed and the concentric tube probe can now pass from the bronchi into the parenchyma to deploy the steerable needle.

The concentric tube probe (and potentially the tendon actuated bronchoscope) orient the initial pose of the steerable needle that passes through the inner concentric tube toward the target. The goal of this alignment process is to set the initial pose of the steerable needle such that

the target lies within the needle's reachable workspace. The reachable workspace of bevel steered needles is "trumpet shaped" for clinically realistic arc lengths, and is bounded by the maximum curvature achievable with the steerable needle in the tissue.

5 An example of aligning the steerable needle reachable workspace by changing the initial tangent angle of the needle is shown in Figures 5A-5B. After the steerable needle is aligned approximately toward the target, the system delivers the steerable needle to the target using the methods described in the following section. Figure 6 illustrates an example setup for
10 system feasibility and accuracy testing. Figures 7A-7B show results of firing the puncture needle.

Steerable Needle Subsystem

 The steerable needle is deployed through the concentric tube probe. In this example, the system uses a flexure-tip needle, a type of bevel-tip
15 needle that consists of a beveled needle tip, a flexible needle shaft, and a flexure joint (see Figure 1B for further information on this tip design). All three components can be made from nitinol. When inserted into tissue, the asymmetric bevel tip creates a force that bends the flexure and causes the needle to travel in a curved trajectory through the tissue. When no load is
20 applied to the tip, the flexure joint straightens and the needle can easily pass through the concentric tube probe. The flexure tip also straightens when axially rotated while in tissue, minimizing tissue damage when a straight trajectory is implemented via continuous axial rotation during insertion.

 In order to accurately deliver the steerable needle through the
25 parenchyma to the target, a sliding mode controller can be used. In the example, magnetic tracking sensors and imaging provide closed-loop feedback of the needle tip pose to the controller.

Motion Planning for the System

 This specification describes a motion planner for this multilumen
30 transoral lung access system. The motion planner computes actions for each of the system's stages to enable the device to safely reach a biopsy target, as shown in Figure 8. The motion planner explicitly considers the coupling between the stages, e.g., the location of the tip of the bronchoscope and the

configuration of the concentric tube probe both greatly affect the reachable workspace of the steerable needle and its ability to safely reach the target. The input to the motion planner includes specifications of the structure and locations of the bronchial tubes, the target, and the anatomical obstacles (e.g., significant arteries and veins in the lung, lung fissures, bronchial tubes), all of which can be either manually or automatically segmented from medical imaging before a procedure. To decrease the risk of internal bleeding, motion plans can be created in which the steerable needle in the third stage has greater clearance from the anatomical obstacles as it maneuvers to the target. The target can be specified as a point or as a region in the lung coordinate frame.

This section describes an example motion planning algorithm (Algorithm 1) for the multilumen lung access system. The motion planner can compute the motions for each stage of the system, including the bronchoscope, the concentric tube probe, and the steerable needle, to enable access to the target.

```

input :  $T$ : time to execute outer loop;  $T_{needle}$ : time
        allotted to individual RRT;  $B$ : surface mesh of
        bronchial tubes;  $V$ : surface mesh of blood
        vessels;  $\kappa_{max}$ : maximum needle curvature;
         $\mathbf{p}_{goal}$ : target site position
output:  $\Pi$ : best motion plan computed by time  $T$ 
 $\Pi \leftarrow \emptyset$ ;
while elapsed time <  $T$  do
     $\mathbf{p}_{scope} \leftarrow \text{sample\_bronchial\_medial\_axis}()$ ;
     $\theta_1 = \theta_2 \leftarrow \text{uniform\_random}(0, 2\pi)$ ;
     $\beta_1, \beta_2 \leftarrow \text{random\_tube\_translations}()$ ;
     $\mathbf{m} \leftarrow \{\beta_1, \beta_2, \theta_1, \theta_2\}$ ;
     $\mathbf{X}_{start} \leftarrow \text{CTR\_tip\_frame}(\mathbf{p}_{scope}, \mathbf{m})$ ;
    if  $\mathbf{p}_{goal}$  is in workspace of needle at  $\mathbf{X}_{start}$  then
         $\Pi_{needle} \leftarrow$ 
             $\text{RRT}(\mathbf{X}_{start}, T_{needle}, B, V, \kappa_{max}, \mathbf{p}_{start})$ ;
        if  $\Pi_{needle} \neq \text{null}$  then
             $\Pi' \leftarrow (\mathbf{p}_{scope}, \mathbf{m}, \Pi_{needle})$ ;
            if  $c(\Pi') < c(\Pi)$  then
                 $\Pi \leftarrow \Pi'$ 
            end
        end
    end
end
return  $\Pi$ ;

```

Algorithm 1: Motion planner for the multilumen lung access system.

In this example algorithm, the motion planner first searches for an optimal placement of the bronchoscope and the concentric tube probe by setting the deployment variables p_{scope} (the position of the bronchoscope's tip) and m (the insertions and rotations of the concentric tubes). A desirable
 5 (p_{scope}, m) pair places the steerable needle's start state X_{start} such that the needle can follow a collision-free path to the target while maximizing the needle's clearance from anatomical obstacles (where c encodes this cost function). We evaluate this property of a sampled (p_{scope}, m) pair by using a
 10 sampling-based motion planner to find a collision-free steerable needle control trajectory ($u_1, u_2, \dots$) to the target location p_{goal} . We re-execute the motion planner for the entire system repeatedly for a given amount of time, leveraging randomization to create many different motion plans and then selecting the one with lowest cost (e.g., greater clearance from obstacles).

We can use a sampling-based approach to create candidate
 15 placements of the bronchoscope tip p_{scope} within the bronchial tree. For efficiency, we leverage the fact that the bronchial tubes form a tree, which is a linear structure, and create a mapping between a parameter $y \in \mathbb{R}$ and the point p_{scope} in the world coordinate system. We assume that all possible bronchoscope placements must lie on or near the medial axis of the
 20 bronchial tree. The method samples points from the line segments of the medial axis by placing the medial axis's line segments $s_i = (p_i, p_{i+1})$ in an ordered sequence $(s_1, \dots, s_n)$ and then viewing this sequence of segments as a piecewise linear (and discontinuous) space curve parameterized by arc length $y \in [0, \sum_i \|p_i - p_{i+1}\|]$. We can therefore sample a parameter y from the
 25 domain of this space curve to generate a placement for the bronchoscope tip p_{scope} in the bronchial tree, and can then directly map y to p_{scope} via the mapping from the medial axis to the world coordinate system.

The sampled placement p_{scope} of the bronchoscope tip describes the start point of deployment of the concentric tube probe. From this point, we
 30 can sample possible deployments of the concentric tube probe, where deployments are parameterized by a vector m (e.g., $m = \{\beta_1, \beta_2, \theta_1, \theta_2\}$ for a 2-tube probe) to encode each component tube's axial rotation and

translation, possibly disallowing some values, for example to achieve approximate follow-the-leader trajectories that do not significantly deform tissues or to achieve computational efficiency.

We can use a mechanics-based kinematic model to compute the tip frame of the concentric tube probe after deployment. This tip frame marks the initial configuration X_{start} of steerable needle deployment. If the target location p_{goal} lies outside of the reachable workspace of the steerable needle when deployed from X_{start} (see Figure 9), we reject this proposed concentric tube probe deployment m . Figure 9 shows an example of a reachable workspace. The reachable workspace of the steerable needle is a trumpet shaped volume defined by its start configuration and the maximum curvature κ_{max} it is capable of achieving in the tissue.

A proposed placement (p_{scope}, m) of the bronchoscope and concentric tube probe fully specifies the start state X_{start} of the steerable needle. We evaluate the placement (p_{scope}, m) by attempting to find a steerable needle trajectory starting at X_{start} that reaches the target while avoiding anatomical obstacles. We can search for this trajectory using a motion planning algorithm for steerable needles.

An example motion planner is a sampling based motion planner such as the Rapidly-exploring Random Trees (RRT) motion planner. RRT incrementally builds a tree of system states that are reachable from X_{start} by collision-free paths. At each iteration, RRT samples a state X_{sample} in the system's state space, uses a distance function distance to select the nearest state X_{near} already in the tree, and uses a function steer to compute a control input u that, when applied to X_{near} results in a new state X_{new} nearer to X_{sample} . If the motion between X_{near} and X_{new} is collision-free, X_{new} is added to the tree. RRT iterates these steps until either (1) the tree connects to the target, or (2) the algorithm exceeds its time allotment.

To compute the steer function, we compute the unique control u_{steer} that directly connects the state X_{near} to the 3D position of X_{sample} , and then clamp the insertion length of u_{steer} to a maximum of l_{max} to generate the resulting control u . To compute the distance function between two states X and X' , we compute the control u_{steer} that connects X to the 3D position of X'

as above and return the insertion arc length of u_{steer} . We check whether the motion between two states is collision-free using software for collision detection.

In order to more quickly generate motion plans to the target site p_{goal} , we can introduce a strong goal bias; after each iteration of RRT, we perform an additional RRT iteration using p_{goal} as X_{sample} in order to bias growth of the tree toward the target.

Additionally, due to stresses on surrounding tissue, bevel-tip steerable needle insertion is typically impeded if the orientation of the needle tip is oriented more than a certain amount (e.g., 90° from its orientation at X_{start}). As such, controls that produce such states can be discarded as invalid.

If the RRT successfully finds a collision-free path from the start state to the target within the allotted time (0.05 seconds in this example), we can use the path's clearance metric (defined, for example, by the integration over the curve of the clearance between the tip of the steerable needle and the closest anatomical obstacle over the continuous path of the tip resulting from a plan) to quantify the cost of this particular placement (p_{scope} , m) of the bronchoscope and concentric tube probe. In practice, we can approximate the integral in clearance metric by finely discretizing the needle's path and using a numerical method such as the trapezoidal rule. We compute the clearance function using a collision detection library. If the RRT fails to find a collision-free path in the allotted time, we can associate a high cost with this placement of the bronchoscope and concentric tube probe.

By generating a placement p_{scope} of the bronchoscope, a deployment m of the concentric tube probe, and a feasible control trajectory (u_1 , u_2 , ...) for the steerable needle, we concatenate these operations to form a motion plan P_i of a collision-free sequence of configurations (q_1 , q_2 , ...) and associated control inputs for the entire multilumen lung access system.

The approach above generates a single plan, but we can repeat the process to generate new, different plans due to the randomization of the parameters. We iteratively create new motion plans P_i and evaluate their quality, always saving the best motion plan found so far. We repeat until we

find a plan with sufficiently high clearance or we exhaust the time allotted for plan computation.

This section described a motion planner for a multilumen transoral lung access system. The planner computes actions for deployment of a bronchoscope into the bronchial tubes, followed by concentric tube probe deployment into the lung parenchyma, and finally deployment of a steerable needle to reach a target while avoiding collisions with anatomical obstacles. The sampling-based motion planner quickly computes plans with high clearance from obstacles. The motion planner can be integrated with the system described above with reference to Figures 1-9.

Discussion

This specification describes a system designed to accurately reach and access targets located in the lung. This design utilizes three separate types of continuum mechanisms and is the first system that combines a tendon-actuated device, a concentric tube probe, and a steerable needle into one system. The robotic system and workflow presented in this specification for targeting sites in the lung has the potential to save lives by enabling earlier stage lung cancer diagnosis via accurate targeting of suspicious nodules and reduced risk of pneumothorax relative to a percutaneous approach. While healthy patients usually recover from pneumothorax, it is a serious complication for all patients, and is potentially life threatening for patients with co-morbidities or reduced lung function. The system can enable biopsy of suspicious nodules in the lung without puncturing the pleura, even for nodules located far from the bronchial tree or inaccessible using previous technologies.

Figure 10 is a block diagram of an example system **2000** for transoral lung access that includes a control system. System **2000** includes a bronchoscope **2002**, a concentric tube probe **2004** deployable from within bronchoscope **2002**, a steerable needle **2006** nested deployable from within concentric tube probe **2004**, and a control system **2008** for deploying concentric tube probe **2004** from bronchoscope **2002** into a lung to a location where a target is within a range of steerable needle **2006** and for deploying steerable needle **2006** from the location to the target.

Concentric tube probe **2004** can include a series of one or more curved tubes configured to translate and rotate inside one another to create curvilinear motion. Steerable needle **2006** can include a flexible needle shaft, a flexure joint at an end of the flexible needle shaft, and a beveled
5 needle tip. Control system **2008** can be configured to insert steerable needle **2006** into tissue and rotate steerable needle **2006** so that the steerable needle **2006** travels in a curved trajectory through the tissue.

System **2000** can include a puncture system **2010** and an actuation unit **2012**. Puncture system **2010** can include a sharp wire configured to
10 deploy through concentric tube probe **2004** and create an opening in a bronchial wall of the lung using a spring-loaded mechanism. Actuation unit **2012** can be configured for deploying the sharp wire and actuating the spring-loaded mechanism to create the opening. Actuation unit **2012** can also be configured for rotating and translating concentric tube sections of
15 concentric tube probe **2004** and for rotating and translating steerable needle **2006**.

Control system **2008** can include a magnetic tracking system and a closed-loop feedback controller for the steerable needle. Bronchoscope **2002** can include a flexible shaft, zero or more levers, zero or more tendons,
20 and a tendon-driver tip that bends when the tendons are actuated by the levers. Bronchoscope **2002** can include a working channel and a thin-walled polytetrafluoroethylene (PTFE) sheath through the working channel, and concentric tube probe **2004** and steerable needle **2006** can be nested within the PTFE sheath. In some examples, bronchoscope **2002** includes a coaxial
25 access tube insertable through a working channel of bronchoscope **2002** and over steerable needle **2006**, creating an access channel to the target. In some examples, an access channel to the target can be created inside steerable needle **2006**. Through the access channel, a biopsy can be collected or a therapeutic agent can be injected or deposited.

Control system **2008** can include an image guidance system **2014** for
30 receiving and displaying an intraoperative image feed and for registering the intraoperative image feed with preoperative data for the lung. In some examples, control system **2008** is configured, by virtue of appropriate

programming, to register the coordinate frames of the tip of bronchoscope **2002**, concentric tube probe **2004**, and steerable needle **2006** with a lung coordinate frame of the lung using breathing phase data from preoperative data for the lung.

5 Figure 11 is a flow diagram of an example method **2100** for motion planning for a multilumen transoral lung access system. Method **2100** can be performed by a system of one or more computers. The computers can be configured to perform method **2100** by virtue of appropriate programming stored on one or more computer readable media.

10 Method **2100** includes receiving, by one or more computers, input specifying a structure of one or more bronchial tubes, a target location, and one or more anatomical obstacles in a vicinity of the bronchial tubes (**2102**). Method **2100** includes selecting, by the one or more computers, a plurality of candidate starting positions and orientations within the bronchial tubes for a
15 lung access system comprising a bronchoscope, a concentric tube probe nested with the bronchoscope, and a steerable needle nested with the concentric tube probe (**2104**).

 Method **2100** includes searching, by the one or more computers using a motion planning algorithm, for a trajectory from each of the candidate
20 starting positions and orientations for the steerable needle to traverse from the concentric tube probe to the target while avoiding the anatomical obstacles, resulting in one or more candidate motion plans, each specifying a starting position and orientation for the lung access system and a trajectory for the concentric tube probe and steerable needle that avoids the
25 anatomical obstacles (**2106**). Method **2100** can include repeating the selecting and searching until reaching an end condition (**2108**). Method **2100** includes determining a cost for each of the candidate motion plans (**2110**) and selecting a motion plan having a lowest cost among the candidate motion plans (**2112**).

30 Method **2100** can include determining, for each of the candidate motion plans, a metric based on one or more distances between the steerable needle and the anatomic obstacles. Method **2100** can include using a mechanics-based kinematic model to compute a tip frame for the

concentric tube probe for each candidate starting position and orientation. Method **2100** can include determining, for each tip frame, whether the target lies outside of a reachable workspace for the steerable needle and rejecting the candidate starting position and orientation for the tip frame if the target
5 lies outside of the reachable workspace for the steerable needle.

Searching using the motion planning algorithm can include incrementally building a tree of steerable needle states that are reachable from the candidate starting positions and orientations by collision-free paths. Incrementally building the tree can include, at each iteration of a plurality of
10 iterations, sampling a possible state of the steerable needle from a state space of the steerable needle, using a distance function to select a nearest state to the possible state from the tree of steerable needle states, and determining a control input that when applied to the nearest state results in a new state that is nearer to the target than the nearest state.

Method **2100** can include, for each iteration, determining whether a motion between the nearest state and the new state is collision-free, and if so, adding the new state to the tree of steerable needle states. Method **2100** can include using a collision library for collision detection between the steerable needle and the anatomical obstacles.
15

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.
20

CLAIMS

What is claimed is:

1. A system for transoral lung access, the system comprising:
a bronchoscope;
5 a concentric tube probe deployable from within the bronchoscope;
and
a steerable needle nested deployable from within the concentric tube probe.
2. The system of claim 1, wherein the concentric tube probe comprises a
10 series of one or more curved tubes configured to translate and rotate inside one another to create curvilinear motion.
3. The system of claim 1, wherein the steerable needle comprises a flexible needle shaft and a beveled needle tip.
4. The system of claim 1, wherein the steerable needle comprises a
15 flexible needle shaft, a beveled needle tip, and a flexure joint attached to the bevel tip.
5. The system of claim 1, comprising a control system for deploying the concentric tube probe from the bronchoscope into a lung to a location where a target is within a range of the steerable needle and for deploying the
20 steerable needle from the location to the target.
6. The system of claim 5, wherein the steerable needle comprises a beveled needle tip, and wherein the control system is configured to insert the steerable needle into tissue and rotate the steerable needle so that the beveled needle tip creates a force that bends the steerable needle to travel
25 in a curved trajectory through the tissue.
7. The system of claim 5, wherein the control system comprises an actuation unit for rotating and translating concentric tube sections of the concentric tube probe and for rotating and translating the steerable needle.
8. The system of claim 5, wherein the control system comprises a
30 magnetic tracking system and a closed-loop feedback controller for the steerable needle.
9. The system of claim 5, wherein the control system comprises an image guidance system for receiving and displaying an intraoperative image

feed and for registering the intraoperative image feed with preoperative data for the lung.

10. The system of claim 5, wherein the control system is configured to register a coordinate frame of a tip of the concentric tube probe and/or a tip of the steerable needle with a lung coordinate frame of the lung using preoperative data for the lung.

11. The system of claim 1, comprising a puncture system comprising:
a sharp wire configured to deploy through the concentric tube probe and create an opening in a bronchial wall of a lung using a spring-loaded mechanism; and

an actuation unit for deploying the sharp wire and actuating the spring-loaded mechanism to create the opening.

12. The system of claim 1, wherein the bronchoscope comprises a flexible shaft, one or more levers, one or more tendons, and a tendon-driven tip that bends when the tendons are actuated by the levers.

13. The system of claim 1, wherein the bronchoscope comprises a working channel and a thin-walled polytetrafluoroethylene (PTFE) sheath through the working channel, wherein the concentric tube probe and the steerable needle are nested within the PTFE sheath.

14. The system of claim 1, comprising a coaxial access tube insertable through a working channel of the bronchoscope and over the steerable needle, creating an access channel to a target through which a biopsy can be collected or a therapeutic agent can be injected or deposited.

15. A method performed by a control system for transoral lung access, the method comprising:

deploying a concentric tube probe from within a bronchoscope into a lung to a location where a target is within range of a steerable needle; and

deploying the steerable needle through the bronchoscope, through the concentric tube probe, and from the location to the target.

16. The method of claim 15, wherein deploying the concentric tube probe comprises translating and rotating a series of curved tubes configured to translate and rotate inside one another to create curvilinear motion.

17. The method of claim 15, wherein the steerable needle comprises a flexible needle shaft and a beveled needle tip and wherein the method comprises inserting the steerable needle into tissue and rotating the steerable needle so that the beveled needle tip creates a force that causes the steerable needle to travel in a curved trajectory through the tissue.

18. The method of claim 15, wherein deploying the concentric tube probe comprises rotating and translating concentric tube sections using an actuation unit and rotating and translating the steerable needle using the actuation unit.

19. The method of claim 15, comprising deploying a sharp wire through the concentric tube probe and creating an opening in a bronchial wall of the lung using a spring-loaded mechanism.

20. The method of claim 15, comprising executing a closed-loop feedback controller for the steerable needle using a magnetic tracking system.

21. The method of claim 15, wherein the bronchoscope comprises a flexible shaft, one or more levers, one or more tendons, and a tendon-driven tip that bends when the tendons are actuated by the levers.

22. The method of claim 15, wherein the bronchoscope comprises a working channel and a thin-walled polytetrafluoroethylene (PTFE) sheath through the working channel, wherein the concentric tube probe and the steerable needle are nested within the PTFE sheath.

23. The method of claim 15, wherein the bronchoscope comprises a coaxial access tube insertable through a working channel of the bronchoscope and over the steerable needle, creating an access channel to the target through which a biopsy can be collected or a therapeutic agent can be injected or deposited.

24. The method of claim 15, comprising executing an image guidance system for receiving and displaying an intraoperative image feed for registering the intraoperative image feed with preoperative data for the lung.

25. The method of claim 15, comprising registering a coordinate frame of a tip of the concentric tube probe and/or a tip of the steerable needle with a lung coordinate frame of the lung using preoperative data for the lung.

26. A method for motion planning for a multilumen transoral lung access system, the method comprising:

receiving, by one or more computers, input specifying a structure of one or more bronchial tubes, a target, and one or more anatomical obstacles in a vicinity of the bronchial tubes;

selecting, by the one or more computers, a plurality of candidate starting states within the bronchial tubes for a lung access system comprising a bronchoscope, a concentric tube probe nested with the bronchoscope, and a steerable needle nested with the concentric tube probe; and

searching, by the one or more computers, for a trajectory from each of the candidate starting states for the steerable needle to traverse from the concentric tube probe to the target while avoiding the anatomical obstacles, resulting in one or more candidate motion plans, each specifying a starting state for the lung access system and a trajectory for the steerable needle that avoids the anatomical obstacles.

27. The method of claim 26, comprising determining a cost for each of the candidate motion plans and selecting a motion plan having a lowest cost among the candidate motion plans.

28. The method of claim 27, wherein determining the cost for each of the candidate motion plans comprises determining, for each of the candidate motion plans, a metric based on one or more distances between the steerable needle and the anatomical obstacles.

29. The method of claim 26, comprising repeating the selecting and searching until reaching an end condition.

30. The method of claim 26, comprising using a mechanics-based kinematic model to compute a tip frame for the concentric tube probe for each candidate starting state.

31. The method of claim 30, comprising determining, for each tip frame, whether the target lies outside of a reachable workspace for the steerable needle and rejecting the candidate starting state for the tip frame if the target lies outside of the reachable workspace for the steerable needle.

32. The method of claim 26, wherein searching comprises incrementally building a tree of steerable needle states that are reachable from the candidate starting states by collision-free paths.

33. The method of claim 32, wherein incrementally building the tree comprises, at each iteration of a plurality of iterations, sampling a possible state of the steerable needle from a state space of the steerable needle, using a distance function to select a nearest state to the possible state from the tree of steerable needle states, and determining a control input that when applied to the nearest state results in a new state that is nearer to the target than the nearest state.

34. The method of claim 33, comprising, for each iteration, determining whether a motion between the nearest state and the new state is collision-free, and if so, adding the new state to the tree of steerable needle states.

35. The method of claim 26, comprising using a collision library for collision detection between the steerable needle and the anatomical obstacles.

36. A system for motion planning for a multilumen transoral lung access system, the system comprising:

one or more processors; and

one or more non-transitory computer readable media storing instructions that, when executed by the one or more processors, cause the one or more processors to perform operations comprising:

receiving input specifying a structure of one or more bronchial tubes, a target, and one or more anatomical obstacles in a vicinity of the bronchial tubes;

selecting a plurality of candidate starting states within the bronchial tubes for a lung access system comprising a bronchoscope, a concentric tube probe nested with the bronchoscope, and a steerable needle nested with the concentric tube probe; and

searching for a trajectory from each of the candidate starting states for the steerable needle to traverse from the concentric tube probe to the target while avoiding the anatomical obstacles, resulting in one or more candidate motion plans, each specifying a starting state for the lung access

system and a trajectory for the steerable needle that avoids the anatomical obstacles.

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

receiving input specifying a structure of one or more bronchial tubes, a target location, and one or more anatomical obstacles in a vicinity of the bronchial tubes;

selecting a plurality of candidate starting states within the bronchial
10 tubes for a lung access system comprising a bronchoscope, a concentric tube probe nested with the bronchoscope, and a steerable needle nested with the concentric tube probe; and

searching for a trajectory from each of the candidate starting states for the steerable needle to traverse from the concentric tube probe to the
15 target while avoiding the anatomical obstacles, resulting in one or more candidate motion plans, each specifying a starting state for the lung access system and a trajectory for the steerable needle that avoids the anatomical obstacles.

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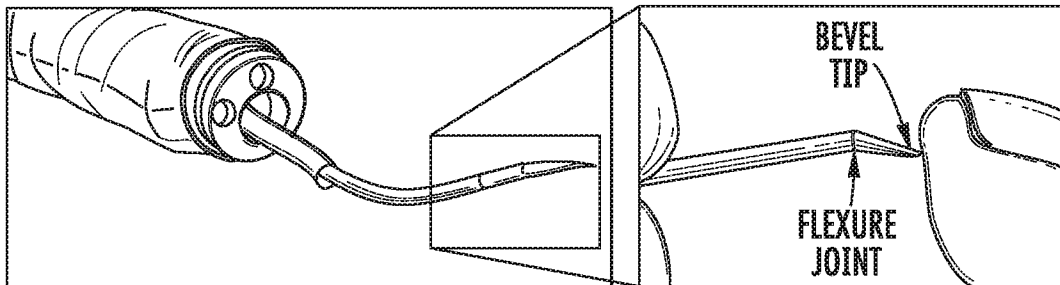


FIG. 1A

FIG. 1B

LUNG TARGETING USING THE THREE-STAGE STEERING SYSTEM ABOVE



FIG. 1C

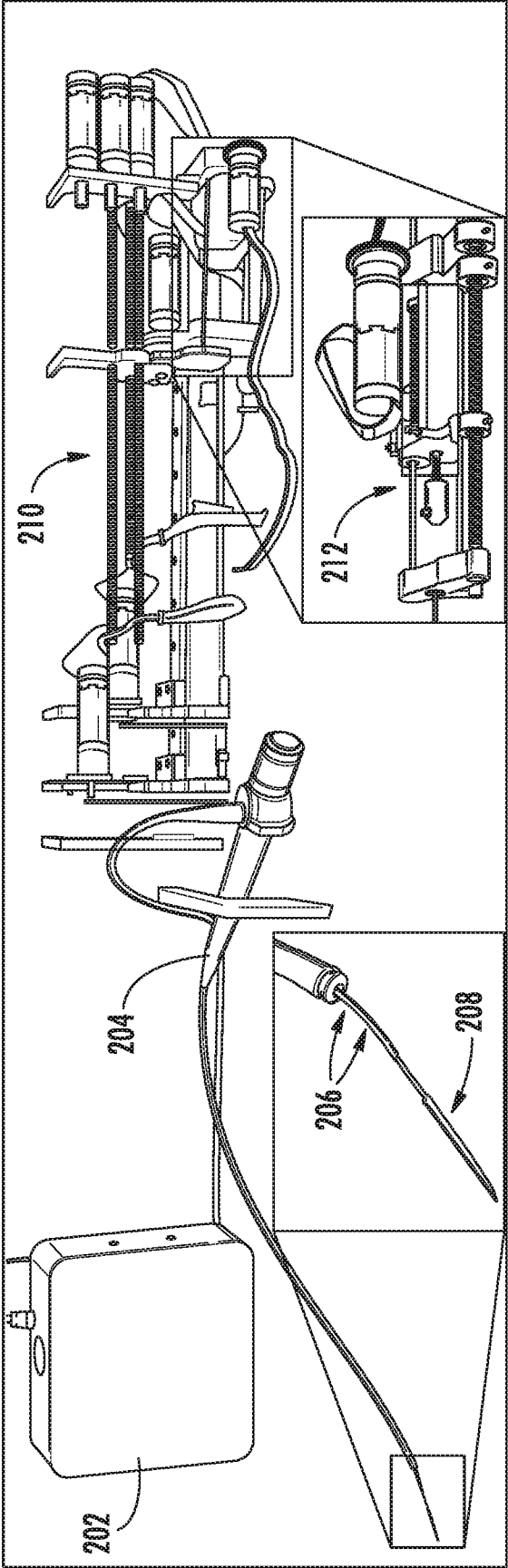


FIG. 2

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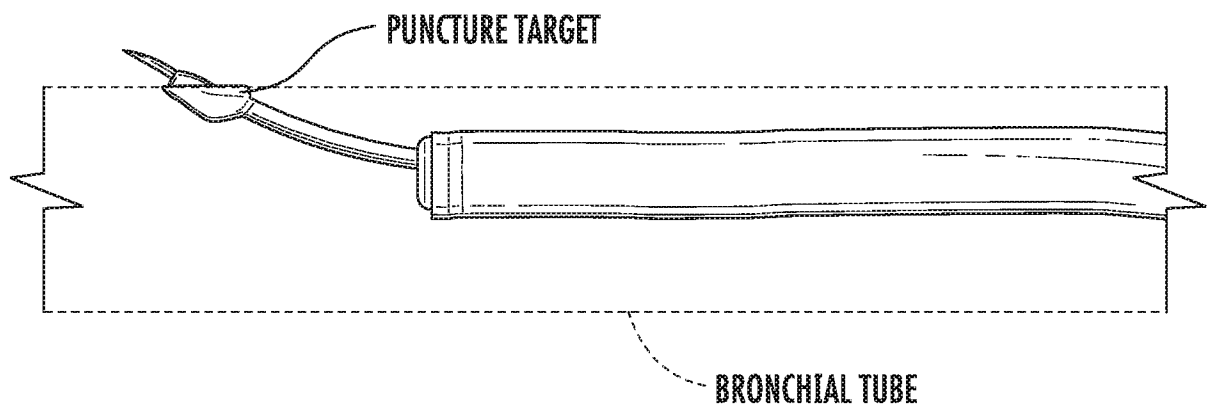


FIG. 3

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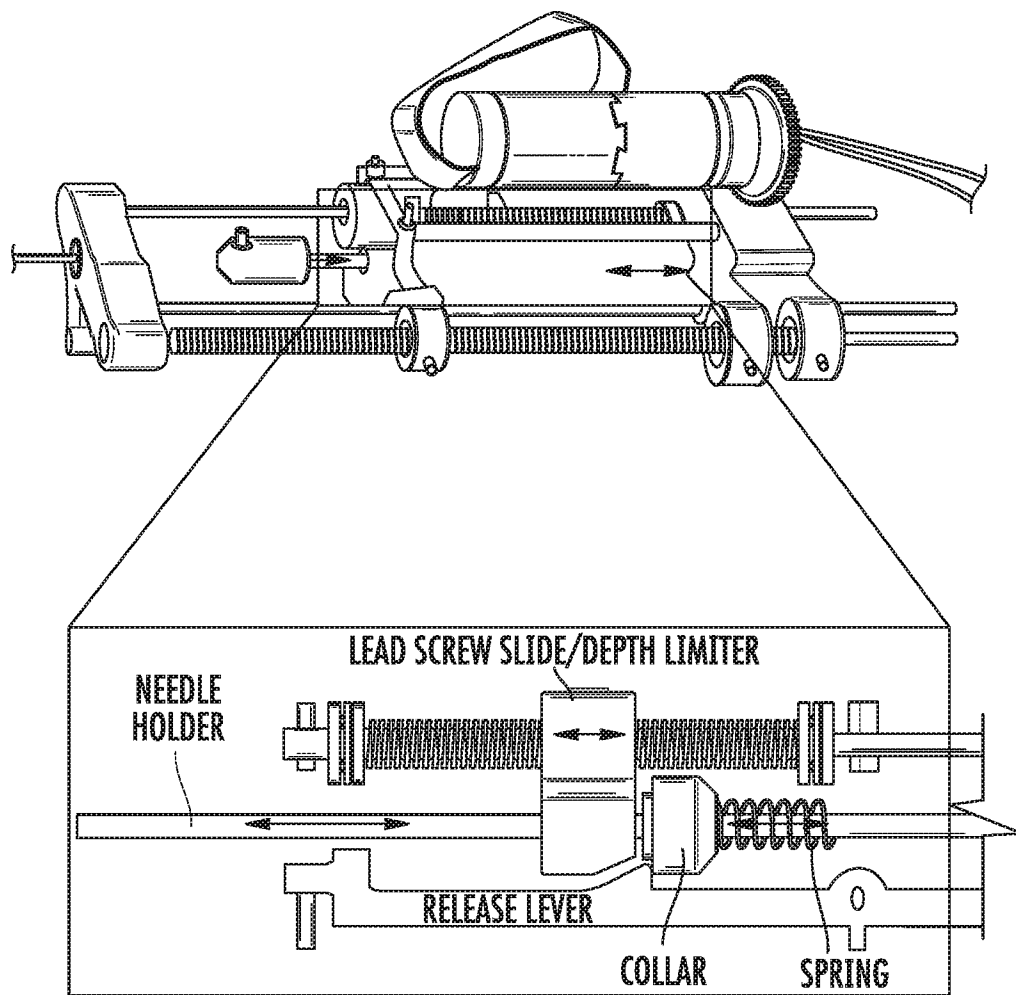


FIG. 4

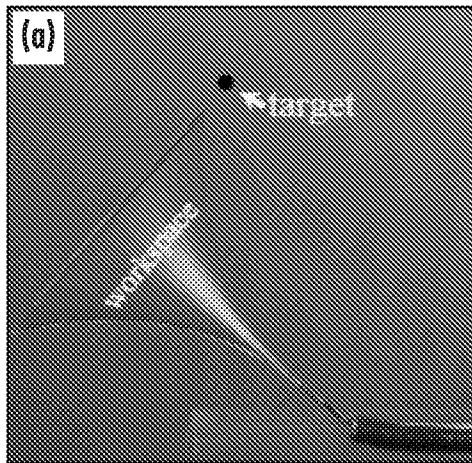


FIG. 5A

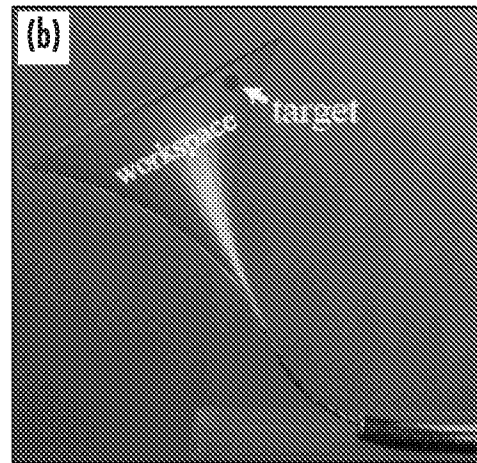


FIG. 5B

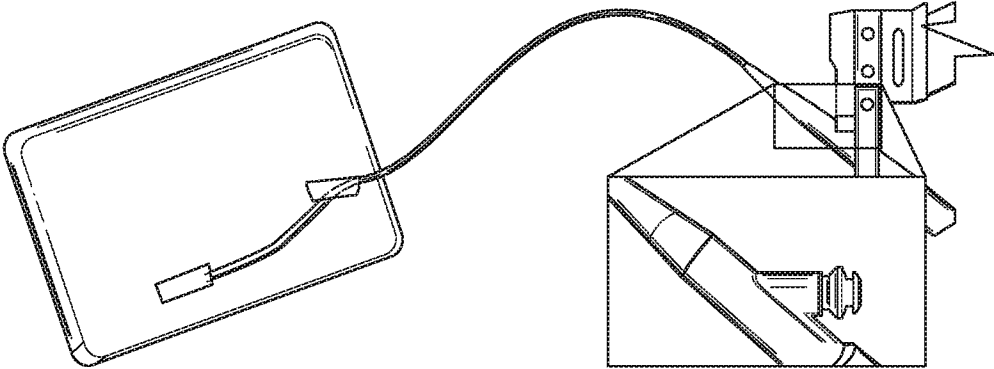


FIG. 6

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FIG. 7A

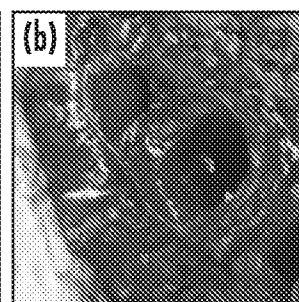


FIG. 7B

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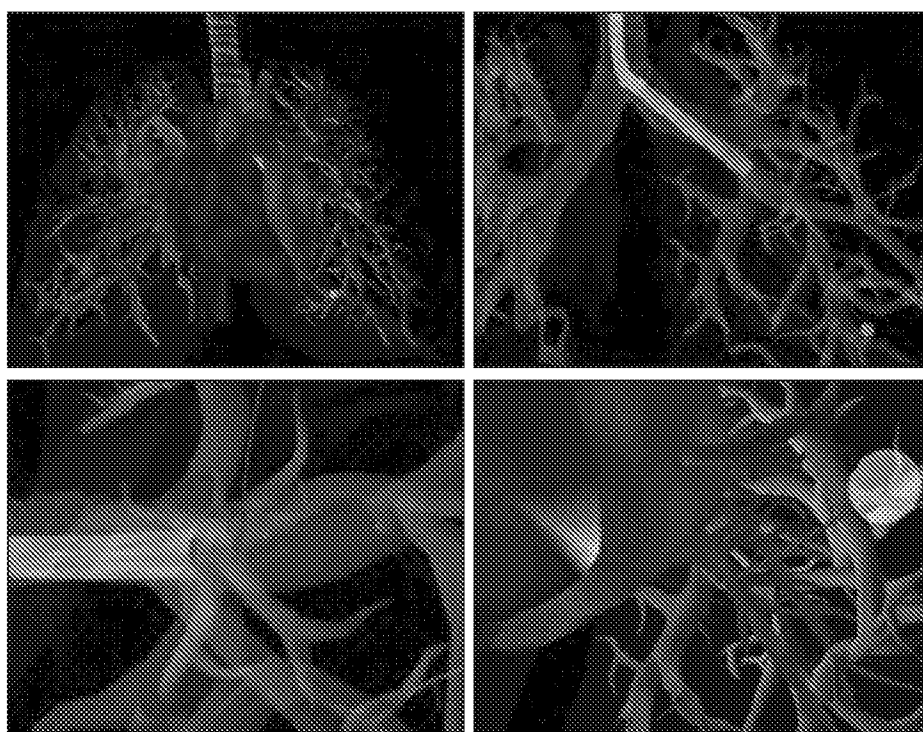


FIG. 8

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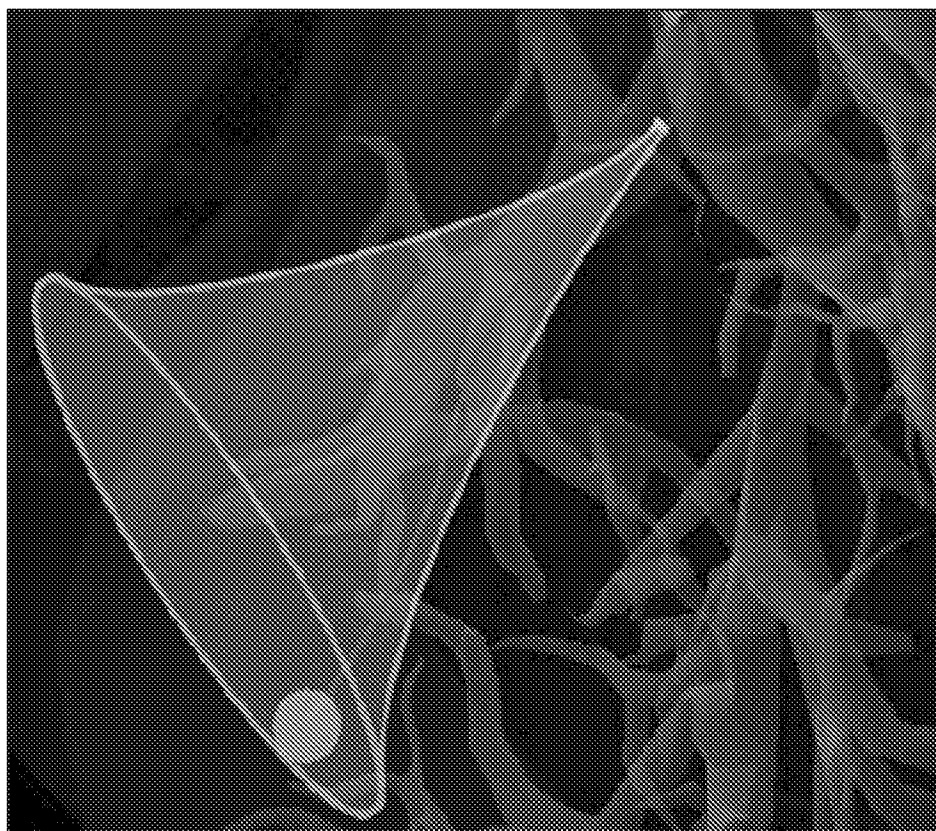
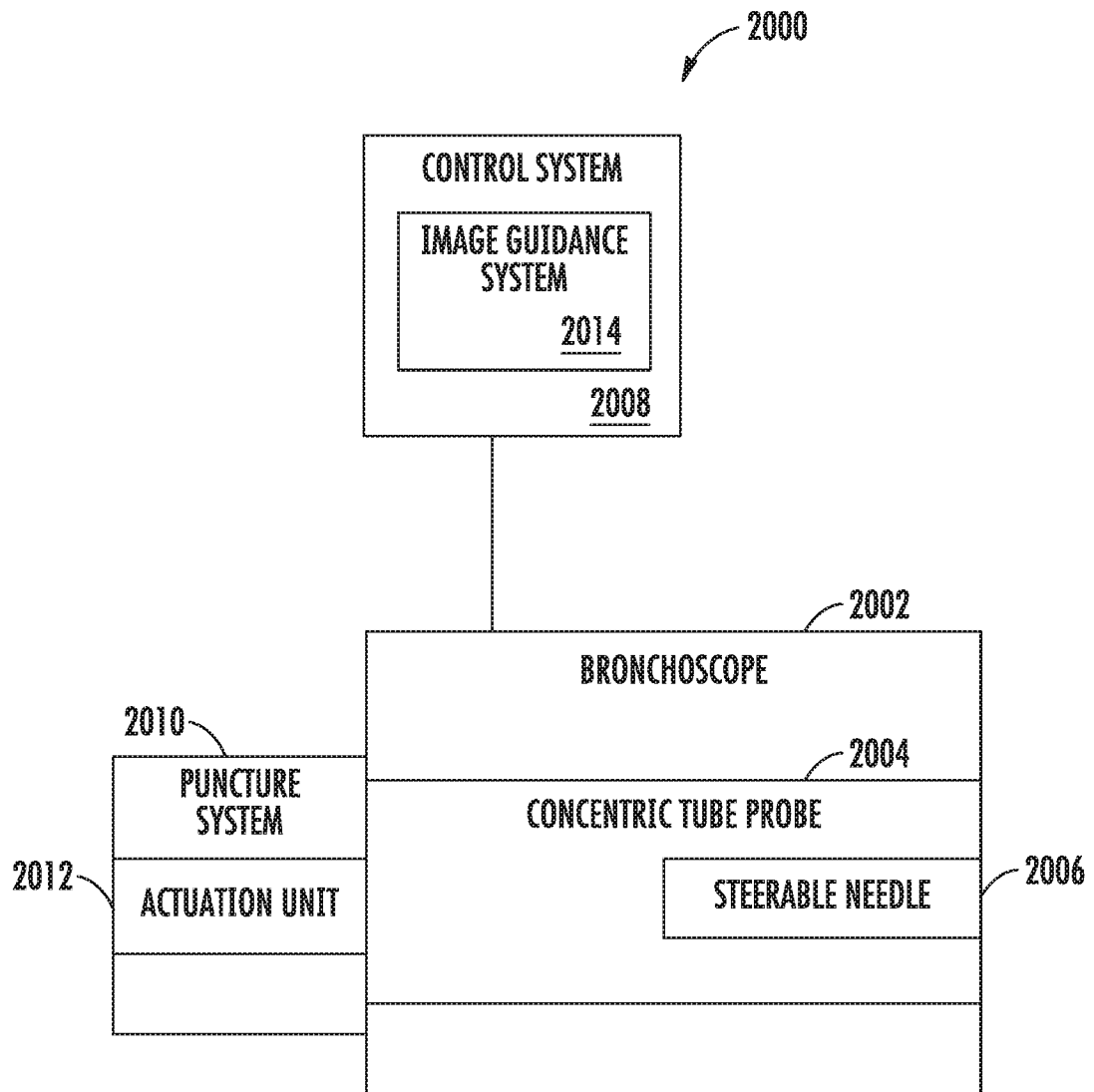
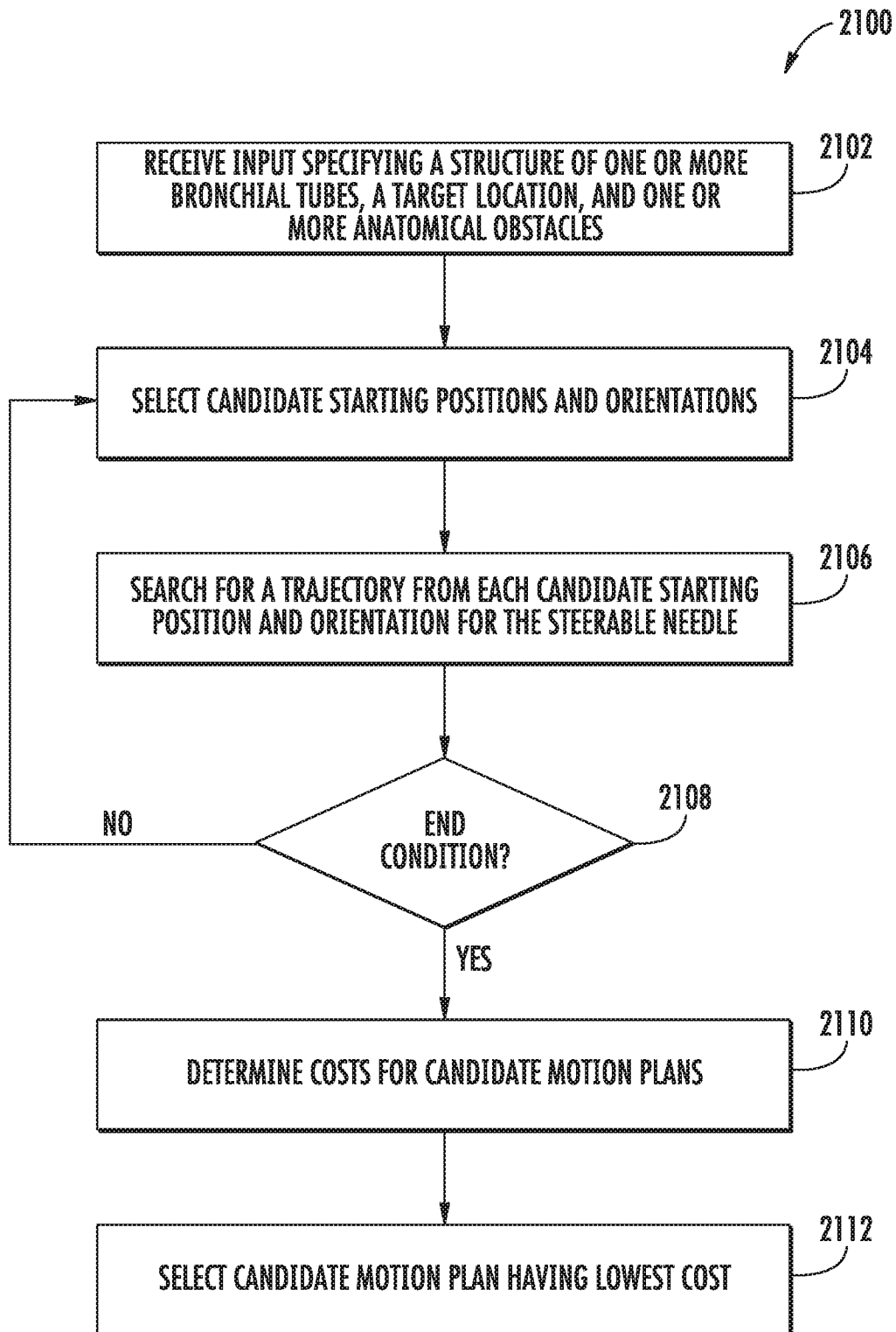


FIG. 9

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**FIG. 10**

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**FIG. 11**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2016/033762

A. CLASSIFICATION OF SUBJECT MATTER		
A61B1/267(2006.01) A61B10/04(2006.01) 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)		
A61B1/267, A61B10/04		
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)		
CIPO, DEPATISNET, DWPI, EAPATIS, ESP@CENET, KIPRIS, MEDLINE, PAJ, PatSearch, RUPTO, SIPO, USPTO		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/00080907 A1 (VANDERBILT UNIVERSITY) 19.03.2015, [0008]-[0010], [0027]-[0029], [0035]-[0049], [0066], fig.8	1-2, 5, 7, 9, 15-16, 18, 24
Y		3-4, 6, 8, 10-14, 17, 19-23, 25-37
Y	WO 01/70114 A1 (RITA MEDICAL SYSTEMS INC. et al.)27.09.2001, p.14 lines 11-31, p.20 line 14- p.21 line 3, p.23 lines 27-32, p.30 line 8-p.31 line 13, fig.3b, 5a-5b	3-4, 6, 8, 10-14, 17, 19-23, 25
Y	US 2009/0156895 A1 (THE PENN STATE RESEARCH FOUNDATION) 18.06.2009, fig.1, 5, abstract, [0048]-[0093], [0107]-[0117], [0138]-[0140]	26-37
Y	US 2012/0062714 A1 (KONINKLIJKE PHILIPS ELECTRONICS N.V.) 15.03.2012, abstract, [0025]	36-37
☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.		
* Special categories of cited documents: “A” document defining the general state of the art which is not considered to be of particular relevance “E” earlier document but published on or after the international filing date “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
06 September 2016 (06.09.2016)		29 September 2016 (29.09.2016)
Name and mailing address of the ISA/RU: Federal Institute of Industrial Property, Berezhkovskaya nab., 30-1, Moscow, G-59, GSP-3, Russia, 125993 Facsimile No: (8-495) 531-63-18, (8-499) 243-33-37		Authorized officer O. Ryzhkova Telephone No. (8-499) 240-25-91