Design of a Teleoperated Robotic Bronchoscopy System for Peripheral Pulmonary Lesion Biopsy

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***Abstract*—Bronchoscopy with transbronchial biopsy is a minimally invasive and effective method for early lung cancer intervention. Robot assisted bronchoscopy offers improved precision, spatial flexibility, and reduced risk of cross-infection. This paper introduces a novel teleoperated robotic bronchoscopy system and a three-stage procedure derived for robot-assisted bronchoscopy. The robotic mechanism allows for translation, rotation, bending of a bronchoscope, and as well as the control of a novel variable stiffness catheter for tissue sampling. Rapid prototype of the robotic system has been fully developed and characterized with in-silico and in-vivo animal experiments in this study. We conducted the studies to evaluate the robot's design concept and feasibility of usage for transbronchial biopsy. The results demonstrate the potential of the proposed robotic bronchoscopy system in enhancing accuracy and safety during bronchoscopy procedures.**

***Index Terms*—Robotic bronchoscopy, Robot assisted surgery, Teleoperation**

I. Introduction

Lung cancer is the third most common cancer, and it has a significantly high morbidity and mortality rates worldwide. This medical condition has been consistently related to an annual death toll of 1.9 million people in the last five years [1]. This type of cancer usually start with the development of peripulmonary nodules in the lungs. Thus, early detection and treatment of pulmonary nodules are sought for effective clinical intervention. This is leading to complete cures for many early-stage lung cancer patients thus reducing the death rates of lung cancer [2]. The conventional methods of carrying out lung biopsy involve the use of percutaneous or bronchoscopic needles [3]. Typically, percutaneous needle biopsy involves inserting a needle into the lung lesion through the chest skin to obtain biopsy tissue. Clinical practice and evaluation shows that percutaneous needle biopsy carries a high risk of complications such as pneumothorax and significant bleeding [4]. Consequently, transbronchial biopsy an alternative as it is done through minimal invasion and possess relatively lower risks [5].

Robotic technology with improved precision, spatial flexibility, and dexterity has the potential to enhance minimal invasive surgeries [6]. Robot-assisted minimal invasive surgeries (RAMIS) enable faster, safer, and more convenient navigation of surgical tools for intraluminal, endoluminal and transluminal interventions without the need for multiple or wide incisions [7]. The absence of large incisions during RAMIS offers numerous advantages such as improved cosmology due to small incision or no visible scarring, reduced postoperative pain, and avoidance of general anesthesia for patients [8]. Similarly, doctors are able to perform different interventions without been exposed to the operational risks [9]. Recently, there have been notable advancements in the development of robot-assisted bronchoscopy systems. A prominent example is the Monarch™ platform (Auris Health, Redwood City, USA). The system incorporates inner bronchoscope and outer sheath equipped with electromagnetic (EM) for teleoperated navigation guidance. Ion™ Endoluminal System (Intuitive Surgical, Sunnyvale, CA, USA) is another iconic bronchoscopy platform used for the intervention of peripulmonary nodules. Rather than using EM, the system employs shape-sensing technology for tool navigation. Typically, shape-sensing Bragg grating fiber and video scope are utilized for navigation guidance during interventions. A common drawback is the lack of direct visualization system during tissue sampling with these systems [10]. The recently FDA approved Galaxy™ system developed by Noah Medical (San Carlos, USA) offers real-time navigation and lesion updates through tomosynthesis during lung interventions. It is worthnoting that the latter is augmented with a readily available C-arm for fluoroscopy; thus, exposing surgeons to X-ray radiation which are capable of causing surgeons head and neck cancer [11] [12].

In addition to commercially available robotic bronchoscopy systems, there have been notable academic efforts in the development of robots for transbronchial lung biopsy. Swaney et al. proposed a robotic system utilizing concentric tube and a steerable needle with magnetic tracking, enabling precise movement through the bronchial wall [13]. Similarly, Amack et al. designed a concentric tubular robot with a compact, modular, and multi-stage mechanism to deploy a steerable needle through a standard flexible bronchoscope [14]. Duan et al. developed a bronchoscope robot with a small end-

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effector composed of a nickel-titanium tube, achieving three degrees of freedom motion [15]. These research efforts have predominantly focused on innovating mechanical structures with focus on novel designs for continuum robots or flexible robots. The transbronchial robots adopted unique design typologies, and offer range of functionalities that contribute to the advancement RAMIS in lung cancer interventions. Taken an alternative path, we have designed a robotic system for intraluminal bronschoscopy. This paper is aimed to present the design details of the robotic system and characterization of its functionalities. Typically, the platform integrates a new robotics mechanism equipped with various biopsy tools which can be used to coordinate a three-stage bronchoscopy routine. The procedure follows initial insertion of a bronchoscope robot, dynamic adjustment of variable stiffness catheters (VS-Catheters), and tissue sampling. To ensure accurate positioning, an endoscopic video and EM tracking fused navigation system is employed. The feasibility and practicality of the proposed robotic system are assessed through simulations and in-vivo experiments.

II. Material and Methods

The system consists of a teleoperated surgical robot designed for trans-respiratory diagnosis, along with a corresponding master-slave control system.

A. System Overview

Fig. 1 illustrates the proposed bronchoscopy robotic system. Our architecture follows mounting the actual tool manipulator on a passive robotic arm to ensure stability during teleoperation by surgeons. For a typical bronchoscopy intervention, the manipulator will be positioned adjacent to a patient with the EM tracking system located next to them. Thus, the robotic system can the simulate surgeons' realistic operating mode during the intervention. During the procedure, the surgeon holds a tablet console to control a flexible visual bronchoscope, inserts a flexible tube into the patient's mouth, and utilizes the robot for advancements, rotations, and adjustment of the bending angle of the front end of the flexible bronchoscope. The robot also enables control of the biopsy forceps for feeding and tissue sampling. Surgical tools such as biopsy forceps, biopsy needles, and cytologic brushes reach the target position through a 2.6 mm-diameter working channel.

B. Bronchoscope Manipulator

The robotic system incorporates various components as shown in Fig. 2, including a flexible bronchoscope, bronchial biopsy instruments, VS-Catheters, and several tablets functioning as master consoles (Microsoft Surface Pro 8). The instructions from surgeons are wirelessly transmitted to robot controller through TCP/IP protocol. Subsequently, the robot responds to surgeons' commnads by navigating the flexible bronchoscope along a given trajectory. In addition, the robot utilizes multimodal navigation, combining EM tracking and visual navigation, to accurately locate the position of the bronchoscope in real time. Employing a multi-operator strategy,

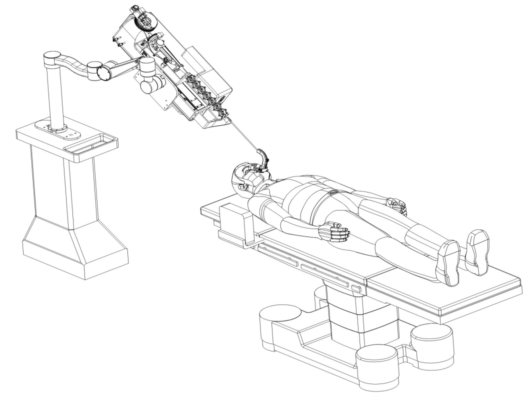

Fig. 1. Illustration of the bronchoscopy system mounted on a robotic arm, a trachea guide apparatus is inserted into patient's mouth to stabilize interventional direction.

the robot is controlled through scheduling arrangement and weight distribution, which enables mentor surgeons and trainee surgeons observe the same surgical site and collaboratively control the surgical instruments simulatanously.

Based on analysis of the flexible bronchoscopy tools, the mechanism is designed to replicate the conventional way of steering bronchoscope and biopsy forceps during manual intervention. The design of the embedded system is based on our advancement in endovascular interventional surgical robot [16]. Following the structure of bronchoscopy robot (in Fig. 2), we installed a Nvidia® Jetson AGX Orin™ Developer Kit, which is programmed for controlling the electric slider (Panasonic®, Osaka, Japan), rotary motor (Orientalmotor®, Tokyo, JP), motor drivers, gear sets, and biopsy forceps. Unlike existing robotic bronchoscopy systems, our newly proposed system integrates a commercial bronchoscope in operating room to improve cost efficiency and reduce usage complexity.

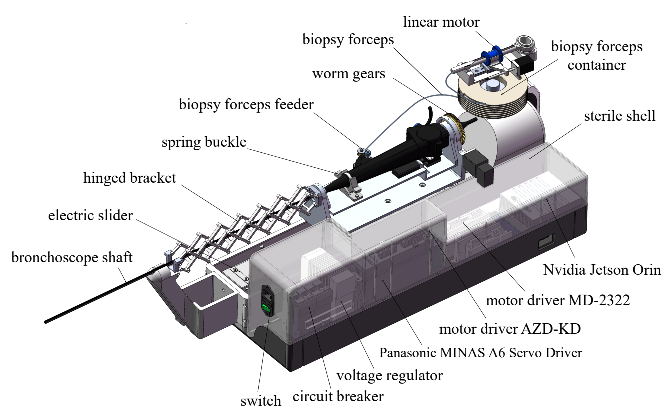

Fig. 2. Structure of the bronchoscope robot.

The bronchoscope (UEWorld™, Xianju, China) used in our work can be replaced easily by other flexible endoscopes. This videoscope has an external diameter of 5.2 mm and working channel of 2.6 mm, with the ability of $160°$ upward and $130°$

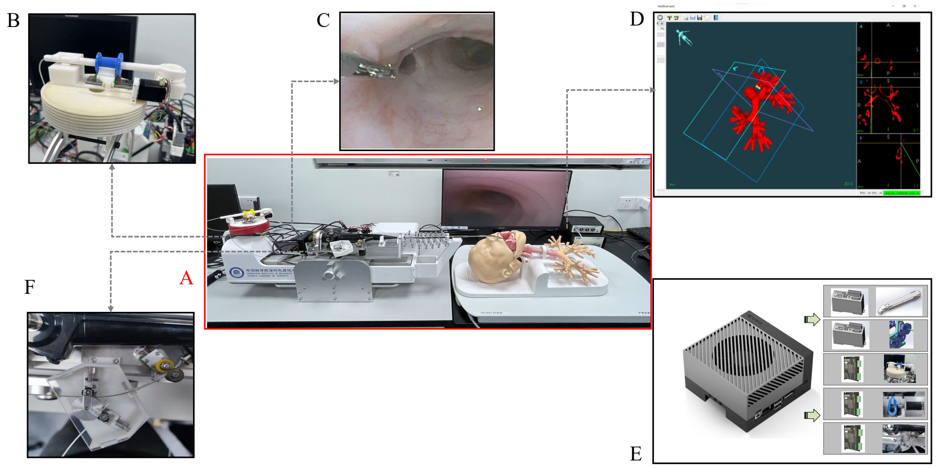

Fig. 3. Robotic Bronchoscopy System. (A) Robot and bronchus phantom; (B) Biopsy forceps manipulator; (C) Bronchoscopic video. (D) EM-Sensor based navigation system; (E) Embedded control system, electrical devices and motors; (F) Biopsy forceps and VS-Catheters delivery device.

downward bending angle. Commercial biopsy forceps can be installed in the forceps container. Several motors are mounted with friction wheel to deliver biopsy forceps and VS-Catheters, as shown in Fig. 3.

C. Multimodal Navigation System

We have installed 6-DoF EM sensors to enable real-time navigation, tracking, and three-dimensional localization of the surgical instruments. For this purpose, an EM tracking system (NDI Aurora, Waterloo, Canada) with a field generator that produces EM field with known geometry, is integrated with the robotic system. This provides information about the position and orientation (roll, pitch, and yaw) of the EM sensor. To integrate endoscopic video and EM tracking information, a multimodal navigation system is employed, utilizing the open-source software CustusX [17]. The software includes a toolbox of navigation features, image-processing algorithms, and connections to external hardware for image-guided therapy. By combining images, tracked surgical instruments, and computer display, a comprehensive navigation system is created, enabling real-time identification of the direction and position of the tip of the bronchoscope.

D. Variable Stiffness Catheter

A catheter with variable stiffness is designed and utilized to facilitate the extension of surgical instruments through the working channel of an endoscope, thereby reducing the potential risk of unintentional tissue penetration [18]. The catheter design was aimed to maintain optimal flexibility for seamless traversal of tortuous intra-luminal pathways in the human body, while also ensuring sufficient rigidity to provide adequate support during tissue biopsy. Specifically, we developed novel VS-Catheter which is composed of low melting point alloy (LMPA) to enhance the catheter's flexibility in the context of RAMIS and expand the accessible area for bronchoscopic biopsy forceps. Unlike the bronchoscope, the VS-Catheter can be inserted into narrower bronchi and offers more flexible control with dynamic stiffness. The VS-Catheter consists of a hollow flexible inner tube and an outer tube incorporating an interlayer infused with LMPA (Field's metal) at a temperature of 47°C. Additionally, a heat-generating resistance wire is helically wound around the flexible inner tube. This wire serves the purpose of melting the Field's metal, thereby providing variable stiffness functionality to the catheter. The resistance wire and the Field's metal together constitute a stiffness measurement circuit, and a controller-based methodology is employed to achieve continuous adjustability of the catheter's stiffness.

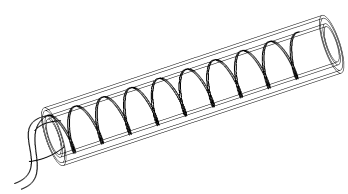

Fig. 4. Structure of proposed VS-Catheter, consist of hollow flexible tube fulfilled with LMPA and heating wire.

The structural design of the catheter exhibits simplicity, ease of manufacture, and cost efficiency. It utilizes Field's metal phase change technology to achieve controllable stiffness. Importantly, the cooling process of the catheter occurs naturally at the physiological temperature of the human body, eliminating the need for external stimuli and ensuring safety and reliability. The catheter incorporates two circuits: the heating circuit and the measurement circuit, enabling real-time adjustment of the catheter's stiffness to accommodate the intricate anatomical environment, thereby enhancing surgical safety.

III. Novel Robotic Bronchoscopy Procedures

The complete procedures of robot-assisted bronchoscopy involve several steps. These are acquisition of imaging data, segmentation, registration, and 3D construction of the bronchus, as shown in Fig. 5. The process begins with acquiring imaging data, typically through CT or MRI scans, to create a 3D map of the patient's airways. This map is integrated into the system to provide a visual representation of the surgical workspace. After the registration is complete, the physician utilizes the 3D map to plan bronchoscopy procedure. After setting up the robotic manipulator on the passive arm and calibrating it, the physician can remotely control the robotic system with the multimodal navigation system. The surgeon identifies location of suspicious areas of tumors or lesions, and determines the optimal route in bronchus to reach them. Table I presents essential mechanical parameters of the bronchoscopic tools.

The application of the VS-Catheter involves a three-stage bronchoscopy surgical procedure, as shown in Fig. 6. In the first stage, the clinician maneuvers the robot to navigate the bronchoscope to a target site. The navigation process involves motions like translation, rotation, and tip bending. The VS-catheter is heated (under safe temperature 53°C) to decrease its stiffness. For stage two, the softened VS-catheter is inserted via the bronchoscope's working channel. Its dynamic stiffness can be adjusted based on factors like heartbeat and respiration. Compared to the bronchoscope, the VS-catheter can be inserted into thinner bronchi and provides more flexible control. Once the softened catheter reaches the precise location of the targeted lesion, the power supply to the heating resistance wire is discontinued, allowing the low-melting-point alloy to cool naturally and restore the catheter's stiffness. Lastly, tissue sampling is performed using the biopsy forceps manipulators in the third stage. The physician can thereby examine patient's airways, search for abnormalities or suspicious areas, and perform tissue biopsy for further testing. Surgeons have the capability to control these three-stage processes using tablets and tele-operate the robot. This emphasizes the importance of robotic surgery, as it enables surgeons to manipulate multiple medical tools without the need for shift changes, ensuring stability within the trachea.

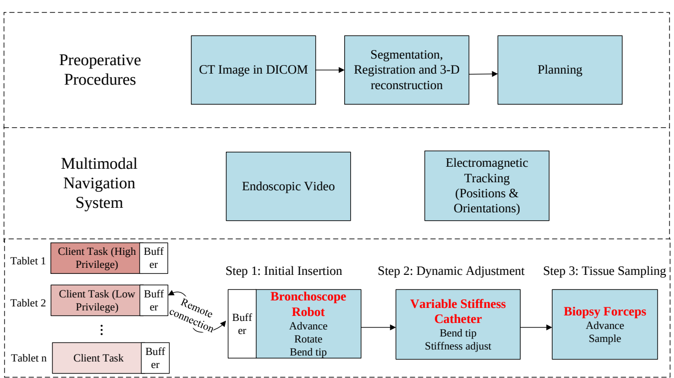

Fig. 5. Proposed three-stage bronchoscopy surgical procedures, with initial insertion, dynamic adjustment, and tissue sampling.

IV. Evaluation and Experiment

We conducted in-silico and in-vivo experiments to demosntrate the usability of the proposed robotic system for bronchoscopy procedures. The robot's model was imported

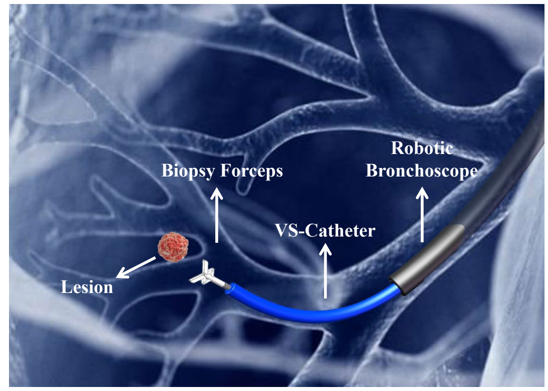

Fig. 6. Three-stage bronchoscopy surgical procedure composed of robotic bronchoscope, VS-Catheter, and tissue sampling by biopsy forceps.

TABLE I
Essential Mechanical Parameters.

Idx.	Tool	Description	Value
1	Bronchoscope	Outside Diameter	5.2 mm
2	Bronchoscope	Inside Diameter (Working Channel)	2.6 mm
3	VS Catheter	Outside Diameter	2.4 mm
4	VS Catheter	Inside Diameter	1.2 mm
5	Biopsy forcep	Diameter	1.0 mm

from Solidworks into Adams View 2020 to analyze its mechanical transmission via dynamic simulation. The results in Fig. 7(A) depict the change in velocity and acceleration over time during axial displacement of the bronchoscope. The velocity change follows a sinusoidal function, initially accelerating and then decelerating. The peak velocity reaches 30 mm/s and the acceleration fluctuates within the range of 124.7 mm/s^2. This decreasing-then-increasing pattern allows the linear sliding table to smoothly reach the desired target position without being constrained by driving speed. Fig. 7(B) presents discrete diagrams illustrating the speed changes of the worm gear under different driving speeds. It is evident that radial rotation is more stable at low speeds, while speed fluctuations become more pronounced at high speeds. This observation aligns with the actual operation of the worm during slow biopsy surgery. The driving speed (red circle) is maintained at approximately 1000 d/s. Fig. 7(C) and (D) simulate the workspace and distribution probability of the endeffector using Cosserat theory in Matlab, respectively. These simulations provide insights into the range and likelihood of end-effector positions during the surgical procedure. Proper cooperation with the mechanical arm ensures that, in theory, the end effector can access all positions within the bronchi.

Similarly, in-vivo animal experiment was carried out in a swine animal with a weight of 30 kg. The study was approved by Institutional Review Board and Ethics Committee of Shenzhen Institutes of Advanced Technology (AAS 201205P). As show in Figure 8, the robotic system place next the animal as described in II-A. The system was controlled by two operators using tablets with different priorities, one with full authority, another only with biopsy forceps control authority. Two EM sensors were attached to the swine's fore breast and the tip of the bronchoscope, respectively. We successfully performed a biopsy procedure in which small tissue was clamped and removed from the tertiary bronchus of the swine. The stiffness of the catheter was adjusted by energizing the resistance wire, providing adaptability based on the specific requirements of the procedure. The usability and effectiveness of the designed bronchoscopy surgical robot were demonstrated. When taking a biopsy sample during the experiment, the presence of the VS-Catheter makes the biopsy process more stable, and the implementation of the VS-Catheter enabled more flexible control of the biopsy forceps within the bronchus.

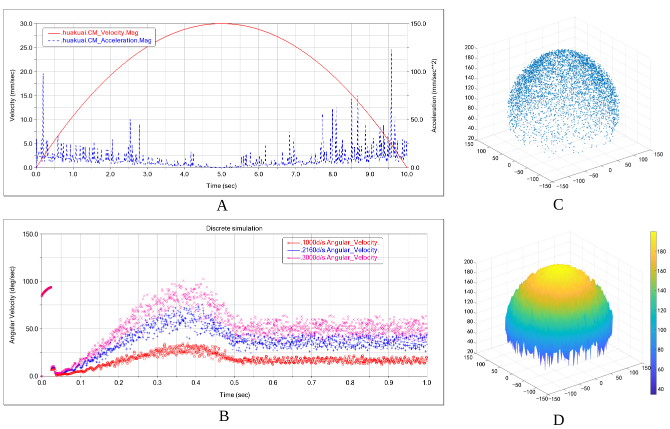

Fig. 7. Simulation results. (A) Translation simulation of endeffector; (B) Rotation simulation in different angular velocities; (C) Reachable workspace of endeffector; (D) Distribution probability of endeffector.

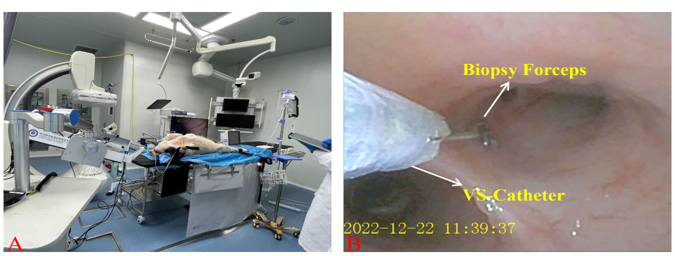

Fig. 8. Proposed bronchoscopy system. (A) In-vivo experiment stage; (B) Intra-body navigation view of the bronchoscopy tools in swine's trachea.

V. Conclusion

This paper introduces a novel teleoperated robotic bronchoscopy system and three-stage bronchoscopy procedure with VS-Catheters. The feasibility of the proposed robotic system is explored through kinematic simulations and analysis of the reachable workspace. The experimental study has validated the design concept and the feasibility of proposed robotic system. However, it is important to note that further validation is required through comprehensive preclinical studies and additional in-vivo tests involving surgeons. These subsequent evaluations will provide more insights into the practicality and efficacy of the system in real-life surgical scenarios.

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