Navigation Testing Procedures for the ENDORO Robotic System

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Abstract. Lung cancer is the leading cause of death among different type of cancers worldwide. To decrease the recorded mortality rates, earlier diagnosis and timely treatment are essential. The two-degrees-of-freedom robotic and image guided navigation system, ENDORO is designed to find peripheral pulmonary nodules using an electromagnetic tracking equipment, a navigation software and a specially designed biopsy catheter. The aim of the present study was to assess the accuracy of the ENDORO system in a rigid lung phantom built from a set of computerized tomography scans of a patient. We describe the testing environment, necessary configurations and navigation results for main lung airways. The evaluation consists in identifying all navigable paths from the entry point to the lung periphery, counting the number of intersection crossing, the time required for navigation and the number of movements the robot performed. The results demonstrate appropriate navigation accuracy for catheters with a rigid tip. Future studies will test robotic navigation with a catheter with a bending tip.

Keywords: Lung Cancer · Robotic System · Electromagnetic Navigation · 3D-Printed Lung · ENDORO Robot Prototype · Testing

1 Introduction

Lung cancer has the highest annual mortality rate globally among all types of cancer [1] and despite the recent advancements, the disease is still detected mostly in its late stages [2]. This problem has worsened due to the COVID-19 pandemic because medical focus and resources have shifted away from cancer detection, and it is anticipated that this shift may result in decreased survival rates in the near future [3]. Earlier diagnosis and timely treatment are crucial in order to reduce the cancer burden, and thus minimize the number of deaths caused by lung cancer [4].

An efficient solution to investigate peripheral pulmonary nodules is the ENDORO robotic system with its navigation software platform iMTECH [5] and special instruments, whose research and development are conducted in the Laboratory of Microtechnologies and Medical Engineering from University of Craiova [6].

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In this paper we propose a framework for testing the ENDORO robotic system prototype. Testing is performed on a novel artificial lung built by 3D printing using computerized tomography (CT) scans. We used this phantom to test the accuracy of the robotic system's navigation. Based upon our testing results, the system can successfully reach the main airways in the lower region of the lung but further accuracy improvements of the navigation platform should be obtained for upper lung investigation.

2 ENDORO Robotic System

The ENDORO robotic system together with the catheter and guide-wire operates by translation and rotation. These are the two degrees of freedom in our robotic system. Translation of the catheter is performed by either retraction and advancement, while rotation is done around the catheter's own axis. Further, the ENDORO robotic system is equipped with a navigation software platform called iMTECH that allows the user to visualize in real time the position of the catheter (Fig. 1).

The ENDORO robot is controlled by two Robotis electric motors Dynamixel AX-12A, connected to a microcontroller OpenCM9.04, and linked to an expansion board OpenCM 485. The movements of the ENDORO robot are performed using a software program running on a Raspberry Pi microcomputer (Raspberry Pi 4, Model B).

The ENDORO platform uses electromagnetic systems developed by Northern Digital Inc. together with the iMTECH navigation software platform. The electromagnetic tracking system consists of:

- a flat field generator (Aurora Planar 20-20);
- a system control unit (Aurora System Control Unit V2);
- two sensor interface units (Aurora Sensor Interface);
- two built-in sensors: in the lung (Aurora 6DOF Reference) and at the top of the catheter (Aurora 5DOF FlexTube).

Using the software platform, the exact location of the medical instrument on a 3D map is displayed in real time.

The prototype of the ENDORO system, as well as the artificial lung model were manufactured and assembled in the Laboratory of Microtechnologies and Medical Engineering (LMME) from the University of Craiova. The robot enclosure's parts were printed

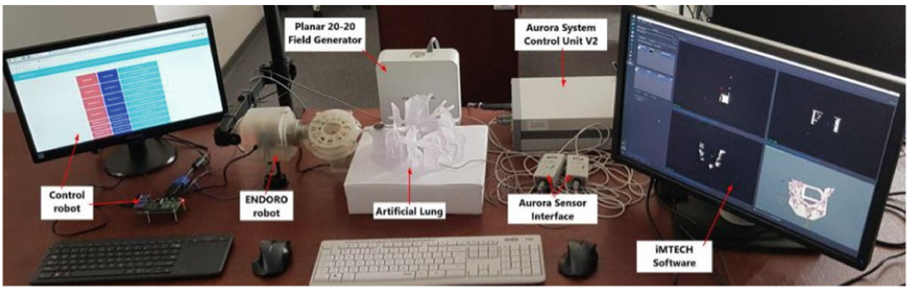

Fig. 1. Testing environment setup of the ENDORO robotic system.

from Formlabs Rigid 4000 type resin, using the existing 3D printer in the laboratory (Formlabs Form 2).

In the construction of the artificial lung, a series of computerized tomography scans performed based on the natural lung model have been analyzed. Compared to the previous artificial model we had in the laboratory, the new model has dimensions similar to those of a natural lung in the body of an adult for a more realistic testing (Fig. 2).

A comparative analysis of the characteristics of the two lung testing models is highlighted in Table 1. The new model has smaller dimensions than the old model for closer approximation to the human lung.

The ENDORO system has the following features:

- The capacity of the rotation system is 300°, supporting 65 movements in steps ranging between 4.5° and 5°. The response time of each movement is 1.5 s.
- The maximum capacity of the translation system is given by the length of the used catheter, having an unlimited number of steps, with an accuracy between 2.3 mm and 2.8 mm for each step. The response time is instantaneous.

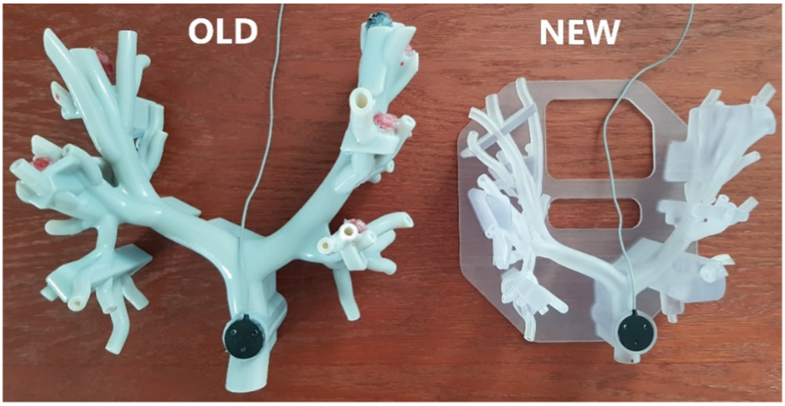

Fig. 2. Old and new lung prototype models.

Table 1. Characteristics of old and new lung prototype models.

Characteristics	Old model	New model
Length	260 mm	210 mm
Width	250 mm	217 mm
Height	164 mm	100 mm
Trachea - Inner diameter	20.5 mm	13 mm
Trachea - Outer diameter	27.1 mm	17.6 mm

3 Experimental Setup and Test Results

The testing of the new lung model aims at traversing all existing pathways and making measurements of time, number of movements performed, and errors.

The test was performed using a 1.7 mm diameter catheter and a 0.7 mm diameter guide-wire. The total horizontal distance available for the wire to travel is 650 mm which is sufficient for a catheter to navigate inside the human body to reach every branch of the lung's airways.

A modified lung biopsy catheter was used to test the ENDORO system in the new lung model (Fig. 3). The catheter was built from the metallic spiral tube of the biopsy catheter in which an Aurora 5DOF sensor and a guide-wire were introduced.

To conduct tests on the new artificial lung, we used the following setup:

1. We set the initial position of the robot with the face of the catheter clamping drum in a horizontal position, and the guide-wire was retracted in the sheath.
2. We 3D-scanned the lung model using a CT scanner, and the resulting images were uploaded to the iMTECH platform.
3. After loading the images into the platform, we calibrated the reference sensor according to the one located on the model.

The new lung model has a total of 46 navigable paths (see Fig. 4), of which only 8 are fully navigable using the catheter previously shown.

As the length of the tracking sensor of the electromagnetic tracking system is 8.2 mm, and since the sensor is positioned in front of the catheter, it is not possible to navigate the paths at an intersection with a curvature less than 10 mm. As consequence, most of the branches in the right upper lobe, right middle lobe, and left upper lobe (4, 9–21, 24, 25, 29–33, 36–46) were inaccessible for this specific instrument.

Other challenges with reaching the target points are internal frictions and the difficulty of guiding the guide-wire towards branches in the bronchial lobar. These errors can be remedied with the help of a traditional bronchoscope, through which the catheter can be placed.

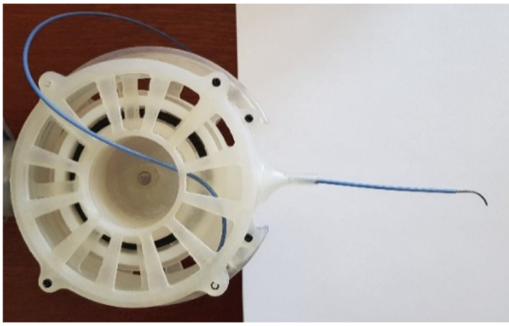

Fig. 3. Biopsy catheter with a guide-wire for navigation and tracking.

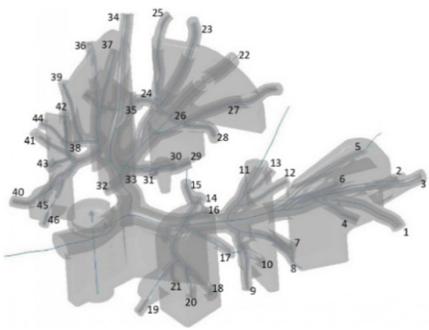

Fig. 4. Graphical representation of the artificial lung, containing markers to all possible inner navigation paths.

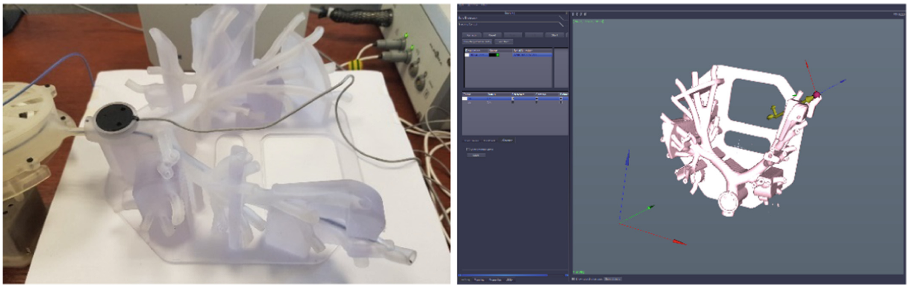

Fig. 5. The physical position of the catheter inside the artificial lung (a). Screenshot of the iMTECH platform to identify the position of the catheter inside the lung (b).

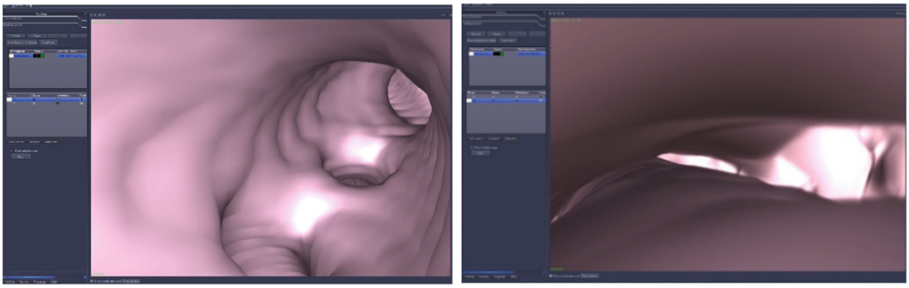

Fig. 6. View of the section inside the lung of a path of interest for correct navigation (a). Exterior view of the path of interest, showing a navigation error (b).

The electromagnetic tracking system, together with the iMTECH software, facilitates navigation by tracking the position of the catheter tip inside the bronchial branches, as shown in Fig. 5.

Figure 6 shows the scenarios in which the catheter moves inside the lung, correctly navigating a path of interest in the first screenshot, and, in the second screenshot, a navigation error, when the catheter is positioned outside the path of interest.

Table 2. The characteristics of the navigable paths of the lung and the performed measurements during the navigation process.

Path-to-target ID	Path length (mm)	Number of intersections to target	Time to reach the target (sec)	Measured movements
7	130	4	60	Rotations: 10 Translations: 42
8	140	4	79	Rotations: 30 Translations: 47
6	165	5	90	Rotations: 25 Translations: 66
3	190	5	180	Rotations: 75 Translations: 84
22	200	4	68	Rotations: 5 Translations: 85
5	200	5	126	Rotations: 30 Translations: 73
1	202	5	140	Rotations: 55 Translations: 81
2	222	5	192	Rotations: 98 Translations: 87

The measurements performed on the 8 navigable paths of the lung of different lengths are presented in Table 2. The information collected for each navigable path is as follows:

- required time to navigate to the target point;
- number of reached intersections;
- number of recorded rotational and translational movements.

As it can be seen, in the case of the path with ID 22, for which 5 rotations were performed, the time is relatively short, although the length of the track is long. In contrast, for the path with ID 5 of the same length, the recorded time is significantly longer because 30 rotations were performed. In addition, we note that the number of reached intersections does not significantly impact the resulting time, given the biological nature of the positions of target points located in the segmental bronchi.

4 Conclusions and Feature Work

A newly modeled artificial lung based on CT scans obtained from patients was used, thus creating a more realistic test environment.

Measurements were made on possible navigation paths, which gives an understanding of the possible correlations between the characteristics of the navigation routes, the number of rotations and translations performed, and the times obtained.

The performed testing procedures point out to some the errors that may occur which can be classified into the following categories:

- Electromagnetic tracking errors

Electromagnetic tracking errors can be caused by the appearance of metallic materials in the area of the electromagnetic field. An alternative to consider is to replace the metal tube of the catheter with a plastic or silicone material.

- Positioning errors

Positioning errors may occur due to incorrect calibration of the reference sensor. These can be remedied by recalibrating the sensor or repositioning it on the model.

- Medical imaging errors

Imaging errors can occur due to incorrect scanning of the lung model with the CT scanner. This type of error can be corrected by performing a new computerized tomography scan.

Additionally, we note that at the moment there are shortcomings of the platform in terms of system accuracy such as:

- moving the instrument outside of the area of interest which leads to measurement errors;
- a longer navigation time - approximately 10–20 times longer than the data collected in Table 2.

This could result in a prolonged medical intervention.

These observations point to possible improvements of the ENDORO robotic system and the iMTECH software platform in the next generation of the system. New catheters design or a bronchoscope can also be used to address the above limitations.

Furthermore, additional procedures to other organs (e.g. vascular interventions) can be added to the testing framework to expand the capability of the tracking and robotic system.

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