A Probabilistic Model for Demonstrating High Path Planning Success Rate in Autonomous Capsule Robots for Bronchoscopies

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***Abstract*—This manuscript describes a probabilistic view of analyzing the possible paths that an autonomous robot may take when traversing through bronchi. We will consider a section of the lung, as a model that can be expanded upon using our work. Using the technique of rapidly-exploring random trees (RRT), we aim to lay down some benchmarks that can be used by clinical experts to meet the goal of the bronchoscopies they perform.**

***Index Terms*—capsule robot, autonomous bronchoscope, path planning, benchmark parameters**

I. Introduction

Bronchoscopies play a vital role in diagnosing a range of pulmonary issues. For example, tumor detection is an important cause for an endoscopy performed by a pulmonologist. However, low diagnostic yields is an existing problem in transbronchial biopsies [1], [2], [3], [4]. Among the many solutions to address this problem, robotic-assisted bronchoscopy is a promising and ever-growing method [5]. In the variety of types of robotic bronchoscopies, a capsule-robot has potential and can be expanded upon in many ways. For example, the existence of the PillCam COLON capsule has shown promise in the last decade [6]. Although again in the realm of colonoscopy screenings, a capsule endoscopy has shown to be considerably more cost-effective as compared to traditional methods [7].

While rigid and fiberoptic methods remain the dominant methods of performing pulmonary endoscopies [5], they also require highly skilled operators in order to be safe [8]. However, given the forecasted shortage in the physician workforce of the United States [9], it is imperative to look for alternative solutions. Autonomous endoscopies are one such solution. In fact, autonomous capsule robots have already been trained using reinforcement learning for usage in endoscopies [10].

However, at the time of the scribing of this manuscript, the existing literature does not show any preliminary benchmark information about this type of robotic bronchoscopy. If clinical operators hope to use autonomous capsule robots for bronchoscopies, there needs to exist guidelines on tuning the autonomous robot such that a high success rate for biopsy yield can be achieved. *The primary objective of this study is to show a simple probabilistic method to achieve over 98% success rate of an autonomous capsule robot to find a given destination in the human bronchi. We will use rapidly-exploring random trees to set up a model that can establish parameters which can be tuned to achieve a high success rate.*

II. Materials and Methods

A. Set up for the model

First we use a simple figure that delineates occupied and free zones of a human pulmonary region. Such a figure is shown in Fig 1. The green region is the the area where the capsule robot is free to move, and the black regions are the 'occupied' zones, signifying the walls of the organ.

Fig. 1. A basic model of the human lung

The capsule robot's dimensions are roughly 10 mm long capsule with 5 mm in diameter, but for the sake of model simplicity, the dimensions are ignored in the path planning. We assume that the robot can start anywhere near the trachea and have a goal position near the end of the narrow bronchi.

B. Occupancy grid and start/goal positions

Next, we read in the image using MATLAB's 'imread' function. Now that we have a raw byte version of the image, we convert it to a gray-scale image. By default MATLAB reads this in as the colored portion marked as black, so our next step is to invert the image, which we can do with a simple logical invert on the image matrix.

1) Restate objective in technical terms: In technical terms, we must first assign frames 0 through 3 for each link of the manipulator. We will then form a table of DH parameters. Using the table, and the general form of the DH matrix, we will find the A matrices for the manipulator i.e. we need to find A_1, A_2, and A_3. Using these, we need to find T_3^0 to give us our final answer. From our textbook [11], the DH Coordinate Frame Assumptions are,

- **(DH1)** The axis x_i is perpendicular to the axis z_{i-1}.
- **(DH2)** The axis x_i intersects the axis z_{i-1}.

2) Assign frames: The first step toward solving our problem is to redraw the robot manipulator in symbolic form, and assign frames for links 0 through 3. Since we are following the DH assumptions, we must follow the frame assignment style shown in Figure 4, which is from our textbook [11]. Our redrawn figure is shown in Figure 5.
As shown, frame 0 ($x_0y_0z_0$) is assigned at the first joint (revolute). Frame 1 ($x_1y_1z_1$) is also assigned at the first joint in order to have DH assumptions satisfied. Frame 2 ($x_2y_2z_2$) is assigned at third joint (revolute). Frame 3 ($x_3y_3z_3$) is assigned at the end of link 3, in a way that also satisfies DH assumptions.

3) Create DH table and set variables/constants: Now that we have assigned the frames, we can use Figure 4 to write the α_i, a_i, θ_i, d_i quantities for each link.

Link	α_i	a_i	θ_i	d_i
1	$-90°$	0	θ_1	0
2	$90°$	0	0	$L_1 + q_2$
3	0	L_3	$90° + \theta_3$	0

TABLE I
DENAVIT-HARTENBERG TABLE FOR PROBLEM 3–5

As seen in Table 1, we have chosen L_1 and L_3 to describe the constant link lengths of links 1 and 3, respectively. Additionally, q_2 describes the variable link length of link 2 (because of joint 2 being a prismatic joint). Furthermore, θ_1 and θ_3 describe the variable angles of revolute joints 1 and 3, respectively.

4) Find A matrices: As given in our textbook [11], the general form of an A_i matrix is,

$$A_i = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where c_{θ_i} is $\cos\theta_i$, s_{θ_i} is $\sin\theta_i$, c_{α_i} is $\cos\alpha_i$, and s_{α_i} is $\sin\alpha_i$. We can write a MATLAB function for this A_i matrix, as follows.

Using this function in our MATLAB Live Script, we produce the following A matrices.

$$A_1 = \begin{bmatrix} \cos\theta_1 & 0 & -\sin\theta_1 & 0 \\ \sin\theta_1 & 0 & \cos\theta_1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & L_1 + q_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} \cos\left(\theta_3 + \frac{\pi}{2}\right) & -\sin\left(\theta_3 + \frac{\pi}{2}\right) & 0 & L_3\cos\left(\theta_3 + \frac{\pi}{2}\right) \\ \sin\left(\theta_3 + \frac{\pi}{2}\right) & \cos\left(\theta_3 + \frac{\pi}{2}\right) & 0 & L_3\sin\left(\theta_3 + \frac{\pi}{2}\right) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Now we are ready to multiply these matrices to obtain the final result of our objective.

III. Results

A. Result for Problem 3–2

For Problem 3–2, we obtained our final result by multiplying all three H matrices that we obtained in the Materials and Methods section. Hence, we obtained the following matrix,

$$H_3^0 = \begin{bmatrix} \sigma_1 & 0 & \sigma_5 & \lambda_1 \\ 0 & 1 & 0 & 0 \\ \sigma_4 & 0 & \sigma_1 & \lambda_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where,

$$\begin{aligned} \lambda_1 = {} & L_1\cos(\theta_1) + L_3\cos(\theta_3)\,\sigma_2 \\ & - L_3\sin(\theta_3)\,\sigma_3 + L_2\cos(\theta_1)\cos(\theta_2) \\ & - L_2\sin(\theta_1)\sin(\theta_2) \end{aligned}$$

$$\begin{aligned} \lambda_2 = {} & -L_1\sin(\theta_1) - L_3\cos(\theta_3)\,\sigma_3 - L_3\sin(\theta_3)\,\sigma_2 \\ & - L_2\cos(\theta_1)\sin(\theta_2) - L_2\cos(\theta_2)\sin(\theta_1) \end{aligned}$$

and,

$$\begin{aligned} \sigma_1 &= \cos(\theta_3)\,\sigma_2 - \sin(\theta_3)\,\sigma_3 \\ \sigma_2 &= \cos(\theta_1)\cos(\theta_2) - \sin(\theta_1)\sin(\theta_2) \\ \sigma_3 &= \cos(\theta_1)\sin(\theta_2) + \cos(\theta_2)\sin(\theta_1) \\ \sigma_4 &= -\cos(\theta_3)\,\sigma_3 - \sin(\theta_3)\,\sigma_2 \\ \sigma_5 &= \cos(\theta_3)\,\sigma_3 + \sin(\theta_3)\,\sigma_2 \end{aligned}$$

The significance of this H_3^0 matrix is that is provides a direct transformation matrix between the base frame (frame 0) and end-effector frame, which is a solution for forward kinematics.

B. Result for Problem 3–5

For Problem 3–5, we obtained our final result by multiplying all three A_i matrices that we obtained in the Materials and Methods section. Hence, we obtained the following matrix,

$$T_3^0 = \begin{bmatrix} \sigma_1 & \sigma_4 & 0 & \lambda_1 \\ \sigma_5 & \sigma_1 & 0 & \lambda_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where,

$$\lambda_1 = L_3 \cos(\theta_1)\ \sigma_3 - \sin(\theta_1)\ (L_1 + q_2) - L_3 \sin(\theta_1)\ \sigma_2$$
$$\lambda_2 = \cos(\theta_1)\ (L_1 + q_2) + L_3 \cos(\theta_1)\ \sigma_2 + L_3\, \sigma_3 \sin(\theta_1)$$

and,

$$\sigma_1 = \cos(\theta_1)\ \sigma_3 - \sin(\theta_1)\ \sigma_2$$
$$\sigma_2 = \sin\left(\theta_3 + \frac{\pi}{2}\right)$$
$$\sigma_3 = \cos\left(\theta_3 + \frac{\pi}{2}\right)$$
$$\sigma_4 = -\cos(\theta_1)\ \sigma_2 - \sigma_3 \sin(\theta_1)$$
$$\sigma_5 = \cos(\theta_1)\ \sigma_2 + \sigma_3 \sin(\theta_1)$$

The significance of this T_3^0 matrix is that is provides a direct transformation matrix between the base frame (frame 0) and end-effector frame, which is a solution for forward kinematics.

IV. Discussion

In the opinion of the author, this homework problem set was insightful. The first problem proved that we do not need to always use the DH convention when solving for forward kinematics in robotic manipulators. In fact, when using tools like MATLAB, manually executing a non-DH method of computing the forward kinematics is no more complex than using the DH method itself.

The second problem reinforced our learnings from RBE 500. We used the DH convention heavily in that class, so it was great to revisit that foundation as we move forward in this class.

A topic for further consideration could be, when would one prefer to use a non-DH method over the DH method? The DH convention can provide a minimal and efficient way to represent and compute the relationship between the base frame and the end effector in many cases, because it reduces the number of variables involved from 6 to 4. However, suppose we want to model the differential kinematics of a manipulator. The screw-based theory [**?**] can provide advantages in such a case. In the referenced paper for screw-based theory, it was found that, when various kinematic modelings for common manipulator configurations where compared, the screw-based theory did not provide any disadvantages in any case. The one noticeable difference was that it provided superior flexibility when differential kinematics was compared. The parameter identification is also a bit simpler in the screw-based theory, as compared to the DH-convention.

It was a great exercise the solve this week's problem set, and the author thanks the Professor for this.

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