An accessible 6-axis testbed for image-guided robotics research

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ABSTRACT

PURPOSE: Cancer can recur after tumor resection surgery if tumor tissue is missed and left behind. We hypothesize that intraoperative robotic imaging could be used to inspect the surgical cavity and localize residual cancer tissue. This technique has the potential to improve the success rate of tumor resection surgery. In this work, we propose and evaluate a benchtop testbed for robotic manipulation of an optical imaging probe. We use low-cost hardware and open-source software to construct the testbed and describe the implementation so that it can be easily adapted to other research areas. **METHODS:** We implemented a reusable, open-source module in 3D Slicer for reading position coordinates and motion planning with an inexpensive 6-axis robotic arm in Robot Operating System (ROS). For demonstration, a custom end-effector was used to fix an optical probe to the robot. To evaluate the accuracy of the testbed, a phantom with 16 target points was scanned using the robotic scanner. We then measured the positioning accuracy of the robot. **RESULTS:** The system had an average positional accuracy of 3.59 $\pm$1.4 mm and the system successfully navigated to the majority of target points. **CONCLUSIONS:** Our open-source benchtop system achieves positional accuracy that would make it a valuable testbed for developing image-guided tumor inspection systems. Future work will explore the application of this test bed within breast conserving surgery.

1. INTRODUCTION

Cancer can recur after surgery if cancer cells were left behind during the initial operation [1]. An example of this is breast-conserving surgery (BCS). This procedure involves removing the entire malignant tumor while preserving as much healthy surrounding tissue as possible [2]. To achieve successful removal of cancer, the tumor bed, the area of tissue remaining after the resection, should consist solely of healthy tissue. However, many cancer procedures require repeat revision surgery to capture missed tumor tissue. For example, in 20-30% of BCS cases, patients require repeat surgery to remove cancerous tissue that was missed and left in the tumor bed during the initial procedure [3]. As a result, the patient faces a higher risk of postoperative complications, reduced cosmetic outcomes, increased psychological distress, and higher costs [4].

Optical imaging and spectroscopy are known to be real-time, sensitive, and non-invasive detecting approaches for human cancers [5]. Deploying these optical imaging techniques intraoperatively can benefit from integration with navigation such as freehand or mechanical tracking. While freehand tracking does provide high quality information on the position and orientation of the tool, as shown in [6], the subsequent movement of the tool based on this information can be challenging for a human operator to control. This is because humans are prone to involuntary tremors and sub-optimal motion [7]. A 6-axis robotic arm could minimize the inefficiencies of manual positioning based on free-hand tracking, ensure complete scanning coverage, and enable cooperative robotic guidance back to individual scan points when residual cancer is identified.

In this paper, we describe a research testbed for deploying tissue imaging with an inexpensive 6-axis robot arm and open-source software. We integrate an imaging probe with the robot using a 3D printed adapter. This testbed serves as an inexpensive, open-source research tool to accelerate the development of robotic tissue scanning and tumor bed imaging. The following sections detail an evaluation of the system's performance, encompassing both positional accuracy and mechanical tracking. Additionally, we provide a detailed description of the software and hardware components, emphasizing the system's adaptability for diverse research applications. This testbed is expected to streamline benchtop testing and therefore advance image-guided medical robotics research.

2. METHODS

The following sections outline the integration of hardware, software, and the experimental design for this study.

2.0 System design

The system consists of three main subsystems shown in Figure 1: an imaging device, a robot, and navigation software.

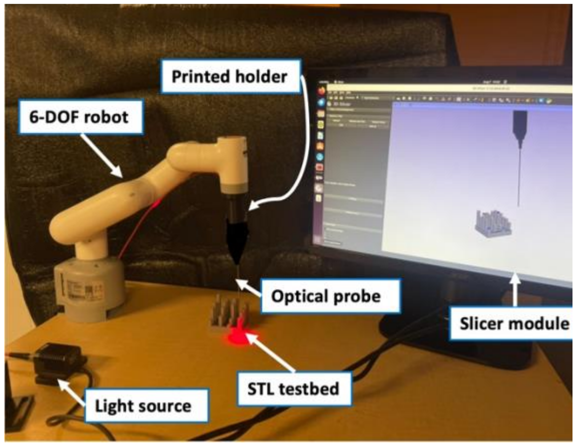

Figure 1: Benchtop robotic imaging system.

The imaging device is comprised of a 3D printed holder, a 660 nm light source, and an FCR-7UVIR200-2 optical fiber reflection probe (Avantes, Netherlands) which is connected to a spectrometer. The 6 degree of freedom (DOF) MyCobot m5 280 robot (Elephant robotics, China) is inexpensive and costs $1,110 CAD [8] compared to a typical research robot like the UR3 which costs close to $33,500 CAD [9]. This device has a 280 mm working radius, can support a payload of up to 250 grams and has a reported precision of ± 0.5 mm. The robot is controlled with ROS for motion planning and manipulation of the probe. The entire testbed is integrated with the open-source medical imaging platform 3D Slicer (slicer.org) for research prototyping.

2.1 Hardware

2.1.0 Custom end-effector

The end-effector system consists of a 3D printed optical probe holder as shown below in Figure 2. The holder was designed with Fusion 360 CAD software and can be easily adapted to fit many other imaging systems.

Figure 2: Custom end-effector designed to fit optical probe.

2.2 Software

Figure 3 below demonstrates the software pipeline for the testbed. The optical data from the spectrometer was sent to 3D Slicer using PLUS and OpenIGTLink for analysis [10] [11]. Although we used a 660 nm light source for evaluation (described Section 2.3), this light source could also be used for broadband spectroscopy as shown in [10].

Reading the position of the robot and sending positional data from 3D Slicer to ROS for motion planning is facilitated with SlicerROS2 [12]. SlicerROS2 relies on the tf2 package in ROS to view the position of the robot in Slicer. In the following sections, we will describe the 3D Slicer module, ROS software components and registration. For more detail on the software pipeline view the GitHub repository.

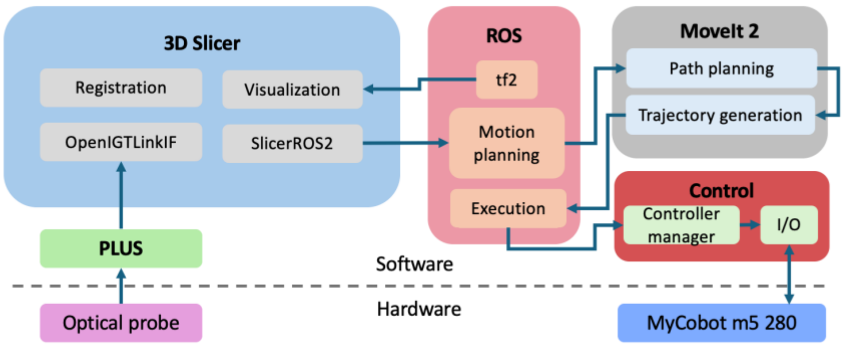

Figure 3: Software and hardware overview for testbed.

2.2.1 Slicer module

The 3D Slicer scripted module is used to send target points from 3D Slicer to the robotic arm. These target points are typically represented as a point cloud using Markups in 3D Slicer. When initialized the module creates a ROS topic with x, y and z values. After initialization, every target point is iteratively sent to ROS over a topic using SlicerROS2. Orientation is fixed for the scan, such that the optical probe is always perpendicular to the scanning surface, so pitch, roll and yaw are not sent.

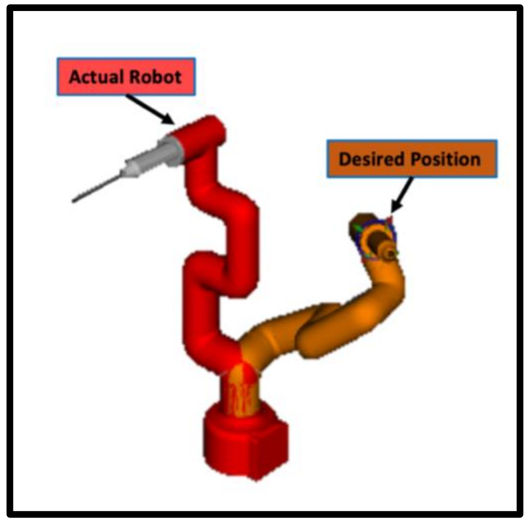

Figure 4: ROS motion planning with MoveIt 2.

2.2.0 Robotics control and path planning

The robotic arm is controlled using ROS2 Humble, which employs the ROS2 control architecture for seamless integration and real-time control. This framework allows for precise control of the robot joints. As shown in Figure 4, path planning for the robotic arm is managed by MoveIt2, which considers kinematics, dynamics, and provides collision-free trajectories, enabling the robot to reach the desired poses accurately.

By utilizing ROS2 Humble and MoveIt2, the robotic arm is effectively controlled by Slicer to navigate the end-effector to the specified target points, while the robot model is broadcasted in real-time to 3D Slicer using SlicerROS2. This system supports the use of various end-effector tools; for this experiment, an optical end-effector was employed to perform spectrometry. Note that the optical end-effector was added to the 3D robot model to be factored into path planning. The robot was also calibrated prior to use, using default settings which required lining up notches sequentially on each of the 6 joints.

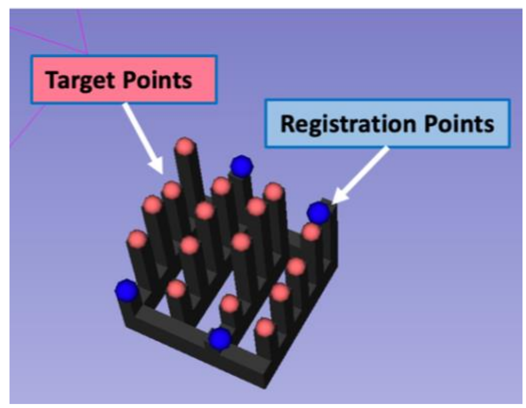

Figure 5: Target and registration points

2.3 Experimental evaluation

We performed an experiment 3 separate times using the phantom shown in Figure 5 [13] to assess the accuracy of our research tool. To register the phantom to the robot workspace, the Fiducial Registration Wizard module, part of SlicerIGT [11], used 4 positions on the phantom. These points were identified on the STL model of the phantom which was loaded into Slicer. The tip of the optical probe on the robot was then guided to each of these four points and the position was captured by reading the reported position of the tip using SlicerROS2.

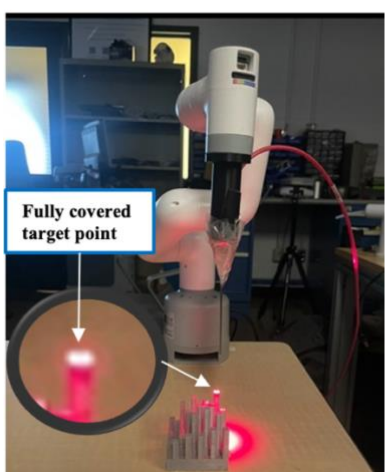

Figure 6: Successful target point in experiment.

We then sent the 16 target points shown in Figure 5 iteratively using our pipeline in Figure 3. The robot was sent the position and path planned to the target point with the probe. We quantitatively assessed the accuracy of the tool by measuring the positional error between the target positions in Slicer and the actual positions of the robot after navigating to these points in X and Y using Slicer. The positional error was calculated using Equation 1 below. Note that the error in the Z-axis was not evaluated, since we add an offset in the Z direction to prevent collision of the light source and the phantom and to emulate the approximate distance the probe should be during tissue imaging.

$$||e|| = \sqrt[2]{(x_{desired} - x_{actual})^2 + (y_{desired} - y_{actual})^2} \quad \text{(Eq. 1)}$$

Where $x_{desired}$ and $y_{desired}$ are target positions and x_{actual} and y_{actual} are the actual position reported in real-time. We evaluated the qualitative accuracy of our research tool by visually assessing the extent of light coverage on the target points. The coverage was classified into four categories: fully covering the point (green), more than 50% of the point covered (yellow), less than 50% of the point covered (orange), or no coverage (red). Figure 6 illustrates the experiment, showing the scanning of a target on the phantom. Quantitatively, the target depicted in Figure 6 achieved a positional accuracy of 2.7 mm and was classified as fully covering the surface (green).

3. RESULTS AND DISCUSSION

The open-source testbed integrating 3D Slicer, a 6-axis robot, and an optical probe achieved an average quantitative positional accuracy of 3.59 $\pm$ 1.4 mm, as shown in Table 1. Additionally, the tool demonstrated an average qualitative accuracy with light coverage of more than 50% of the 50 mm^2 square surfaces.

Table 1: Results obtained from three tests with error and standard deviation.

Coverage category	Error (mm)	Standard Deviation ± (mm)
Total green average (100% Coverage):	2.12	0.89
Total yellow average (>50% Coverage):	3.45	1.00
Total orange average (<50% Coverage):	4.47	1.07
Total red average (0% Coverage):	4.99	0.61
Total average:	**3.59**	**1.40**

Several limitations contributed to the error in the system. For example, there are potential inaccuracies in the robot and end-effector models within ROS and consequently the reported position of the end-effector. The robot also has an inherent accuracy of 0.5 mm as reported by the manufacturer and the spectrometer did not match the virtual model perfectly due to bending and wobbling. These factors contributed to the overall error observed in the experiments, which explains the average positional accuracy of 3.59 $\pm$1.4 mm. The diameter of the optical probe beam is 5mm, therefore, this testbed is still sufficient for our proposed clinical application. In future work we will also design an end-effector attachment that looks more like a cannula and can compensate for the flexibility and wobbling of the fiber probe.

5. CONCLUSIONS

In conclusion, we integrated an open-source 6-axis robotic arm with 3D Slicer, creating a versatile and cost-effective platform for robotic imaging applications. The system was developed entirely with open-source software using ROS, 3D Slicer, PLUS, and OpenIGTLink standards. The system has a positional accuracy of 3.59 mm. This testbed can serve as a flexible research tool for advancing robotic-assisted surgery and investigating tissue. We anticipate that this testbed will significantly reduce barriers to research in robotic tissue scanning, enabling faster progress and broader accessibility.

6. NEW OR BREAKTHROUGH WORK TO BE PRESENTED

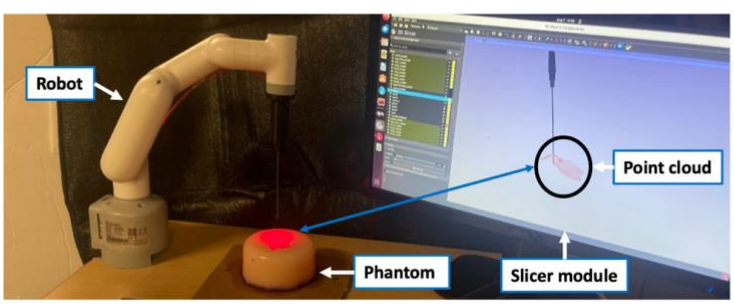

Figure 7: Testbed demonstration on breast phantom. Point cloud from RealSense shown as future work.

In this paper we describe an inexpensive and accessible test bed for researching robotic tissue imaging and evaluated the system. Future work will use this testbed to develop a tool that can intraoperatively scan a cavity during BCS surgery. We are currently integrating a RealSense camera (Intel, USA) to assist in cavity detection. The system will then be used to scan the tumor bed with the optical probe and guide the surgeon to cancer tissue that was missed during surgery. Figure 7 demonstrates this proposed workflow on a breast phantom that was used in a parallel study.

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