Robotic tracking of a resection cavity using a low cost bench-top robotic arm and electromagnetics

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ABSTRACT

INTRODUCTION: Roughly 40% of breast cancer patients are required to undergo corrective surgery after tumour resection via breast-conserving surgery (BCS). Sweeping of the cavity, resulting from the tumour resection, by spectroscopy and ultrasound imaging is emerging as a potential solution for identifying leftover cancer. However, the use of imaging modalities in the cavity is challenging as breast tissue is soft, malleable, and moves frequently. This paper presents and verifies an approach for tracking the relative motion of a resection cavity with a robotic arm. **METHODS:** We use electromagnetic tracking and a low cost 6-axis robotic arm to track a simulated resection cavity. We embed an electromagnetic sensor in a 3D printed retractor that is designed to hold the cavity open. An open-source module in 3D Slicer is then used to detect cavity motion from the retractor and command the robotic arm to follow the relative movement while incorporating motion planning to prevent collisions and unsafe actions. To assess this approach we move the retractor to 36 positions in the robotic arm workspace and measure the latency between when a command is published to the robotic arm and when it begins to move to this position. In addition, we attach a camera to the end-effector (EE) of the robotic arm to determine when the robotic arm has successfully tracked the cavity by checking if it is visible in the center of the camera frame. **RESULTS:** The latency was recorded to be 832.1 milliseconds on average with 132.6 standard deviation. We can also successfully track the motion of the cavity in almost every test position. **CONCLUSIONS:** These results suggest that tracking of the breast cavity using EM tracking and robotics is feasible. Future work focusing on the integration with spectroscopy and cavity servoing.

Keywords: Soft Tissue, Tracking, Robotics

1. INTRODUCTION

In 2024, breast cancer presents as the most commonly diagnosed cancer among women around the world.[1] The current standard of care is breast-conserving surgery (BCS), accompanied by radiotherapy. The benefit of BCS over traditional Masectomy is the psychological benefit of retaining healthy breast tissue.[2,3] In addition, the rates of tumour recurrence are roughly equal in both approaches, making BCS the preferred treatment choice. BCS involves resection of the tumor as well as a margin of tissue whilst preserving healthy tissue. This is done through cavity shaving (CS), in which the margins of the cavity created by the resection are iteratively shaved.[4] However, up to 40% of patients receive corrective surgery as residual cancer was left in this process.[5]

Currently, pathological assessment of the resected tissue is done to determine whether the cavity has been safely shaved. This technique assumes that the border of the resected specimen matches the surface of the surgical cavity. When a thick cautery tip is used, which is common in BCS, this assumption does not always hold true as tissue that is presumed to be left behind on the border is actually incinerated. We hypothesize that if the cavity can remain open after the initial tumor is removed, an imaging sweep, such as ultrasound or spectroscopy, of the cavity can aid in the detection and identification of missed cancer.[6] If residual cancer is identified in the tumor bed, action can be taken to remove the cancerous tissue which will ultimately reduce the likelihood of future corrective surgery.

Performing an imaging sweep of the resection cavity is challenging because of the nature of breast tissue. Specifically, the post-operative cavity is soft, deformable and moves as the patient breathes. To address these challenges, we propose a pipeline for tracking the cavity with a robotic arm using a custom retractor that has an embedded electromagnetic (EM) sensor. To assess the feasibility of this solution, we implement a framework in 3D Slicer and ROS that can track a resection cavity using the sensor data, and command a robotic arm to follow the relative motion.

2. METHODS

2.1 System Overview

Figure 1 illustrates our proposed framework. The two core systems include: the EM tracker and the robotic arm. The robotic arm, with six degrees of freedom, is controlled using a Linux computer through ROS. The EM data is passed through a Windows computer. The breast phantom in Figure 1 is a cylinder made from plastisol with a mock resection cavity carved into it. A 3D printed retractor, with an EM sensor embedded within, is used to prop open the cavity, as shown previously in Radcliffe et al.[7] An emitter is placed beside the phantom to generate the EM field. Motion of the resection cavity is captured by the retractor, and reflected in EM tracking data; this data is used within ROS to facilitate robotic path planning.

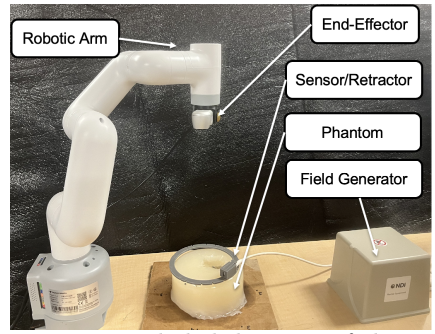

Figure 1: Labeled diagram of the proposed framework. Observe the robotic arm, an attached camera end-effector, a breast phantom with a retractor, as well as the field generator.

2.2 Robotics

MyCobot 280, an inexpensive bench-top robotic arm with six degrees of freedom, is used in our proposed framework.[8] The modular EE of the MyCobot system makes it well suited for testing and customizing image-guided robotics systems. Control through the Linux computer was achieved with ROS Humble, a ROS2 distribution which interfaces between various software (Python and C++) packages and robotic hardware. Path planning is performed using MoveIt2, a package that operates on top of ROS. MoveIt2 factors in robotic arm kinematics, dynamics, and obstacles to safely plan and execute trajectories to given points.

2.3 Tracking

We use the Ascension 3DG EM Tracker (Northern Digital Inc, Waterloo, Canada) to monitor the position of a 3D printed retractor and stylus. The retractor serves two purposes: keeping the cavity open, whilst also tracking changes to the position and orientation of the phantom. To do this, an EM sensor is inserted inside a housing within the retractor. A seperate stylus with an embedded EM sensor is used to perform registration between different coordinate systems.

Step 1 Step 2 Step 3 Step 4

Figure 2: Progression from Hough Transform to a rough segmentation, the final cavity segmentation, and the point cloud visualized inside the retractor.

In addition, we attach the Intel RealSense 415 to the EE of the robotic arm to capture RGB and Depth camera data for visualizing the cavity and to test our proposed pipeline. Before we begin tracking, we use this camera to obtain a point cloud of the resection cavity. Figure 2 illustrates how the cavity is segmented using computer vision techniques. A Hough transform to identify the retractor in the image (Step 1), a depth filter is applied to isolate the cavity from the surrounding tissue (Step 2), and finally island removal is used to segment the cavity alone (Step 3). This segmentation is transformed into a point cloud (Step 4), a list of coordinate points, using a 3D Slicer module.[9] This point cloud is visualized in the center of the retractor model in 3D Slicer for navigation.

2.4 Integration

Figure 3 illustrates the hardware-software integration in our pipeline. To facilitate communication between the system components in our framework we utilize 3D Slicer, a platform for biomedical image visualization and analysis. Specifically, we leverage peer-to-peer (P2P) connections to integrate our components.[10] We use PLUS Server to read in data from our depth camera and EM tracker on the Windows computer, which is streamed to 3D Slicer using OpenIGTLink, an open-source communication platform for computer-assisted interventions.[11,12] The transmission of EM and point cloud data from Windows to Linux is also facilitated by OpenIGTLink. The need for two separate computers is warranted because the Ascension tracker does not have an open-source Linux driver or ROS wrapper.

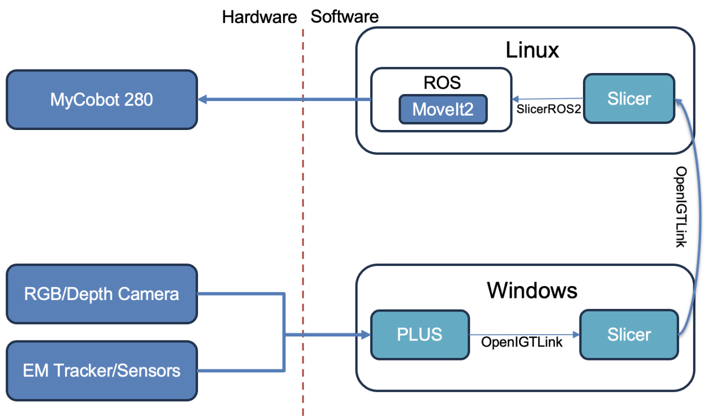

Figure 3: Illustration of the software-hardware integration. The camera and EM capture data from the phantom, and send it to Slicer on Windows through PLUS and OpenIGTLink. This is then transferred to Linux Slicer through OpenIGTLink. The proper coordinates are published to ROS using SlicerROS, from which MoveIt path plans the robotic arm.

To allow Slicer to directly communicate with the robotic arm, we use SlicerROS2, a Slicer module for image-guided robotic interventions.[13] SlicerROS2 provides access the the kinematic chain of the robotic arm in 3D Slicer as well as the position of the tip of the EE for registration. It can also be used to publish commands directly to the robotic arm interface for the MyCobot using a simple ROS publisher.

2.5 Study Protocol

We have three coordinate systems in our study: the point cloud, EM tracker, and robotic arm. To register the point cloud to the robotic arm, four points adjacent to the phantom, as shown in Figure 2 Step 1, are placed using markups in 3D Slicer over the aligned RGB image from the RealSense. Slicer is then able to project these onto the point cloud obtained from RGB-D data using the point cloud module described earlier. We next register the EM tracker to the robotic arm by placing the tip of the EM-tracked stylus, that has been pivot calibrated, and robotic arm EE on the same registration points around the phantom. Please note that a stylus was attached to the EE of the robotic arm, calibrated to the kinematic chain and used for this step of registration. Fiducial Registration Wizard, a SlicerIGT module, was used to do a point to point registration from the point cloud to the EM tracker, and EM tracker to robotic arm.[14] After this step, the point cloud obtained from the RealSense and EM tracked retractor are all transformed to the robotic arm coordinate system.

After registration, we swap the EE of the robotic arm out for a camera mount and attach the RealSense. We then select a point in the center of the point cloud, and track changes to its position using the EM sensor in the retractor. Once a change in position has been detected, the x and y of this new point location are published to the MoveIt2 interface using SlicerROS2. This subsequently commands the robotic arm to keep this point in the center of the EE and consequently, camera frame.

To evaluate this approach, we move the phantom 36 times within the accessible workspace of the robotic arm and evaluate the latency and success of cavity tracking. The latency is reported as the time difference between when we publish a position command from Slicer to MoveIt2 and when the robotic arm actually begins moving. This represents the delay associated with our communication pipeline and motion planning. This data was extracted from 720p 30 FPS video playback, which was scrubbed through manually. All time stamps were reported to an accuracy of 0.01 seconds. Tracking success is evaluated from the camera feed on the EE of the robotic arm. We discovered that occlusion occurs when the chassis of the robotic arm interferes with the field of view of the camera. In these cases, the cavity is not visible in the camera frame. Therefore, we only consider successful cavity tracking as points in the workspace when the cavity is both visible and approximately centered in the image.

3. RESULTS AND DISCUSSION

The average occlusion percentage was 16.66%, the average latency from Slicer to the robotic arm was 832.1 milliseconds with a standard deviation of 132.6 milliseconds.

The average latency, along with its standard deviation supports that our proposed framework may be feasible in a clinical setting. A typical respiration rate under general anesthesia is 8 to 12 breathes per minute, averaging to 5 to 7.5 seconds between each breath. As our latency is below 1 second, the robotic arm will be able to comfortably adjust its position after a patient takes a breath, and finish before the patient breathes again.

An occlusion percentage of 8.33%, meaning 6 out of 36 positions had partial or total occlusion of the surgical scene. Figure 4 illustrates the visual comparison between a non-occluded frame and an occluded frame. This statistic becomes useful in the applications of this pipeline, particularly when visual servoing the robotic arm in relation to the surgical scene during tasks such as obtaining a cavity sweep. Further work should be done on path planning to minimize the observed frequency and degree of image occlusion.

No Occlusion　　Occlusion

Figure 4: A comparison of a non-occluded and centered frame versus a fully occluded frame. The occluded figure is a close-up of the robotic arm chassis.

There are some limitations to the pipeline and experiments presented here which should be addressed. A problem in data collection was the risk of exiting the EM field when moving the phantom: this would prevent the EM sensor from detecting the motion and Slicer from updating the point cloud. As a result, the robotic arm would not update its position. Future experimentation should be done on expanding the field to accommodate more radical movement in the surgical scene. Another limitation was the robotic arm itself: we encountered singularities in early data collection. Singularities are critical coordinates which result in unplanned robotic arm behavior. This erratic behaviour can be dangerous to persons nearby due to physical stress from the robotic arm or a dangerous EE being moved to an unplanned point.

4. CONCLUSION

In this study, we demonstrate the feasibility of soft-tissue tracking using an inexpensive bench-top robotic arm and open-source networking. In addition, we present a method for incorporating EM tracking into our pipeline. We quantified the performance of our framework using the average percentage of occlusion, and latency between receiving a point and path planning. We achieved an occlusion percentage of 8.33% and 832.1 milliseconds latency with a 132.6 standard deviation. Our findings underscore the viability of integrating this system with potential cavity scanning methods such as ultrasound or spectroscopy. Future work will involve the integration of this system, with a parallel study on the feasibility of spectroscopy to achieve residual cancer detection in a clinical setting.

5. BREAKTHROUGH WORK TO BE PRESENTED

We present a soft-tissue cavity tracking system, developed and integrated through open-source software, utilizing a cost-effective bench-top robotic arm. In addition, we leverage electromagentic tracking to provide the robotic arm with coordinate positions to follow the cavity.

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