EN.601.656 Computer Integrated Surgery II
Project Final Report

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1 Introduction

Interventional guidance systems are becoming increasingly common in modern surgical procedures to track the surgical tools [1]. In nerve sparing radical prostatectomy, surgeons need to track their surgical tools to avoid the intro-operation trauma of nerves and minimize the post-operative complication. In addition to the endoscopic camera, transrectal ultrasound (TRUS) imaging has been widely used in robot-assisted laparoscopic prostatectomy (RALP) due to its real-time imaging and simple implementation. Although the community has several endeavors to directly track the surgical tool tips with TRUS imaging [5, 4], these works surfer from the low accuracy in localizing the tip in the elevation direction. Driven by this issue, photoacoustic markers are proposed by Cheng, *et al.* [2] to enable the registration of TRUS and video as well as the surgical tool tracking. Specifically, a laser source can be detected by both the camera and TRUS so that multiple point pairs can be obtained from these two frames.

By leveraging this property, we develop a **Photoacoustic Image Based Intro-Operative Surgical Guidance System in a da Vinci Surgical Robot Platform** to solve the registration problem. This system consists of an endoscopic camera and a transrectal ultrasound. One of the key component for this system is the registration between the ultrasound and the endoscopic camera. In this work, we leverage photoacoustic effect to develop a registration pipeline without using any physical markers. The goal of this project is to automate this registration procedure with a high accuracy, which can lead to a better tracking performance for the whole system.

In particular, we implemented a searching algorithm to localize the point in TRUS frame and we automated the workflow by integrating each components into a whole system. The simulation study demonstrates the effectiveness of our proposed searching algorithm. The video of our demo and the experimental results on phantom would be uploaded in later days.

2 Method

2.1 System Overview

The overall system architecture is shown in Fig. 2. The proposed surgical guidance system consists of several modules including two host computer (Host 1 and Host 2), da Vinci surgical robot system, a pulsed-laser system, an actuator control module, and a US + PA imaging system.

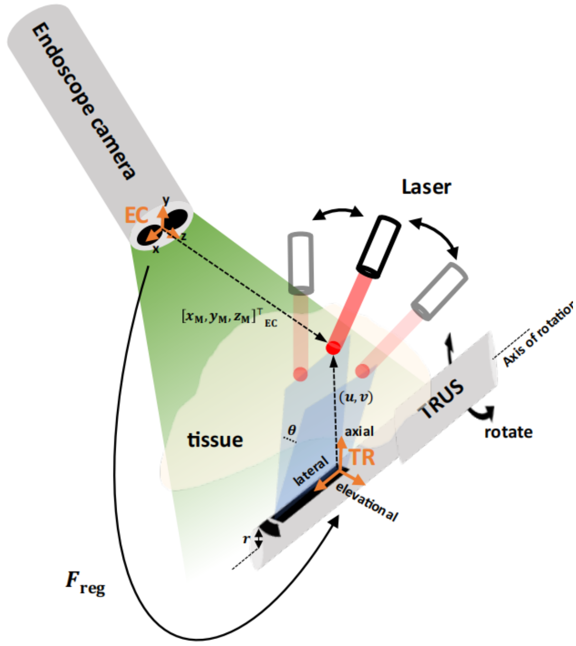

Figure 1: Conceptual illustration of registration and tracking using photoacoustic markers (PM) [6]

The registration process can be illustrated as Fig. 1. The control of the laser, management of samples and computation of the registration results are implemented in the Host 1. To do this, Host 1 process the FL image and calculate the coordinates of PA virtual markers in FL image. At the same time, the Host 1 will send trigger message to Host 2 to require the coordinates of PA markers in the PA image.

The functions of the Host 2 include reading data from the DAQ, performing PA marker's location search algorithm, calculating the coordinates of PA markers in the PA image, and driving the actuator to rotate. In our project, we mainly focus on implementing and verifying the modules in the Host 2 and the communication between each component.

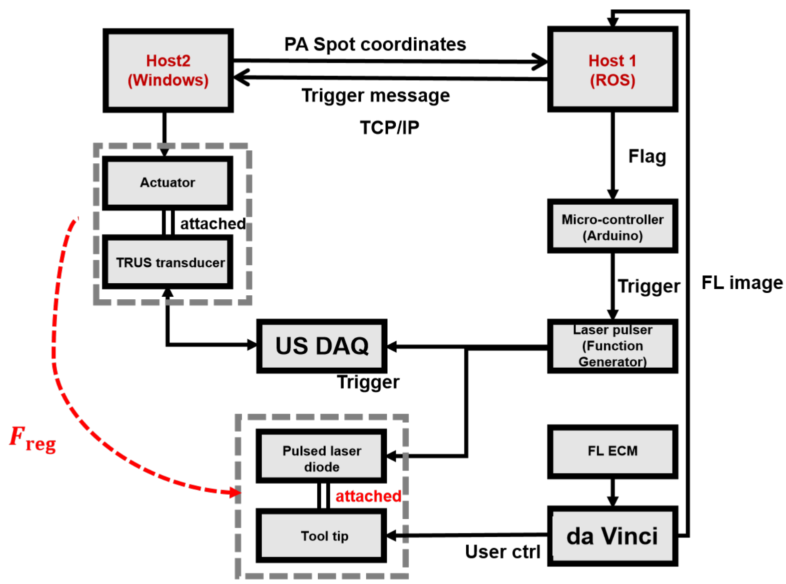

Figure 2: The system diagram of the surgical guidance system

2.2 System Integration

We designed a Graphical User Interface (GUI) for this system as shown in Fig. 3. The goal is to facilitate the integration and evaluation of the components without manually manipulate the physical components of robot. The system integration relies on RQt to develop GUI and ROS for inter-process communication. Each hardware component in the system is operated by a separate node in the ROS network. The implemented GUI can automatically turn on/off the laser excitation, achieve convenient management of point-pair samples, calculate and save the registration result. The effectiveness of the whole system would be demonstrated in the demo video.

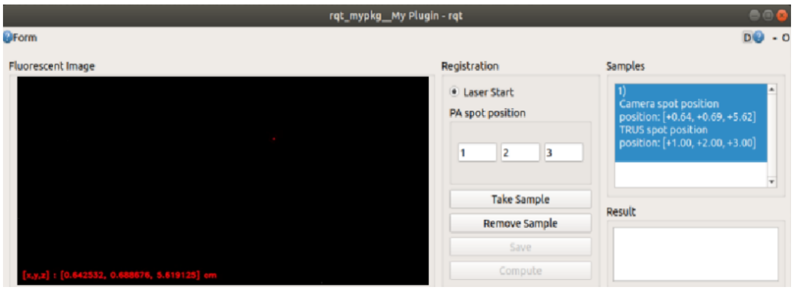

Figure 3: Screenshot of the GUI used to manually control the registration

2.3 Registration

After obtaining at least three-point pairs in fluorescent and photoacoustic images, Horn's method [3] is adopted to compute the registration result F_{reg}.

2.4 Search Algorithm for PA Markers

In the registration workflow, the imaging plane of the TRUS is manually rotated to align to the PA virtual marker. While relatively accurate, this procedure is cumbersome and time-consuming. Driven by this limitation, we propose and implement an automatic registration pipeline. In this pipeline, due to the long time required for imaging, designing a search algorithm to reduce the positions that need to be imaged can greatly improve the efficiency of the system. In our project, an image-based coarse-to-fine search method is proposed to determine the location of the PA virtual marker.

2.4.1 Coarse Search

The field of view of the ultrasound is about 30° to -30°, while the sensitive range is relatively narrow, only about 5° to 10°. Only the PA spot is within the sensitive range, the valid intensity values can be extracted from the image. Naturally, the first task is to narrow the search range to a sensitive range, i.e., coarse search.

The motorized TRUS rotates from -27° to 27° in increments of 6° at θ_i. Once the intensity of the PA marker $S(\theta_i)$ at θ_i is greater than the threshold, it can be considered that the PA virtual marker is already within the $\theta_i \pm 3°$ range.

2.4.2 Fine Search

When the PA virtual marker is within the $\theta_i \pm 3°$ range, the fine search will determine the accurate location of the PA marker. Physically, the closer the imaging plane is to the PA virtual marker, the lighter the spot in the photoacoustic image. According to this rule, the function of the distance and spot intensity is unimodal, and the goal is to determine the maximum point in this single-peak function.

Ternary search algorithm is a classical algorithm to solve this problem. The ternary search determines either that the minimum or maximum cannot be in the first third of the domain or that it cannot be in the last third of the domain, then repeats on the remaining two thirds[1]. The drawback of ternary search is that this method depends on the smoothness of the function. In reality, the search may fall in to the local minimum point because of the noise.

The other approach is to rotate the TRUS from $\theta_i - 3°$ to $\theta_i + 3°$ at equal interval, like 1°, and record the intensity at each position. The multivariate normal distribution with two terms is adopted to model these data. In this way, the data is fitted to a smooth function. The maximum point of this function can be determined directly. In this report, this approach is called the fit-based algorithm.

3 Experiment

The PA location search algorithm and the registration algorithm need to be verified experimentally. So the experiment can be divided into two parts. For PA location search algorithm, we will randomly set a location of PA as the ground truth. This section of the experiment needs to do 10 times. Due to the good performance of the simulation results of fit-based algorithm, this method has been tested experimentally. For the registration algorithm, at least 3 point pairs in the FL and PA image are required to calculate the rigid transformation. The Euclidean distance represents the error between the ground truth position and the detected position. In our project, the conventional registration algorithm was verified by experiments.

3.1 Simulation Analysis

Before experimental verification, Simulation analysis for the ternary search algorithm and the fit-based algorithm is conducted. Two kinds of data are used for simulation, one is generated from the Field II Ultrasound Simulation Program, and the other is the out-of-plane signal from the experiment. In this report, these two kinds of data are called artificial data and experimental data respectively.

For each search algorithm, 2000 angles are randomly generated as the locations of the PA virtual markers. If the calculated angle that differs from the ground truth by more than 5° it is considered a failed search. The simulation uses both artificial data and the experimental data. The success rate, iteration times and error will be recorded.

3.2 Experiment Setup

The experiment setup is shown in Fig. 4. The fluorescence endoscopic camera and TRUS are used to generate the FL image and PA image. A ICG dye-stained ex vivo chicken breast is placed on the phantom. The TRUS transducer with the actuator is fixed underneath the phantom. Blue light indicates the fluorescence illumination from the camera module. The pulsed-laser-diode emits the laser to generate the markers on the surface of the chicken breast.

[1] https://en.wikipedia.org/wiki/Ternary_search

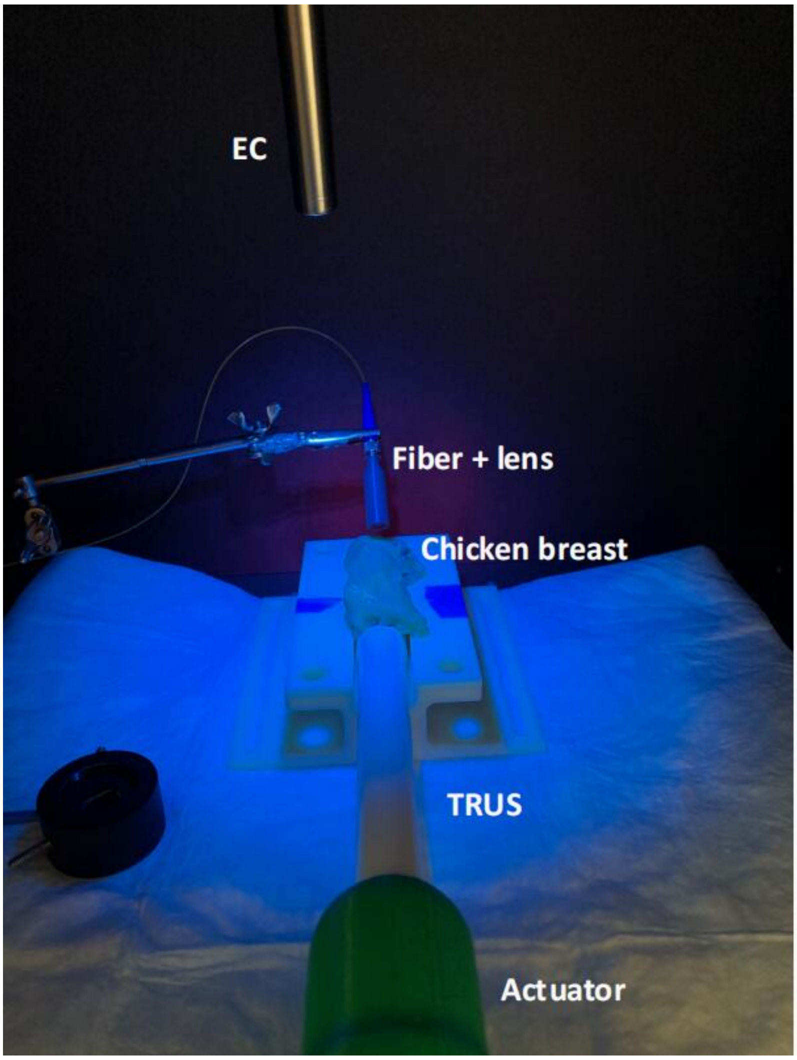

Figure 4: The experimental setup mimicking the surgical scene

3.3 Results

3.3.1 Results of Simulation Analysis

Table 1: Quantitative results based on the artificial data and experimental data using fit-based algorithm.

Data Type	Average Error (°)	Average Iteration Times (s)	Success Rate (%)
Artificial Data	0.1018	15.47	100
Experimental Data	0.2871	15.78	100

The simulation analysis for ternary search algorithm was conduct first. The data generated from the simulation software Field II is used to analysis. while the error of ternary search is pretty low, almost close to zero, the successful rate is 99.10% in 1000 times tests, not 100%. The reason is that the noise may cause the search fall into the local maximum point. Thus, we adopt the fit-based algorithm and conduct the simulation for this method on both artificial data and experimental data. The table 1 shows the results of simulation analysis of the fit-based search algorithm. Even the error is a little bit greater than the ternary search, the success rate is 100%, meaning this is a robust method.

4 Management

4.1 assignments

Shuojue Yang mainly worked on the system integration and Zijian Wu mainly worked on the searching algorithm.

4.2 Completeness v.s. Plan

We planned to finish the novel registration algorithm (the maximum deliverable) at the beginning, but we can only finish the conventional registration.

4.3 Future Work

Now the conventional registration pipeline is semi-automated and we plan to make it fully-automated. Besides, the tracking function should also be integrated into the system.

4.4 What We Learn

Zijian: I am very excited to be involved in such a project that is closely related to clinical applications. Compared with the theoretical knowledge of CIS 1, the personal practice has given me a deeper understanding of the surgical guidance system. I also learned some general techniques, such as running ROS in multiple machines. Besides, I have knowledge of ultrasound technology and photoacoustic imaging technology. From a collaboration standpoint, I'm getting used to how to work with teams, which is useful for my future research or work.

Shuojue: I learned and practiced most of my ROS skills in this project. The most meaningful thing I learned from this course is the preparation before starting my research. This paradigm of carrying research definitely provides a good template for my future projects.

References

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