Robot-Assisted FBG-based Sensorized Needle Calibration

Project Proposal

EN. 601.656 Advanced Computer Integrated Surgery

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1. Clinical Motivation

The motivation of the project comes from current procedures in prostate biopsy and brachytherapy, of which a stiff needle is inserted manually to the targeted region in the prostate tissue with guidance of an ultrasound probe either to retrieve a slice of potential cancerous tissue or to implant radioactive seeds into the tissue. This approach is problematic as ultrasound is inadequate for visualization of cancerous region or the seeds to be implanted. In addition, it is common that the prostate rotates and deforms during the insertion of the needle, which often causes displacement of the target region. In this situation, the straight needle trajectory becomes insufficient, and will often result in poor accuracy and poor repeatability of the insertion. Thus, an updated approach was proposed, which includes inserting a flexible needle using robotic assistance with real-time MRI image guidance.

2. Prior Work

The flexible bevel tip needle was chosen to be the needle for the updated approach mentioned in the previous section, and FBG sensors are attached to the inside of the needle to constantly monitor its curvature. Since then, a lot of progress has been made in generating various mathematical models and algorithms for the needle, including real-time needle navigation algorithm, shape determination model, and trajectory generation algorithm. In addition, a manual calibration procedure has been setup for the needles to precisely and consistently calculate the curvature value of the needle from the FBG sensor readings. However, as the needles are very sensitive, the current calibration procedure is very time consuming and can take several hours for each needle, and even with the careful handling of the needle the calibration process is still prone to human error.

3. Objectives

As mentioned in the previous section, the current manual calibration process of the FBG based sensorized needle is time consuming and subject to human error. Thus, the goal of this project is to build a robotic system for (semi)automatic calibration of flexible needles with FBG-based shape-sensing capabilities. It is hypothesized that the robot-assisted needle calibration would optimize needle construction and improve its shape-sensing accuracy.

4. Technical Approach

The desired robotic system will have the elements diagram as shown in Figure 01. According to the diagram, the approach of this project was divided into three sections, and the integration of these three sections will form the desired robotic system for needle calibration.

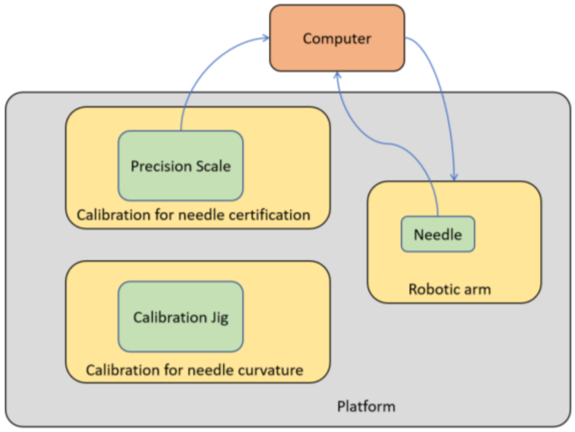

Figure 01. Simple element diagram of the desired robotic system. The arrow represents the data transmission with the arrowhead pointing to the element that receives data.

a. Calibration Platform

According to the diagram of the system, two types of calibration are needed to fully calibrate a needle, so a calibration platform needs to be built in order to have the correct setup for both calibration processes.

The first calibration process aims to ensure that the needle is working properly. It is done by having the needle bent downwards on a platform set up on a precision scale and plotting the FBG sensor readings with respect to the bending force measured from the scale (Figure 02). If the relationship between the two measurements is not linear, then the needle is determined to be faulty and cannot be used if not fixed. For this process, the robotic arm and the precision scale need to be fixed on the platform at known locations. As the precision scale is shared with other projects in the lab, its fixation mechanism also needs to be removable.

The second calibration process aims to calibrate the readings of the FBG sensor inside the needle with the actual curvature of the needle. In order to do that, the needle is inserted repeatedly into a calibration jig with multiple slots of constant curvature (Figure 03). Thus the calibration jig also needs to be fixed at a precise location on the platform. In addition, it is desired for the calibration jig to be swappable so the platform is applicable to more needles and various calibration needs.

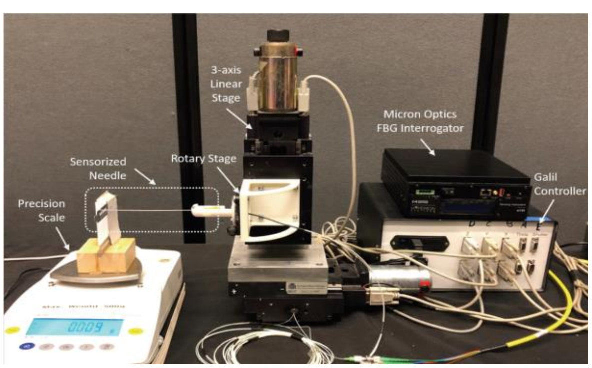

Figure 02. First calibration process with the precision scale.

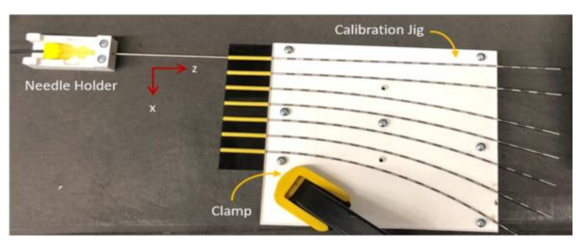

Figure 03. Second calibration process with the calibration jig.

b. Algorithm for robot arm

With the calibration platform set up, the next step would be to design an algorithm for the robotic arm to move around the platform and perform calibration steps. The overall workflow of the algorithm is shown in Figure 04, in which the operations in red are performed automatically, the operations in yellow are performed automatically in an ideal setting but can be controlled manually, and the operations in green are performed under user control. In addition, the entire calibration algorithm needs to be completed in a time span of minutes, preferably under 10 minutes.

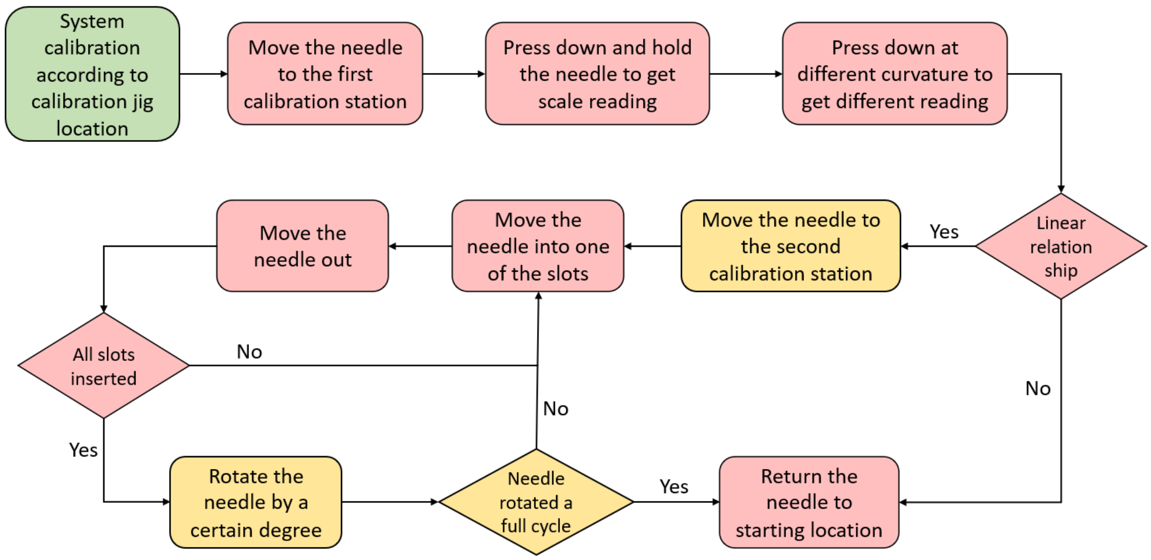

Figure 04. Workflow of the algorithm for the robotic arm movement.

c. Data processing

According to the element diagram of the system, there are three data sources in the system: the FBG sensors in the needle, the scale, and the curvature parameters of the calibration jig. Thus the purpose of this section is to compile all three data inputs and calculate the calibration matrix for each FBG sensor on the needle. There are two main tasks in this section. The first task is to set up a unified data input format into one Matlab program, as each of the data source connects differently to the computer. The other task is to calculate the calibration matrix from the source data. There is an existing mathematical algorithm developed for this purpose (Figure 05), so the main task is to migrate the mathematical algorithm into a Matlab function and integrate it to other program codes of the system.

$$\Delta\lambda_i = C_i[\kappa_{yz,i},\ \kappa_{xz,i}]^T \qquad \begin{aligned} C_1 &= \begin{bmatrix} -0.2686 & 0.039 & 0.2295 \\ -0.1234 & 0.239 & -0.1156 \end{bmatrix}^T; \\ C_2 &= \begin{bmatrix} -0.24 & 0.0498 & 0.1901 \\ -0.0779 & 0.2478 & -0.1699 \end{bmatrix}^T; \\ C_3 &= \begin{bmatrix} -0.1355 & 0.0227 & 0.1128 \\ -0.0559 & 0.143 & -0.0871 \end{bmatrix}^T. \end{aligned}$$

Figure 05. Mathematical algorithm to calculate the calibration matrix (left) and example calibration matrices obtained in the paper (right). $\Delta\lambda_i$ is the wavelength shift vector of each FBG sensor and $\kappa_{yz,i}$ and $\kappa_{xz,i}$ represent the curvatures in the yz- and xz-plane at the same position. (Kim *et al.*, 2017)

5. Deliverables

The deliverables of the project are listed in Figure 06. It is divided into the minimum, expected and maximum deliverables. Essentially, the minimum deliverable is able to perform a needle calibration with reduced human error but still require extensive user interaction. The expected deliverable is able to further reduce the human interference and the maximum deliverable performs needle calibration completely automatically.

	Hardware	Algorithm	Experiment data	Documentation
Minimum	Calibration platform	Semi-automatic code (manual movement between jigs + manual needle rotation) with comments	Calibration matrices for one needle	User manual for the system
Expected	Updated platform	Most automatic code (manual needle rotation) with comments		Updated user manual and example calibration video
Maximum		Fully automatic code with comments	Calibration results using other calibration jigs	Updated user manual and example calibration video

Figure 06. Deliverables of the project.

6. Dependencies

The dependencies of the project are listed in Figure 07. Most of the dependencies have been acquired, and the contingency plans for the dependencies that have not been resolved are listed. The contingency plan will be executed if the dependency is not resolved by the planned deadline.

Dependency	Status	Contingency plan	Planned DDL	Hard DDL
Acquire robotic arm and data acquisition unit	Acquired	Both robot and the data acquisition unit have a backup model	Feb 19	Feb 19
Several needles for testing	Acquired	Currently the lab has multiple needles	Feb 19	Feb 19
Curvature jig model	Acquired	More models can be 3D printed fairly quickly	Feb 19	Feb 19
Lab access	Acquired	N/A	Feb 12	Feb 12
Aluminum breadboard	Not acquired	Multiple backup choices including acrylic base and aluminum profiles	Feb 25	March 12
Substitute force sensing mechanism for precision scale	Not acquired	Continue using the scale	March 29	N/A

Figure 07. Dependencies of the project.

7. Timeline

The timeline is shown in Figure 08 with the expected completion date for the deliverables. Upon the completion date, the deliverables are assessed with a trial run of the needle calibration process.

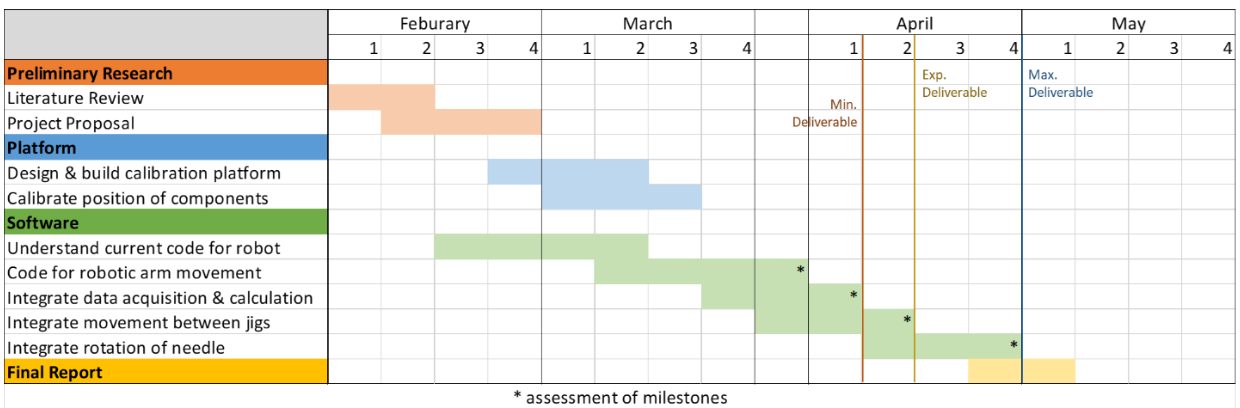

Figure 08. Timeline of the project.

8. Team Members

Kefan Song is the only member of the team and is responsible for all tasks required for this project. The mentors of the team include:

Dr. Iulian Iordachita: principal investigator of the project.

Dimitri Lezcano: primary mentor of the project.

Dr. Jin Seob Kim: mentor on mathematical model and algorithms.

Ge Sun: Mentor on robot control and needle calibration steps.

9. Management Plan

The management plan include weekly meetings and in-person interactions. The team will meet weekly on Wednesdays via Zoom in which the team member will report the weekly progress of the project. In addition, there will be ad hoc in-person interaction in the lab for specific problems that come up.

10. Reading List

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Chen, X., Yi, X., Qian, J., Zhang, Y., Shen, L., & Wei, Y. (2020). Updated shape sensing algorithm for space curves with FBG sensors. Optics and Lasers in Engineering, 129, 106057.

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