iPASS: Photoacoustic Catheter Tracking

Project Report

600.646 Computer Integrated Surgery II Spring 2016

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1 Introduction

This project proposes new way of tracking technology by integration of the laser technology with the computer vision, and also piezoelectric effect. The goal of this project is to track a catheter using a stereo camera and applying laser spots on the patient surface, which can be seen by the stereo camera and generate a photoacoustic (PA) signal observed by the piezoelectric element. The previous preliminary results show reasonable repeatability of element localization.

1.1 Background and Significance

Photoacoustics is an acoustic wave generation by an absorption of light. The history of photoacoustic effect discovery starts from 1880 when Alexander Graham Bell observed it. The photoacoustic effect is broadly applied for using in various fields, especially medical field for spectroscopy. While the piezoelectric element is a device using the piezoelectric effect to measure changes in pressure, temperature or force by converting them to the electrical charge. Piezoelectric effect is used in many applications, such as detection of sound and generation of electronic frequency.

When comparing to other guidance systems, the benefit of this project is that this method does not require any physical markers in order to create a coordinate transformation, also it does not need to have calibration processes because we can directly compute the coordinate transformation from the collected data. The significance of this project is to enable an innovation to track the tool in interventional photoacoustic system with no additional trackable markers and/or calibration processes. The concept of our system is illustrated in figure 1.

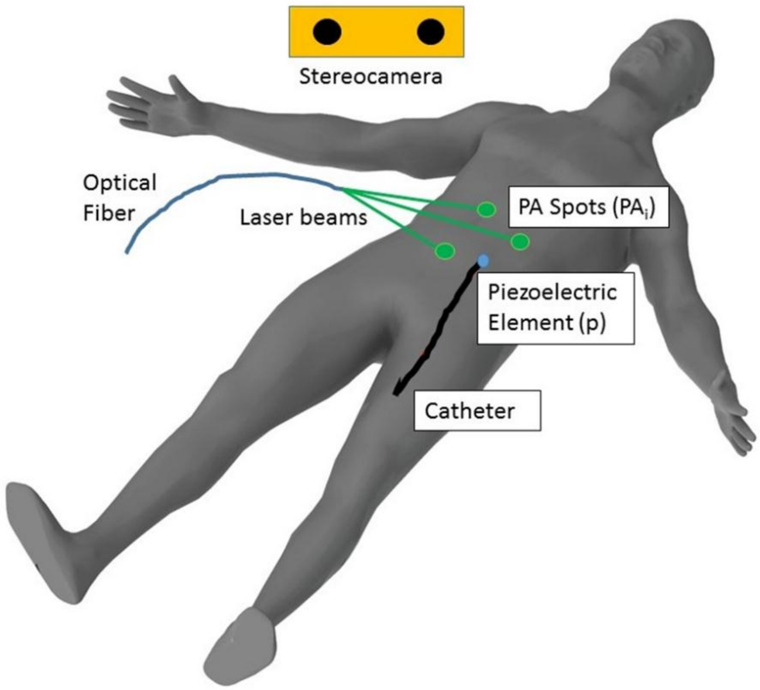

Figure 1. Figure of Photoacoustic Catheter Tracking Concept

1.2 Goal

The goal of this project is to develop a system that can track a catheter using a stereo camera by applying laser spots on the surface, which can be seen by the stereo camera and generate a photoacoustic signal observed by the piezoelectric element. We also present experimental results on a synthetic phantom and an *ex-vivo* phantom.

2 Technical Approach

To conduct our experiments, A laser system, Q-switched neodymium-doped yttrium aluminum garnet (Nd:YAG), Brilliant (Quantel Laser, France) laser is used to generate a photoacoustic effect on the phantom with approximately 0.1 mJ/cm^2. And to capture the camera images, we use two CMLN-13S2C cameras (Point Grey Research, Richmond, Canada) as our stereo camera system. A customized PZT5H tube with 2.08 mm and 1.47 mm as outer and inner diameters, respectively is used as our piezoelectric element in our experiment. We also use the Sonix DAQ (Ultrasonix, Canada) and its associated software to collect the signal from the piezoelectric element. One of the data acquisition system channels is used to operate on that function with 6μs Rx delay as DAQ data delay. The synthetic phantom is made of plastisol and black dye. The *ex-vivo* tissue phantom for both experiments is made of a gelatin solution and a porcine heart. The surface of the heart is not covered by gelatin and partially exposed. Figure 2 shows the workflow of our system. And figure 3 illustrates the system setup. The details of our method are described as the following sections.

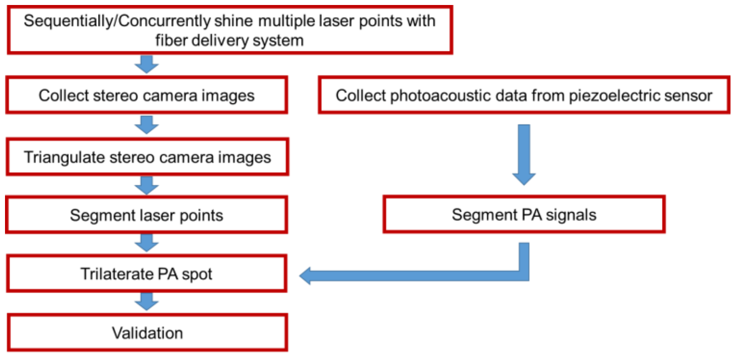

Figure 2. Workflow of the system

2.1 Stereo camera point segmentation

This approach is to locate the laser points in stereo camera images. Since we are dealing with multiple image frames, composed of either images with or without the laser point, the efficient segmentation method for those points is needed. Some characteristics of images are determined to be used as parameters of this segmentation method, such as intensity thresholds based on histogram of intensities, pixel size threshold, and shape filter. The setup is shown in figure 4.

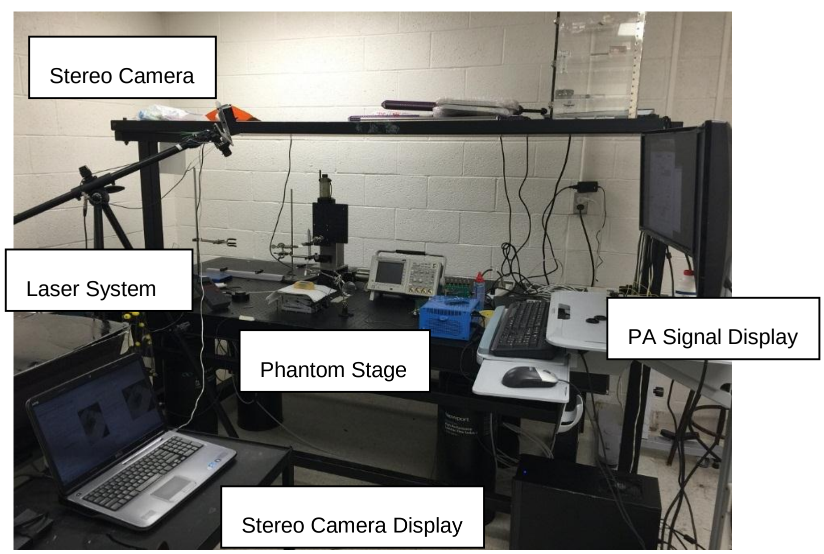

Figure 3. System Overall Setup

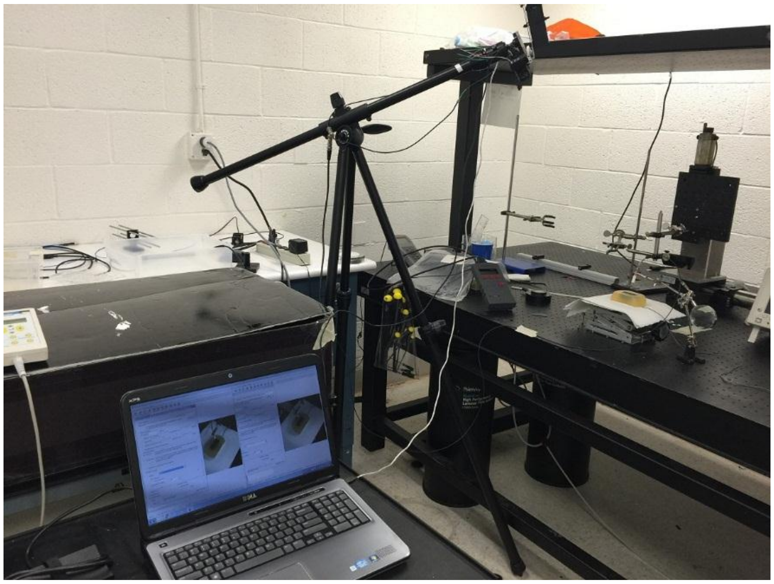

Figure 4. Stereo Camera Setup

2.2 System overview for PA signal acquisition

The reason for this approach is to acquire the PA signal. We use the DAQ system to collect the signal. We not only use a filter to remove some unwanted feature noises from a signal before being sampled in the DAQ, but also apply the impedance matching design to improve the signal-to-noise ratio. The diagram of our PA signal acquisition is shown in figure 5.

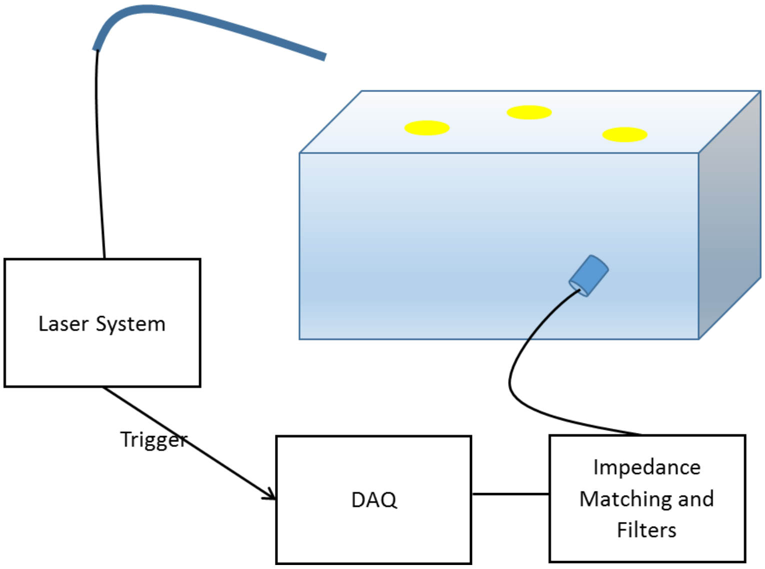

Figure 5. Block Diagram of PA Signal Acquisition

2.3 Trilateration method

The reason for this approach is to acquire the location of piezoelectric element point or the location of catheter tip in this project. Trilateration is the method of calculating locations of points by measurement of distances, and applying the theory of geometry of circles and spheres as shown in figure 6. Because the PA signal is synchronized with the laser, the signal location represents the time between the laser firing event and the PA signal reaching the PZT element, denoted as ToF_i. Speed of sound, *SoS*, is one characteristic of time of the medium in which the PA signal is going through and we can convert this value to the distance. Then we can write a distance equation as shown in equation 1.

$$||PA_i - p||_2 = ToF_i * SoS \quad (1)$$

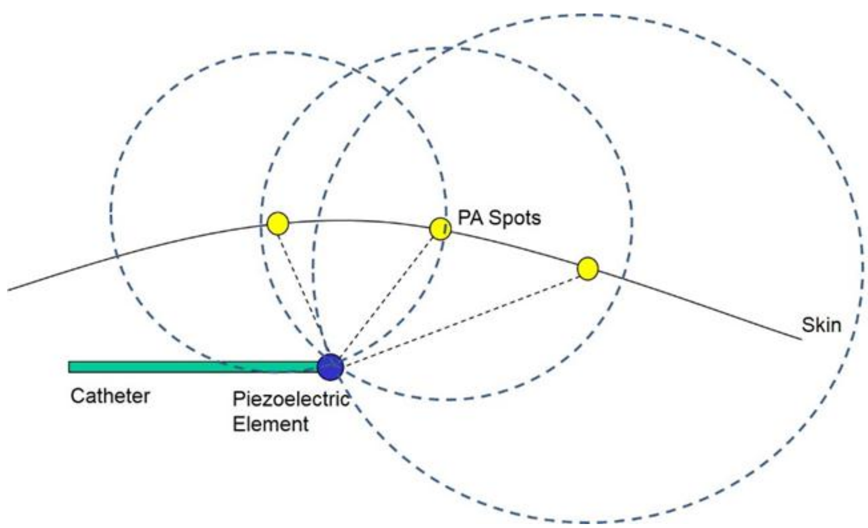

Figure 6. Piezoelectric Element Localization

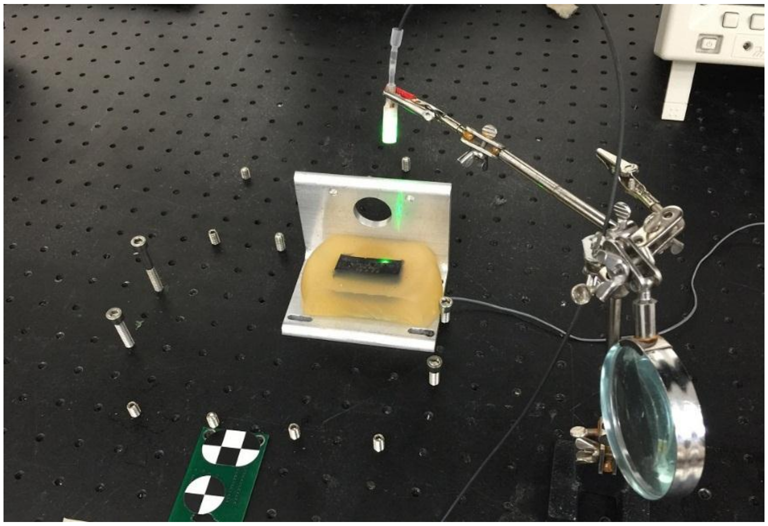

Figure 7. Image of Shining Laser on Synthetic Phantom

2.4 Validation

The reason for validation is to show that this system succeeds the project goals. We will use two methods to validate the system. One of them is “repeatability”: the result of calculation with different subsets of PA spots data should give the same location of catheter tip. Another method is “relative distance”: the results of calculation of at least two different set-up tip locations will be compared with known distance of those points.

In our experimental setup, we designed to test the repeatability of the PZT element localization method and the relative distance method. We conduct the experiment by constructing the stage (101.6 x 76.2 mm) where the phantom is placed on with limited workspace at known dimensions (195.07 x 147.32 mm) as shown in figure 8. Then we set the locations at each corners of workspace as shown in figure 9-12. Data from a total of twenty photoacoustic markers at each location was acquired while the PZT element remained stationary. Actually, three photoacoustice spots are enough to perform localization and any three can be used to acquire the same PZT element position theoretically. However, multiple points of photoacoustic spots (4-9 spots) are performed to compare their results.

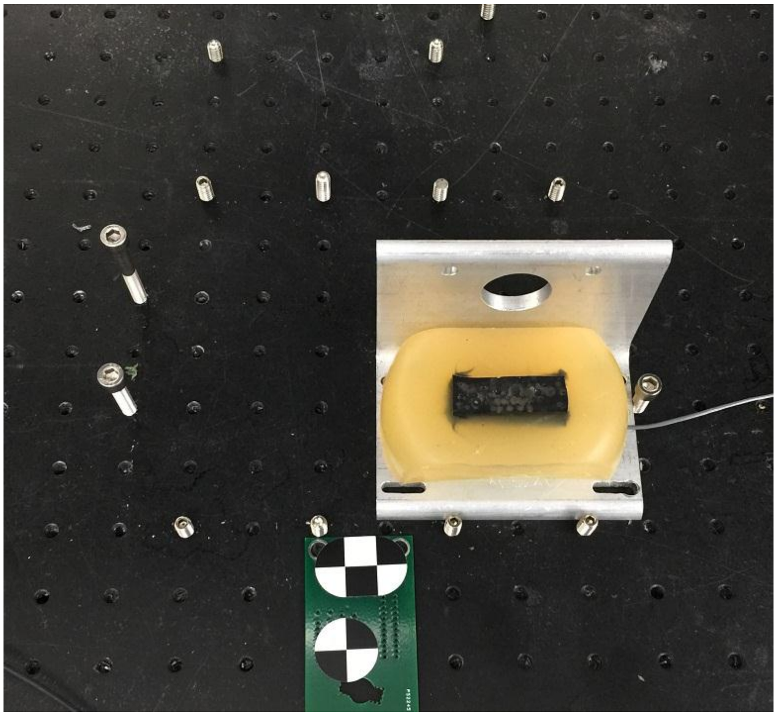

Figure 8. Workspace and Stage of Phantom

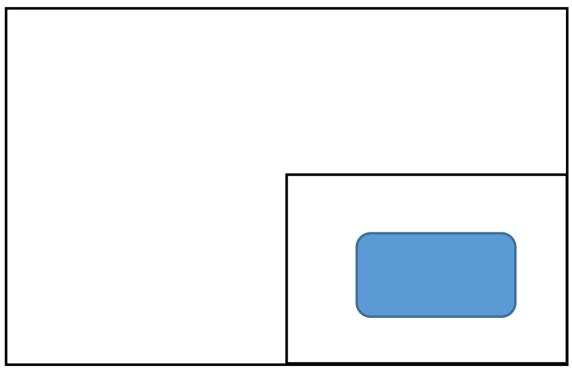

Figure 9. Bottom Right (RB) Location

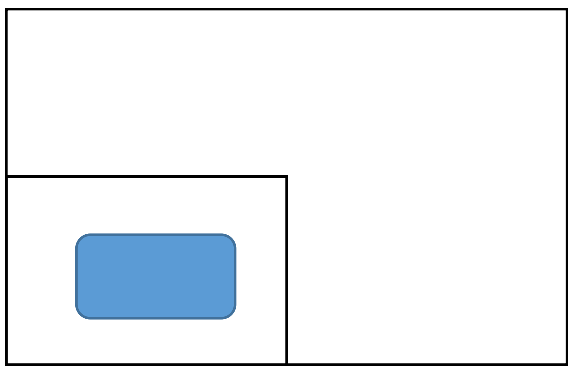

Figure 10. Bottom Left (LB) Location

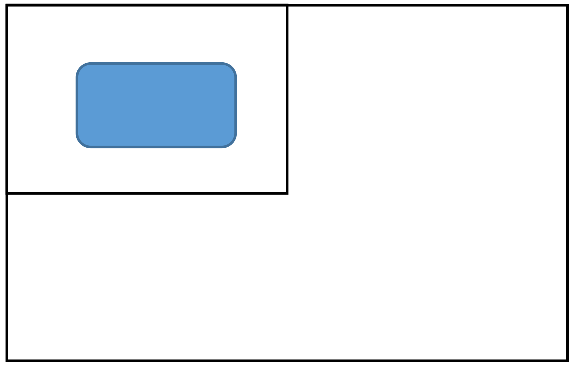

Figure 11. Upper left (LU) Location

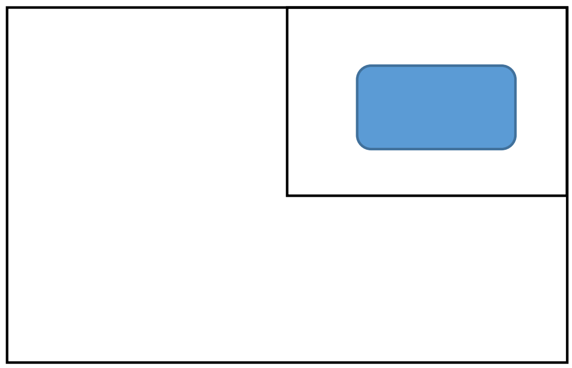

Figure 12. Upper Right (RU) Location

3 Results

We use the measures to evaluate the repeatability of the PZT element localization method as shown in equations 2 and 3. The repeatability is the mean and standard deviation of the distances between each localized point and the mean point. Numerically, the repeatability and the relative distance validation results of synthetic phantom experiment at each location by using three photoacoustic spots are shown in table 1 and 2 respectively. Figure 13-16 graphically shows the spread of the localized piezoelectric element over 200 trials in the stereo camera coordinate system at each location.

$$d_i = ||p_i - mean(p)||_2 \quad (2)$$

$$Repeatability = mean(d) \pm std(d) \quad (3)$$

Location	Repeatability (mm)
Bottom Left (LB)	1.60 ± 1.13
Upper Left (LU)	1.46 ± 0.94
Bottom Right (RB)	2.14 ± 1.46
Upper Right (RU)	3.12 ± 2.43

Table 1. Repeatability Validation Results of Synthetic Phantom Experiment at Each Location Using Three Photoacoustic Spots

Locations	Distance Between Mean Points (mm)	True Distance (mm)	Error (%)
Bottom Left & Upper Left (LB & LU)	69.93	71.12	1.71
Bottom Right & Upper Right (RB & RU)	68.43	71.12	3.93
Bottom Left & Bottom Right (LB & RB)	96.66	93.47	3.30
Upper Left & Upper Right (LU & RU)	96.30	93.47	2.94

Table 2. Relative Distance Validation Results of Synthetic Phantom Experiment between Mean Points of Locations Using Three Photoacoustic Spots

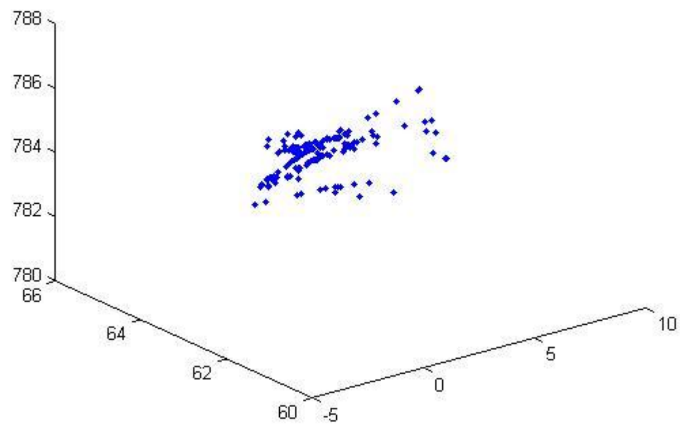

Figure 13. Localized piezoelectric element positions over 200 trials at Bottom Left (LB) location

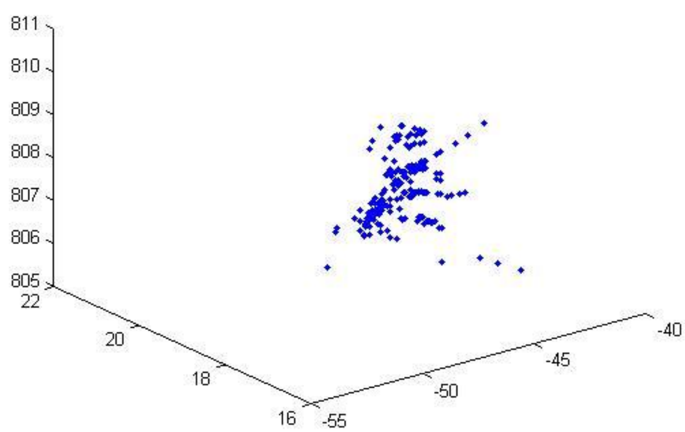

Figure 14. Localized piezoelectric element positions over 200 trials at Upper Left (LU) location

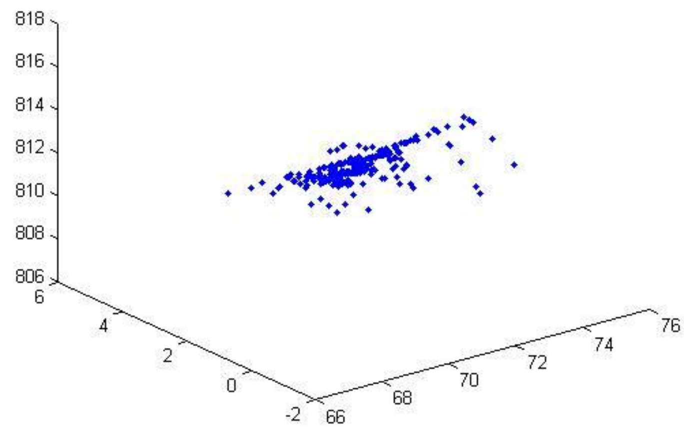

Figure 15. Localized piezoelectric element positions over 200 trials at Bottom Right (RB) location

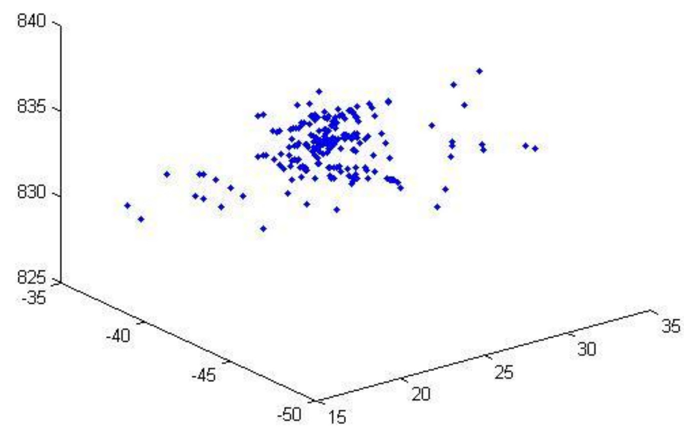

Figure 16. Localized piezoelectric element positions over 200 trials at Upper Right (RU) location

With multiple points of photoacoustic spots, we compare the results of the percent of errors of the relative distance validation method at different number of spots as shown in figure 17-18.

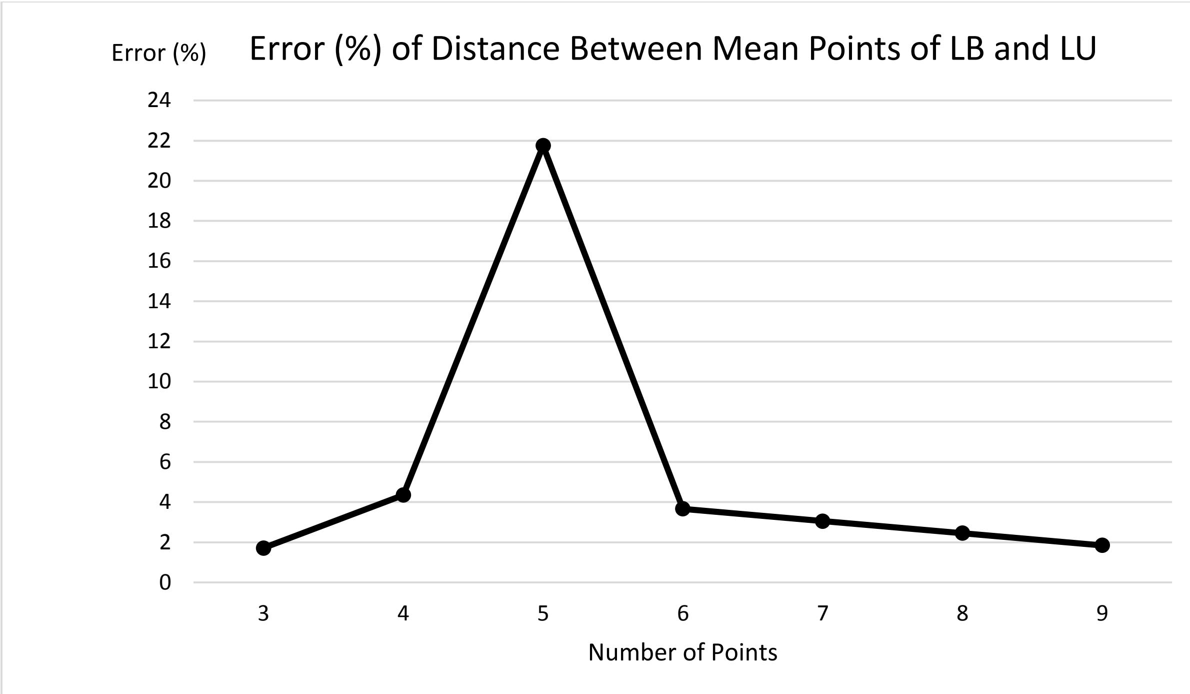

Figure 17. The percent of errors of distance between mean points of LB and LU

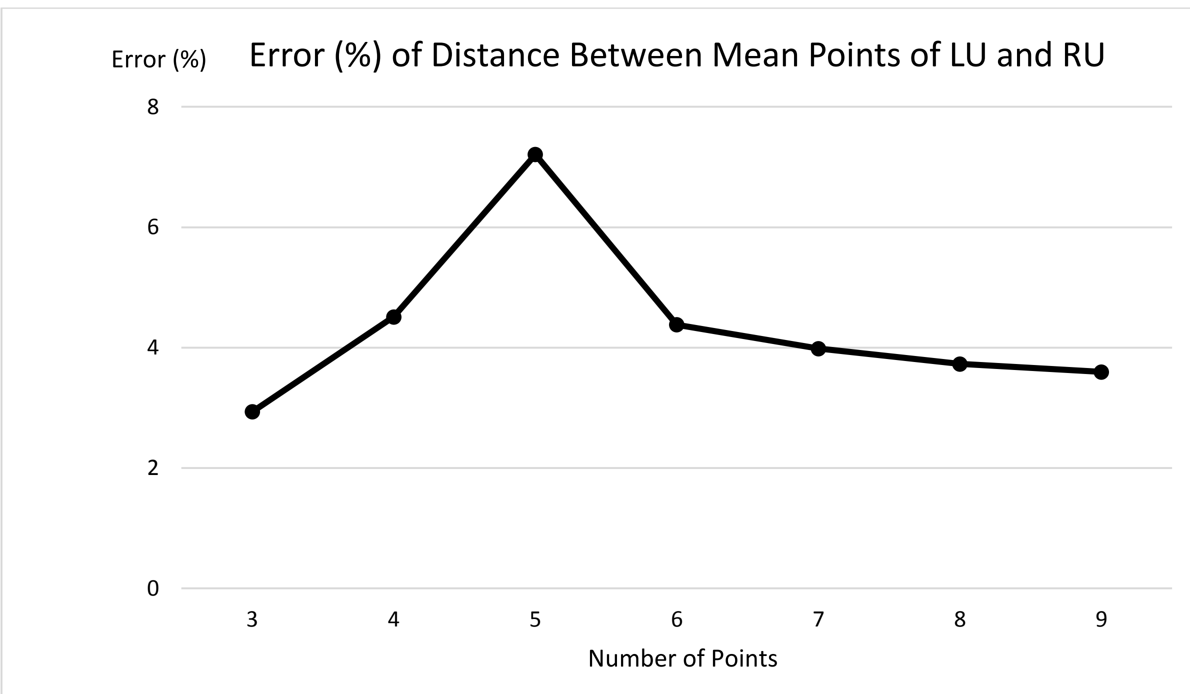

Figure 18. The percent of errors of distance between mean points of LU and RU

4 Discussion

We have shown results in table 1 that the PZT element localization results with three PA spots are repeatable and comparable to existing tracking-based systems. We report errors of around 2 mm. While the results of the relative distance showed that there are approximately errors of 3% whereas the results of multiple spots of photoacoustic markers (4-9 spots) in figure 17 and 18 showed that the errors tend to decrease over higher number of spots (6-9 spots). But with four and five spots the percent of errors are quite higher than others. There are several hypothesis of error that contributed to these results. Segmentation errors of the photoacoustic markers and acoustic signal will propagate to the final localization result. Secondly, the geometry of the PZT element may cause the variation of detected signal intensity. We use the element with cylinder shape at 4 mm length. When looking into the results of the relative distance validation in table 2, the number of errors is quite close to the length of element. Thirdly, the laser beam width may be larger than the width of the PZT element, this may cause the position errors to the results.

5 Conclusion

We demonstrated the experiments of the localization of a single piezoelectric element. The proposed system can be used to track catheters. The results of localization repeatability is comparable with existing tracking methods. Future work will include the development of real-time tracking system and the study of how photoacoustic marker shape affects localization errors.

6 Acknowledgements

I would like to thank Alexis Cheng, and Younsu Kim for their help in setting up the system. I would also like to thank Dr. Boctor, and Dr. Taylor for their helpful guidance throughout the project.

7 Management Summary

Milestone	Expected Completion	Actual Completion	Status
Phantom Acquisition	February 27, 2016	February 27, 2016	Done
Circuit Board Refinement	February 27, 2016	February 27, 2016	Done
Synthetic Phantom/*Ex vivo* Experiment	March 12, 2016	March 26, 2016	Done
Analysis and Validation of Experimental Data	March 19, 2016	April 2, 2016	Done
Synthetic/Ex-vivo Experiment for optimizing the number and pattern of spots	April 16, 2016	April 16, 2016	Done
Analysis and Validation of Experimental Data	April 23, 2016	May 5, 2016	Done

Table 3. List of Project Milestones and Status

Gantt chart

Minimum

Expected

Task	14 Feb	21 Feb	28 Feb	6 Mar	13 Mar	20 Mar	27 Mar	3 Apr	10 Apr	17 Apr	24 Apr	1 May
Phantom Acquisition												
Circuit Board Refinement												
~~*In vivo* Experimental Protocol~~												
Synthetic/*Ex vivo* Experiment												
Analysis and Validation of Experimental Data												
~~Concurrent Projection Method Development~~												
Synthetic/*Ex vivo* Experiment for optimizing the number and pattern of spots												
Analysis and Validation of Experimental Data												
Real-time Tracking System												
~~*In vivo* Experiment Feasibility Study~~												

8 Appendix

The code and documentation can be found on the project webpage.

References

1) Xiaoyu Guo et al. “Active Ultrasound Pattern Injection System (AUSPIS) for Interventional Tool Guidance”. PLoS ONE 9(10) 2014
2) Alexis Cheng et al. “Catheter Tracking in an Interventional Photoacoustic Surgical System”. Submitted to CLEO 2016
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4) Alexis Cheng et al. “Direct three-dimensional ultrasound-to-video registration using photoacoustic markers”. Journal of Biomedical Optics 18(6), 066013 (June 2013)
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6) Alexis Cheng et al. “Direct ultrasound to video registration using photoacoustic markers from a single image pose”. SPIE 2015