Interventional Photoacoustic Ultrasound System

600.446 Computer Integrated Surgery II

Final Project Report

Team Members: Saurabh Vyas, Steven Su, Robert Kim

Mentors: Dr. Russell Taylor, Dr. Emad Boctor

Abstract

In this paper, we describe a tracking system that does not require physical markers or fiducials. Using the photoacoustic effect, we were able to perform the rigid registration between ultrasound imaging system and stereocamera module. The accuracy of the registration ranged from 0.3838 mm to 3.0028 mm.

1. Introduction

1.1 Clinical Need

There are approximately 6000 hospitals in the United States, of which approximately 5400 employ minimally invasive surgical robots for a number of procedures. Furthermore, 95% of these robots require extensive registration before they can be fitted into the OR. These "registrations" are performed by surgical navigation systems which allow the surgical tools, the robot and the surgeon to be synched together—hence operating in concert. Current surgical tracking systems are limited in their capabilities and lack effortless integration into a surgical setting. These technologies include electromagnetic (EM) and optical tracking modalities. The primary shortcomings of such systems include their intrusive integration into the OR, sterility, and cost-effectiveness. A typical EM tracking system setup is depicted below in Figure 1.

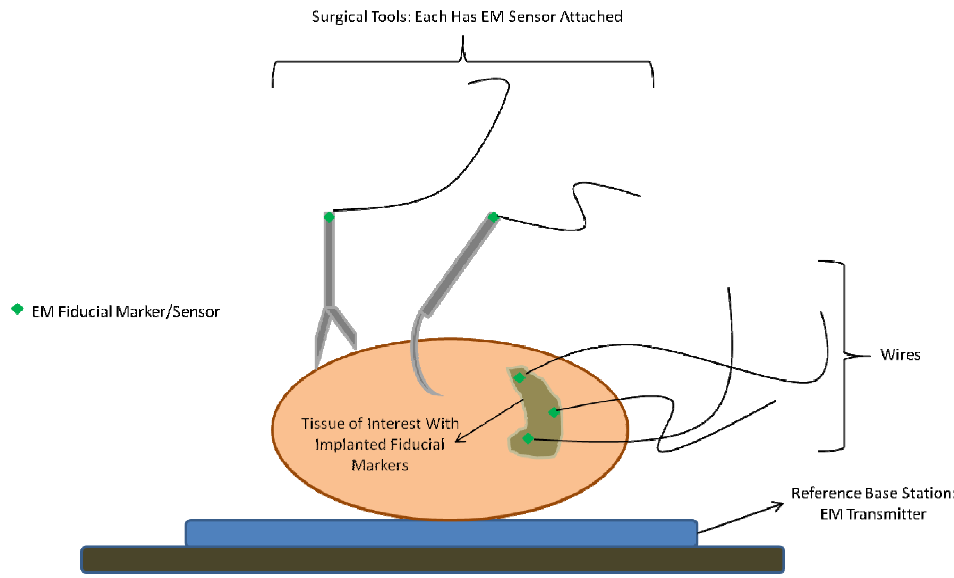

Figure 1. The complex and intrusive setup of current EM tracking systems. The body in the figure is a transverse cross sectional cut of the abdomen area of a patient.

EM and optical tracking systems usually consist of a third party reference base station, implantable fiducial markers, and associated surgical instruments, each of which has a sensor attached to it. In order to track the position of each tool with respect to the patient, fiducial markers first need to be implanted in the patient so that a patient to base station "registration" (i.e. a mapping of the current patient position and base station position) can be computed. Only after completing this initial registration can each surgical instrument be registered to the base station and tracked with respect to the patient.

Base stations are intrusive due to their large form factor and complicate the layout of an OR. Additionally, base stations can limit the physical capabilities of a surgeon due to the fact that the patient can only be place on the base a specific way and the surgeon must work around that placement. In optical tracking systems, a clear line of sight between each optical sensor and the reference tracker must be constantly maintained in order to track each tool. All personnel in the OR, including the surgeon, must be careful in his/her movements to prevent blocking this line of sight. In EM tracking, any metal object in the OR can cause interference between the EM transmitter base and each surgical tool. Furthermore, mutual interference between tools can occur if tools are brought into close proximity with one another, which is required in most surgical procedures.

The attachment of sensors onto every surgical instrument also presents sterility and cost issues. The EM and optical sensors attached on surgical instruments cost about $500 per unit – an expensive cost for such a small piece of equipment. As a result, most ORs have a limited quantity of these trackers; the number of surgical tools usually greatly outnumbers the number of trackers. Sterility issues arise from the fact that every instance a new surgical instrument is required by the surgeon, a sensor must be sterilized and attached onto the tool. This can get complicated when there are tools of many sizes; if a surgeon selects a specific size tool pre-surgery and intra-surgery realizes he needs a different size, he needs to wait for a sensor to be sterilized before he can use the new tool since it is likely that all other available sensors are being used on other tools. This time could be critical to the success of the surgery and could separate life from death.

1.2 Photoacoustic Imaging

Photoacoustic imaging is a promising new technology that has the potential to replace existing registration methods such as EM and optical tracking. Photoacoustic imaging involves irradiating tissues with rapid pulses of laser. The pulses are then absorbed by the tissues which go through thermoelastic expansion. This rapid expansion produces transient acoustic waves due to pressure variations in the environment around the medium. These acoustic waves can be then detected by acoustic devices such as ultrasound.

1.3 Motivation and Significance

Currently, most computer-integrated surgical systems use electromagnetic (EM) or optical tracking methods. Both of these methods have weaknesses that can be overcome with photoacoustic tracking methods. One principle weakness common to both EM and optical tracking is the necessity for EM markers or LEDs in or around the surgical site. Both types of markers are wired, meaning that the surgical area may be complicated by the wiring emanating from these markers. Photoacoustic registration and tracking does not require the placement of wired markers on or around the patient. Recent research and literature review indicates that the photoacoustic effect can be observed using a 532 nm source laser (green) without using any physical fiducial markers.

An additional weakness of optical tracking is that it is an all or nothing process. If the line of vision between the optical tracker and LEDs is blocked, tracking cannot occur. With photo-acoustic registration, laser sources will be closer to the surgical site and ultrasound will be positioned closer to the patient. This avoids the possibility of interference and blockage of tracking.

In this paper, we present an image registration technique using ultrasound-photoacoustic imaging system combined with a stereocamera module. Using the photoacoustic effect, we were able to perform the rigid registration from the stereocamera to the ultrasound coordinate system without using any physical markers.

2. Methods

2.1 Design of Combined Ultrasound and Photoacoustic Imaging System

Ultrasound and photoacoustic signals were acquired simultaneously. In our imaging system, an Nd: YAG laser operating at 532 nm or 1064 nm wavelength was used to irradiate our phantom. For our ultrasound system, Sonix CEP ultrasound system and Sonix DAQ module were used to detect and acquire the acoustic waves. The block diagram and the picture of our combined imaging system setup are shown in Figure 2.

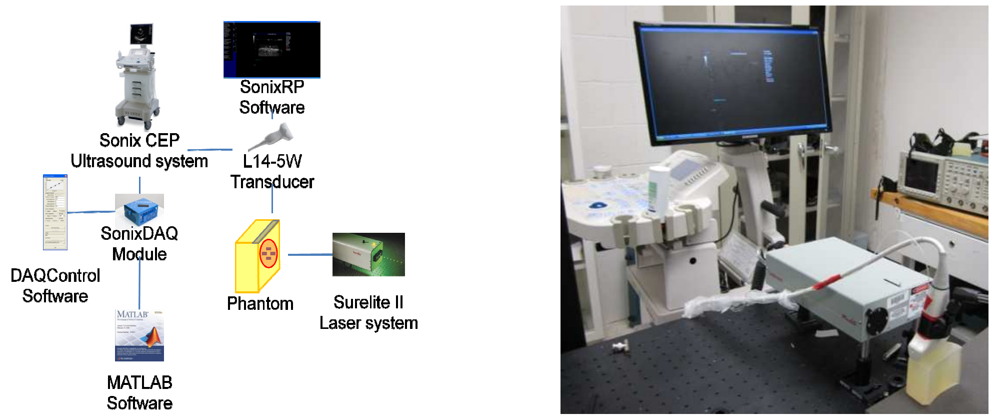

Figure 2. Combined ultrasound and photoacoustic imaging system.

2.2 Experimental Setup

Several “one-point” experiments were performed. In these experiments, a single laser point was projected onto the phantom, and the photoacoustic waves were acquired. A single laser source with 1064 nm wavelength was projected onto the phantom with no brachytherapy seed, one seed, and three seeds. In addition, a laser source with 532 nm wavelength was projected onto the phantom without any seed.

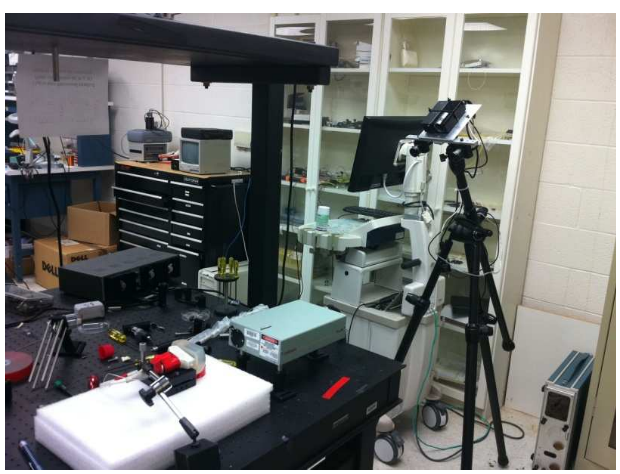

Figure 3. Ultrasound-photoacoustic imaging system combined with a stereocamera.

2.3 Image Processing Steps

Ultrasound signals were converted to pre-beamformed images which were in turn transformed to beamformed images. In order to detect the point on the ultrasound image where the laser was projected, the brightest (highest intensity) point was detected by detecting the brightest point (via centroid function) in the thresholded version of the beamformed image. The stereocamera images were thresholded to find the coordinates of the points where the laser was projected.

2.4 Interventional PhotoAcoustic Surgical System (iPASS)

We designed a surgical navigation technology named iPASS which could eliminate all drawbacks of current surgical navigation systems and submitted our design to the BMEStart Competition. Surgical navigation is not a new technology, and similarly the Photoacoustic effect is not a new phenomenon. The iPASS platform, however, is the first surgical system that is able to combine the two into creating one powerful, potent, and most importantly easy-to-use next-generation technology. Perhaps one of the most desirable features of the iPASS technology is its easy integration (with a minimal learning curve) into a surgical setting. Unlike its predecessors, the entire registration process takes less than a second to perform; calibration and registration of EM and Optical navigation system could take several minutes to an hour in some cases. Additionally, the only training the medical staff would require is a one-hour online laser safety-training course.

The iPASS platform technology goes beyond just basic surgical tracking. The iPASS system is also capable of providing real-time video overlay of anatomical features of interest onto the patient to help guide the surgeon with a specific procedure. An application of such a powerful feature would be in Laparoscopic Partial Nephrectomy. The surgeon is interested in finding and excising a tumor, with the help of real-time video overlay the surgeon is able to pinpoint the incision spot and guide his surgical instrument to scoop out the tumor while avoiding critical anatomy (arteries, etc) and minimizing loss of good tissue. The iPASS is referred to as a "platform technology" not only because of its tracking ability, or its video-overlay application, but because it contains several other common features which are critical in several procedures. The iPASS platform is capable of performing temperature imaging which is common in tumor ablations; iPASS already contains an integrated laser source as well as an ultrasound system. The ultrasound system is able to record changes in the temperature (speed of sound changes due to heat) while the surgeon moves the laser around to remove the tumor. There are numerous other such applications as well such as molecular imaging, thermal imaging and elastography. Therefore, it is clear that the iPASS platform is not only able to perform basic surgical navigation (with added precision and elimination of all the problems with current EM and Optical systems), but is also has the potential to replace numerous surgical devices (with redundant functions) and drive down costs associated with purchasing and maintaining other devices.

3. Results and Discussion

3.1 One-Point Experiments

For the one-point experiments, the photoacoustic waves were detected using the phantom with either 532 nm or 1064 nm wavelength laser. The results are shown below:

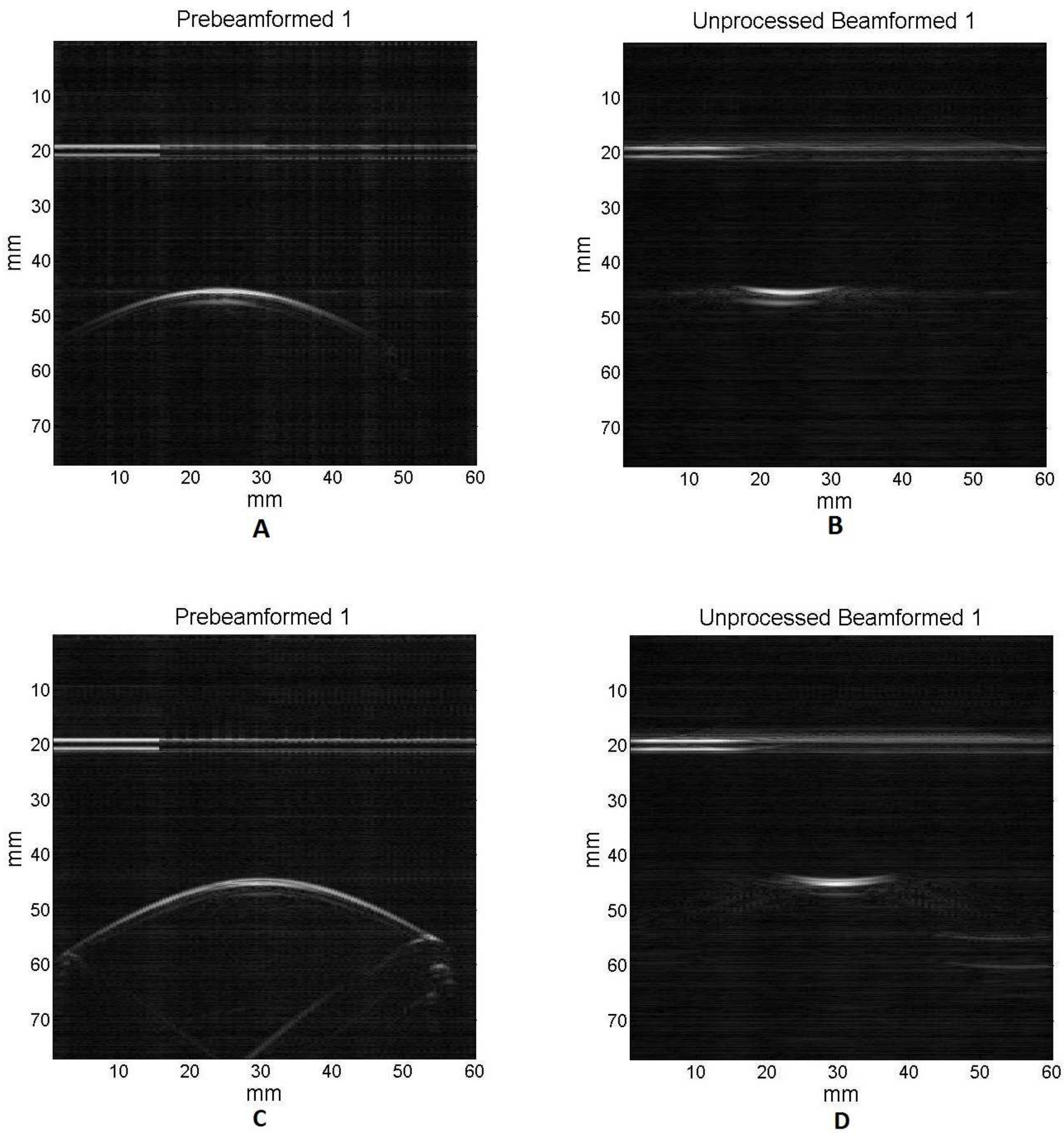

Figure 4. A and B are prebeam and beamformed images using a 532 nm wavelength laser source, respectively. C and D are prebeam and beamformed images using a 1064 nm wavelength laser source, respectively.

3.2 Three-Point Experiment and Registration

A single laser point was projected onto the phantom at three different locations sequentially and the stereocamera image at each location was acquired as shown below:

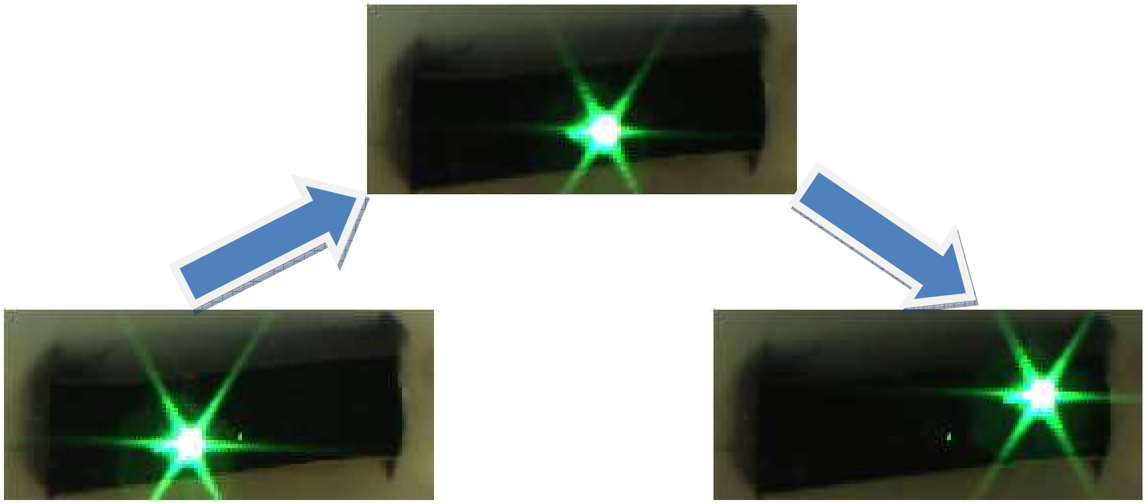

Figure 5. Three-point pattern created by projecting a single laser point at three different locations: left, center, and right.

Ultrasound images of the phantom and the laser point at each location were acquired simultaneously, and the rigid registration from the camera domain to the ultrasound domain was performed. In order to verify the registration, a single unknown laser point was projected onto the phantom and the coordinates of the point in the ultrasound coordinate system were compared to the coordinates computed from the registration. A laser points projected to the upper right corner and the lower left corner of the phantom were used for the verification process. The registration performed the best when the upper right corner laser point was used for the verification, while the worst registration performance occurred when the lower left corner laser point was used. Table 1 summarizes the results of the registration, and Figure 6 and 7 show the computed and the actual coordinates of the verification points.

	Best	**Worst**
Computed Result (mm)	(44.2528, 46.3150, 0)	(42.6340, 44.7994, 0)
Actual Centroid (mm)	(43.8694, 46.2970, 0)	(43.0688, 47.7706, 0)
Error (mm)	0.3838	3.0028
Average Error (mm)	1.6933	

Table 1. Table comparing the actual coordinates of verification points with that of coordinates predicted by the rigid transformation. The error between the data as well as the average error is also reported.

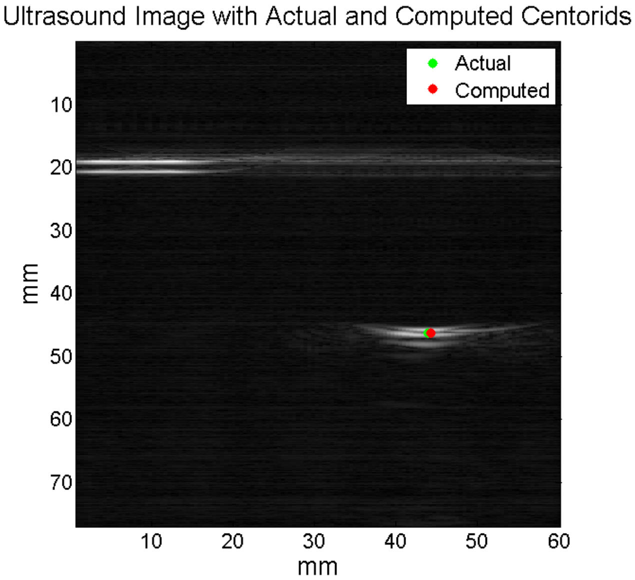

Figure 6. Beam formed image showing the actual centroid (green) computed using image processing algorithms as well as the centroid predicted by the rigid transformation (red) from the stereocamera to the ultrasound plotted together. The error in this trial was 0.384 mm.

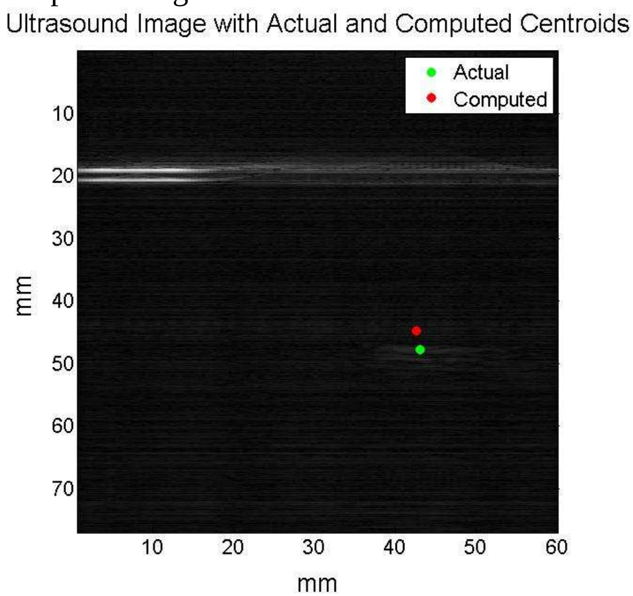

Figure 7. Beam formed image showing the actual centroid (green) computed using image processing algorithms as well as the centroid predicted by the rigid transformation (red) from the stereocamera to the ultrasound plotted together. The error in this trial was 3.0028 mm.

3.3 Discussion

We were able to perform the point cloud transformation between stereocamera and ultrasound domains using the photoacoustic effect. Therefore, we have achieved the maximum deliverable which was to integrate a stereocamera and perform the point cloud transformation. However, we have encountered several technical problems.

For the three-point experiment, we planned to project three laser points at the same time on the phantom instead of projecting them one by one sequentially. Unfortunately, we did not have the right equipments (mirror mounters, optical fibers, etc…) to split the laser into three beams. In addition, when the laser was projected through an optic fiber, its power was reduced.

Our registration was overall very accurate, but it can be improved further by calibrating the stereocamera and employing more points for the registration.

4. Conclusion

Using the ultrasound and photoacoustic imaging system combined with a stereocamera, we were able to show that the combined system can track a point in the ultrasound domain without using any physical markers. The next step for out project would be to improve our registration method (camera calibration, more laser points, etc…), to develop a prototype of the iPASS platform, and to design a more complex “caged optics laser system” setup to produce a less scattered laser beam.

5. Acknowledgements

We would like to thank Nathanael Kuo for consistently taking time out of his schedule every week to help us. We would also like to thank Dr. Taylor and Dr. Boctor for their support and encouragement with this project.

Management Summary

This was an extremely challenging proof-of-concept project. We needed to all work together in order to figure out how the overall system and experiments would be run, and how the results would be analyzed. We, however, came up with an extremely thorough management plan to ensure our project would go smoothly. The following table contains our milestones, the initial date we wanted to complete it by, the actual data of completion and the current status.

	Milestone Description	Expected Completion Date	Actual Completion Date	Current Status
1	Calibrate and Synchronize Laser with the US probe	3/05/11	3/05/11	Done
	Build Phantoms for testing	3/11/11	3/11/11	Done
2	1064 nm one-seed experiments	3/20/11	3/20/11	Done
	1064 nm three-seed experiments	3/24/11	3/24/11	Done
	Rigid Transformation using the US model.	3/28/11	3/28/11	Done
3	Set-up 532 nm laser source	4/06/11	4/12/11	Done
	532 nm one-point experiment	4/10/11	4/18/11	Done
	532 nm three-point experiments	4/18/11	4/20/11	Done
4	Integrate Stereocamera (SC)	4/22/11	5/10/11	Done
	Registration between US and SC	5/10/11	5/16/11	Done
5	BMEStart Competition Portfolio	5/13/11	5/16/11	Done
	Software Documentation Complete	5/14/11	5/18/11	Done
	Final Report, Poster, & Website	5/15/11	5/18/11	Done

Milestones and Progress summary

Future Endeavors

- Design a "Caged Optics" Setup to obtain higher quality data (i.e. significantly greater number of points) needed to compute the registration with added accuracy and efficacy.
- Design and implement a platform independent technology, such as the iPASS Platform, which employs the photoacoustic surgical navigation methodology.
- Use the registration algorithms developed in this project to do a real-time video overlay for a particular application.
- Integrate the photoacoustic registration system onto current technologies, such as the ISI DaVinci Surgical Robot.

Lessons Learned

- In-depth crash course on medical and ultrasound imaging and technologies.
- Gained great-deal of experience with photonics, lasers, and imaging instrumentation.
- Experience in designing modular image processing software and proficiency with image segmentation algorithms and protocols.

Division of Labor

The team worked together on almost all aspects of the project; all individual parts of the project were discussed amongst all the members. The final project presentation, which included the poster, the poster teaser, the final report, and the website maintenance were made possible by a combined effort.

The final implementation of the project was made possible by equal contribution by all members of the team.

Main Scripts/Functions:

register.m : (MATLAB Script)

INPUT: User selects appropriate directory

OUTPUT: Outputs error between calculated and actual photoacoustic signal on test data. Also plots the predicted and calculated coordinates.

To run, type 'register' into the main command window and hit enter.

The user first selects an appropriate directory. The directory name indicates the position of the verification/test coordinate. The script uses getUltrasoundPoint.m and getCameraPoint.m to obtain the corresponding coordinates in the ultrasound and stereocamera images. getCameraPoint.m requires the user to select the region of the laser spot on the stereocamera images. The script then uses PointCloudTransform.m to compute the transformation (R,p) between the ultrasound and stereocamera domains. This completes the registration of the two domains.

A verification of the obtained transformation is then performed. The coordinate of a laser spot on a new stereocamera image (not used in the registration) is obtained with getCameraPoint.m. The obtained transformation is then used to calculate the predicted position of the photoacoustic signal in the corresponding ultrasound image. The script then plots the actual coordinate and predicted coordinates of the photoacoustic signal on the same ultrasound image and computes the error between the two.

getUltrasoundPoint.m: (MATLAB Function)

INPUT: A path to a folder with all the DAQ files

OUTPUT: Centroid position of the photoacoustic signal based on beamformed image.

The function first uses readDAQ.m to obtain the prebeamformed image. It then uses beamformDAQ.m to obtain the beamformed image. Using various thresholding methods (i.e. intensity level thresholding, minimum pixel count thresholding), the beamformed image is thresholded so that only the photoacoustic signal remains on the beamformed image. The centroid of each frame is then calculated and averaged. If a frame returns more than one centroid, the frame is ignored for computing the average centroid. The centroid is then outputted.

getCameraPoint.m: (MATLAB Function)

INPUT: The name and path of an image

OUTPUT: The weighted centroid of the position of a laser spot on a stereo camera image.

The function first imports the image and converts it to a grayscale image. The image is then thresholded by various methods (i.e. intensity level thresholding and minimum pixel count thresholding). After the image has been thresholded, the user then needs to select the region where the laser spot is located.

The weighted centroid of the laser spot is then calculated and outputted. The weighted centroid is then plotted over the original image.

Helper Functions

PointCloudTransform.m (MATLAB Function)

INPUT: Two matrices of corresponding vectors in each space. The vectors should be vertical (i.e. for n vectors, the matrices will be 3 x n in dimension).

OUTPUT: The transformation (R,p) of the two point clouds using Arun's method.

beamformDAQ.m (MATLAB Function)

INPUT: The image matrix of a prebeamformed image and the aperture size. Set the aperture size to 64.

OUTPUT: The image matrix of a beamformed image.

readDAQ.m (MATLAB Function)

INPUT: Path to folder of DAQ files, the number of channels (always 128), the frame number (always 5), and a Boolean command whether to reroute the transducer elements (set Boolean to TRUE for all cases)