Enabling Technologies for Robot Assisted Ultrasound Tomography

Computer Integrated Surgery II

Group 11

Project Proposal

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Goal

The Ultrasound penetration is 10-15 cm maximum. The deeper the tissue, the more attenuation is caused, and consequently, the less quality images can be obtained. This is why ultrasound cannot be used for thick tissues or obese patients. In addition since ultrasound waves cannot travel through air, ultrasound imaging has limitations to be used for tomography. In this project, we develop a system which is a combination of human operated probe and a probe attached to a robotic arm. This system can be used to offer higher imaging depth, and to enable ultrasound tomography imaging.

Statement of Relevance/Importance

Ultrasound machine is inexpensive, has a light weight, and more importantly, does not produce ionizing radiation which is believed to be dangerous to human health. In addition, CT is mostly used for bony structures while ultrasound is used for soft organs. Table 1 compares ultrasound and CT.

These advantages are the reasons why when the ultrasound was introduced to medical imaging in mid-twentieth century, many people started to build ultrasound systems for tomography to create 3D diagnostic images. However, since ultrasound waves do not travel in air, they had to ask the patient to lie in a pool of water and then they rotated ultrasound probes around the patient. These types of systems soon were retired or some were never used in clinics because first, it was difficult to lie in a pool of water for many patients; second, the ultrasound image quality was not as good as other modalities and its penetration is limited to 10-15 cm; and third, the sonographer did not have enough control over the ultrasound probe to exactly determine the part to be imaged.

Table 1. CT vs Ultrasound (Ref: http://www.diffen.com/difference/CT_Scan_vs_Ultrasound , http://www.dimensionsinfo.com/how-big-is-a-ct-scanner/ , http://www.absolutemed.com/Medical-Equipment/Ultrasound-Machines/GE-Vivid-e-Portable-Ultrasound-Machine)

	CT	Ultrasound
Cost	$1200-$3200	$100-$1000
Imaged structure	Bony structures	Soft or internal organs
Radiation exposure	2-10 msv	None
Weight	2000 kg (1000 mm diameter x 5000 mm long)	> 5 Kg
Scan time	30 secs	10-15 min

Today with the help of advances in computer systems and medical imaging technologies, we have access to better quality ultrasound images and faster processors which can perform much more complex tasks in seconds. This has on one hand authorized us to combine imaging technologies and on the other hand emerged the need for inventing new ultrasound systems. In this project, we build a system which can be used for ultrasound tomography but does not require the use of the pool of water; can cover higher imaging depth; and in addition is directly controlled by sonographer.

In this project we develop a system which combines a human operated ultrasound probe with a robotic one. Figure 1 shows an example of such system to produce ultrasound images of patient's leg. In this case, the sonographer starts scanning the area to be diagnosed; and a robot tracks the sonographer hand, on the other side of the patient's body, in order to align the two probes. These two probes can both contain their own transmitter and receiver (a normal probe), or one of them take the transmitter role and the other be the receiver. This system can be used to cover higher depth imaging, to produce ultrasound tomography images, or even just for faster real-time scanning. However, the final future goal (not expected to be done in this project) is to achieve ultrasound images that could be used to generate an ultrasound tomographic scan of a soft tissue phantom (gel or animal tissue).

Figure 1. An example of a robot assisted ultrasound scanning

Technical Summary of Approach

To develop the system mentioned above, first of all, we will use an optical tracking system (MicronTracker) to track the human operated probe. Advantages of the MicronTracker include light weight, easy installation, low cost, and passive markers. In addition microntracker can later be attached to the robot arm to compensate the accuracy and FOM. In order to have the position and orientation of the probe's tip, we put a marker on the probe and then use microntracker's TT block. When a point on a tracked object is put on the center of the TT block, the position of that point can then be reported by the microntracker. This is shown in Figure 2.

This probe's position is then analyzed on the computer and commands are sent to the robot to move the other probe such that the two probes become aligned. At this point, we need to transform the coordinate system of the optical tracker to the coordinate system of the robot. For this reason, we use a reference coordinate and do the registration as shown in Figure 3. In this project, we use a passive arm instead of human hand, and an arbitrary cylinder (or a cylindrical phantom) instead of tissue. The passive arm helps us reduce the instability of the freehand probe. In addition, in the first phase of the project, we will use mock ultrasound probes. Figure 3 shows the schematics of the experiment setup. Another calibration is needed to find the transformation from the robot coordinate system to ultrasound probe's. This calibration can be done using the optical tracker.

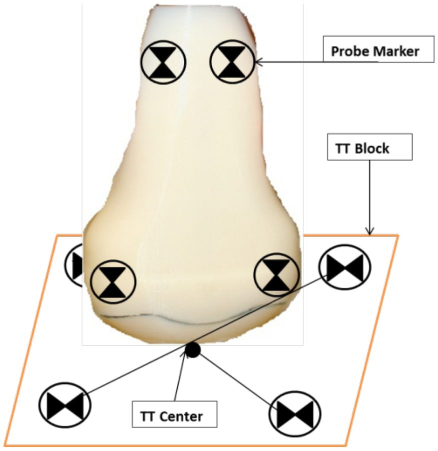

Figure 2. Probe calibration to optical tracker

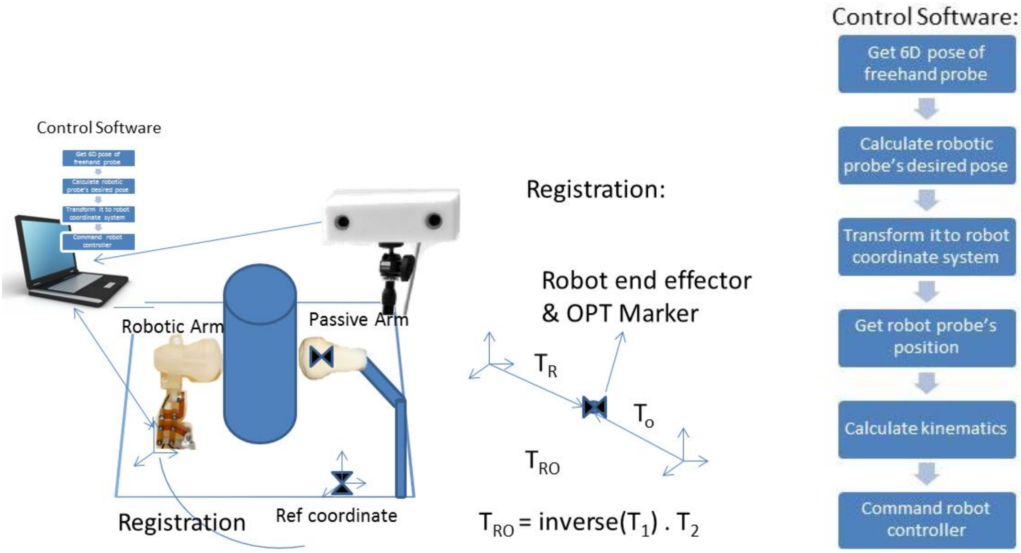

Figure 3. Project Schematics

In the second phase of the project, we will replace the mock probes with real ones and enable the data collection. Since the optical tracking system has the accuracy of more than a millimeter, we will, then, investigate and develop an Energy Profile Tracking (EPT) and a B-Mode Tracking method to improve the tracking accuracy.

The intuition of the EPT method comes from the energy distribution of ultrasound waves shown in Figure 4. As can be seen in the figure, the energy is not equally distributed in the space. This property can be used to align the probes more accurately by aligning the peaks as shown in Figure 5. A transmitter and a receiver might be used to enable EPT. The B-Mode tracking follows the same idea but this time using ultrasound images and trying to align the image planes. An example is shown in Figure 6.

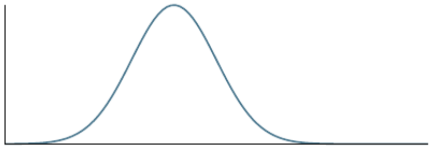

Figure 4. Energy Distribution of Ultrasound Waves

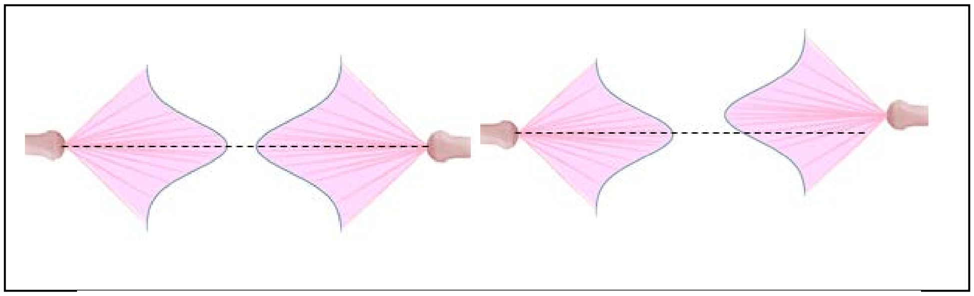

Figure 5. Probes on right are not aligned while those on left are.

In the third phase, we will implement EPT or B-Mode and conduct an accuracy study for tracking. Finally, time allowing, we might use reconstruction algorithms to display on screen more interesting real-time images.

Figure 6. Miss alignment in B-Mode Tracking

List of Deliverables

- **Minimum Deliverables: (Expected by April 1)**
  - A robotic arm should follow the position of a mock ultrasound probe attached to a passive arm, on the other side of a cylinder, using optical tracking system.
- **Expected Deliverables: (Expected by April 22)**
  - Build a transparent (with respect to ultrasound) cylindrical phantom
  - The mock probes should be replaced with real ones.
  - Real data should be collected.
  - Study EPT and B-Mode. This should be thoroughly investigated.
- **Maximum Deliverables: (Expected by May 6)**
  - Implement EPT or B-Mode and conduct its accuracy study.
  - Real images shall be collected and reconstructed on a PC to display real-time ultrasound images.
- **Future Directions:**

A force sensor can be added. A system can be developed to determine the shape of the tissue and consequently improve the tracking. More irregular tissues can be experimented. More advanced reconstruction algorithms and imaging techniques can be developed.

Key Dates and Assigned Responsibilities

The following table shows the project timeline.

Week Starting with	Responsible*	Feb. 4	Feb. 11	Feb. 18	Feb. 25	Mar. 4	Mar. 11	Mar. 18	Mar. 25	Apr. 1	Apr. 8	Apr. 15	Apr. 22	Apr. 29	May 6
Setup preparation (0.5 week)	T	▨	▨					Spring Break							
Optical tracking training (1 week)	F	▨	▨												
Robot training (2 weeks)	R		▨	▨	▨										
Integration & Code development (1 week)	T				▨	▨									
Experiments & evaluation (2 weeks)	T				▨	▨	▨		▨						
Ultrasound machine training & embedding (0.5 week)	F								▨	▨					
EPT & Bmode investigation (2.5 weeks)	T								▨	▨	▨	▨			
Backup week or maximum deliverables (2 week)	T												▨	▨	
Final Documentation (1 week)	T													▨	▨

T: Together, F: Fereshteh, R: Rishabh

List of Dependencies and Plan for Resolving

	Dependency	Plan/Source	Status/Comments	Not met?	Due date
Phase 1	5 DOF robot and training	Robodoc/ Min Yung	In process	Learn ourselves	Mar 4
	Mock ultrasound probes	Rapid prototyping	In process	Project will be delayed	Feb 22
	PC or laptop	Provided by Prof. Iordachita	Acquired	Project will be delayed	Feb 11
	Optical tracking system	Micron Tracker by Prof. Boctor	-Order in process -Using Prof. Kazanzides's tracker in the mean time	Use Dr. Kazanzides OPT	Feb 28
	Cylindrical solid phantom	Acquired	Will get transparent one	Build ourselves	Mar 30
	Mechanical designs & interfacing of robot wrist to probe	Prof. Iulian if we cannot handle	Arranged with Prof. Iulian	Project will be delayed	Mar 15
	Required wires/ cables/ tools	Prof. Iordachita lab	Or from Profs Iordachita and Boctor internal funds	Project will be delayed	TBD
	Matlab	Requested	In progress	Contact technical	Feb 28

	Visual Studio			support	
	Weekly meeting with mentors	Arrange via email	In progress	Project will be delayed	Feb 28
Phase 2	Ultrasound machine & probes	Provided by Prof. Boctor	Considered 2 in Dr. Boctor's lab One probe available and the other order in progress	Expected deliverables will be delayed	Apr 1
	Ultrasound physics and images	Prof. Boctor	We rely on Dr. Boctor on ultrasound technical information	Investigate	Apr 1
Phase 3	Transmitter, receiver and processing units	From Profs Iordachita and Boctor internal funds	Upon necessity	Maximum not met	Apr 22
	Ultrasound imaging reconstruction resources	Provided by Prof. Boctor	Upon necessity	Maximum not met	Apr 22

Management Plan

We are planning to spend average of 15-18 hours/team member/week on this project. We have assigned Monday, Tuesday, Wednesday, and Thursday as "working on project" days and will try to maximize the "working together" time on these days. We have weekly meeting with mentors. We will have weekly progress reports to be discussed in the meetings. We have assigned responsibilities to each person but we are planning to do most of the work together and help each other so that both of us will learn the most from this project.

Reading List

The reading list is divided into subcategories.

Ultrasound Calibration

[1] J. D. Achenbach., "Wave Propagation in Elastic Solids," volume 16 of North-Holland series in applied mathematics and mechanics, North-Holland, 1973.

[2] D. V. Amin, et al, "Calibration method for determining the physical location of the ultrasound image plane. In Proceedings of the fourth International Conference on Medical Image Computing and Computer-Assisted Intervention," Lecture Notes in Computer Science, volume 2208, pages 940-947. Springer-Verlag, 2001.

[3] K. S. Arun, T. S. Huang, and S. D. Blostein, "Least-squares fitting of two 3-D point," IEEE Transactions on Pattern Analysis and Machine Intelligence, 9(5):698-700, 1987.

[4] L. G. Bouchet, et al, "Calibration of three-dimensional ultrasound images for image-guided radiation therapy," Physics in Medicine and Biology, 46:559-577, 2001.

[5] M. Burcher, "A force-based method for correcting deformation in ultrasound images of the breat," PhD thesis, University of Oxford, Oxford, United Kingdom, 2002.

[6] R. M. Comeau, A. Fenster, and T. M. Peters, "Integrated MR and ultrasound imaging for improved image guidance in neurosurgery," In Proceedings of SPIE, volume 3338, pages 747-754, 1998.

[7] S. Dandekar, Y. Li, J. Molloy, and J. Hossack, "A phantom with reduced complexity for spatial 3-D ultrasound calibration," Ultrasound in Medicine & Biology, 31(8):1083-093, 2005.

Hand-eye calibration

[1] Y. Shiu, S. Ahmad, "Calibration of Wrist-Mounted Robotic Sensors by Solving Homogeneous Transform Equations of the Form AX=XB," IEEE Transactions on robotics and automation, Vol. 5, No. 1, Feb. 1989

[2] K. Daniilidis, "Hand-Eye Calibration Using Dual Quaternions," The International Journal of Robotics Research, Vol. 18, No. 3, March 1999, pp. 286-298.

Robotic Ultrasound Technology

[1] Pezhman Foroughi, "Tracked Ultrasound Elastography," Johns Hopkins Universiy PhD Thesis, June 2012.

[2] S. E. Salcudean, et. al, "Robot-Assisted Diagnostic Ultrasound – Design and Feasibility Experiments," Medical Image Computing and Computer-Assisted Intervention – MICCAI'99 Lecture Notes in Computer Science Volume 1679, 1999, pp 1062-1071.

[3] Purang Abolmaesumi, et. al, "Image-Guided Control of a Robot for Medical Ultrasound," IEEE Transactions on Robotics and Automation, Vol. 18, No. 1, Feb. 2002, pp. 11-23.

Ultrasound Tomography

[1] Christian Hansen et. all, "Ultrasound Breast Imaging using Full Angle Spatial Compounding: In-vivo results," IEEE International Ultrasonics Symposium Proceedings, 2008.

[2] T.S. Kim, S.H. Do, V.Z. Marmarelis, "Multi-band Tissue Differentiation in Ultrasonic Transmission Tomography," Ultrasonic Imaging and Signal Processing, Medical Imaging (SPIE), 2003.

[3] V.Z. Marmarelis, T.S. Kim, R. E. N. Shehada, "High Resolution Ultrasonic Transmission Tomography," Ultrasonic Imaging and Signal Processing, Medical Imaging (SPIE), 2003.

[4] U. M. Hamper, M. R. DeJong, L. M. Scoutt, "Ultrasound Evaluation of the Lower Extremity Veins," Radiol Clin N Am Elsevier, 2007, pp. 525–547.

[5] X. Pan, Y. Zou, and M. A. Anastasio, "Data Redundancy and Reduced-Scan Reconstruction in Reflectivity Tomography," IEEE Transactions on Image Processing, Vol. 12, No. 7, Jul. 2003, pp. 774-795.

[6] David Gillespie, and Carolyn Glass, "Importance of Ultrasound Evaluation in the Diagnosis of Venous Insufficiency: Guidelines and Techniques," Elsevier Seminars in Vascular Surgery, 2010, pp. 85-89.

Optical Tracking System

[1] Claron optical tracking system manual

Robotics

[0] Fundamentals of serial robots

[1] Denevit Heartenburg and Jacobian matrix derivation

[2] Robot’s manual and tutorials

[3] Kinematics and inverse kinematics

Telerobotic soft tissue imaging

[1] Jeffrey Schlosser, Kenneth Salisbury, and Dimitre Hristov, “Telerobotic system concept for real-time soft-tissue imaging during radiotherapy beam delivery,” Medical Physics, Vol. 37, Issue 12, Radiation Therapy Phsyics, 2010, pp. 6357-6367.