Synthetic Aperture Ultrasound Imaging with Robotic Tracking Technique
600.446 Computer Integrated Surgery II, Spring 2014

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Stated Topic and Goal

Synthetic apertures improve the resolution of deep sight by utilizing expanded aperture size. Knowing a precise orientation and location of ultrasound transducer using robotic tracking system can generate imaginary elements, which eventually expand the aperture size more.

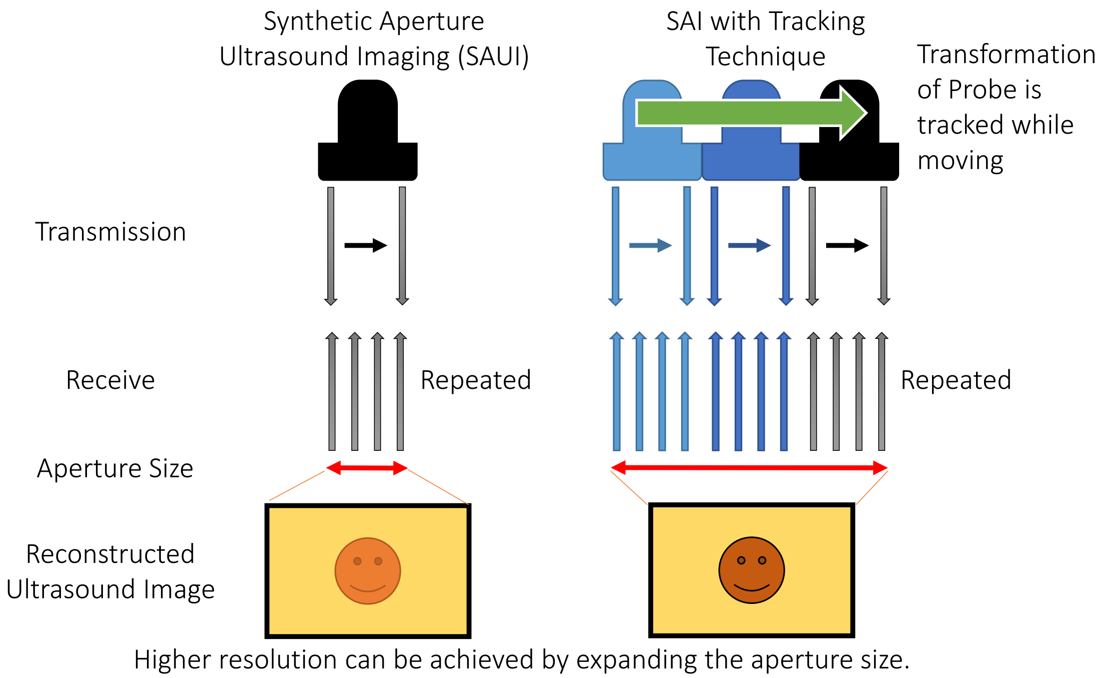

Figure: The goal of the project. How the tracking technique expands the aperture size for reconstruction.

The final goal of this project is to combine robotic tracking technique into synthetic aperture ultrasound imaging and to achieve higher resolution images. During the process, we also would work for inventing a new ultrasound calibration method with sub-millimeter error, which is necessary to reach the final goal.

Background

Ultrasound imaging is used in various medical diagnosis. The resolution of ultrasound image can be divided by axial resolution and lateral resolution. Axial resolution is determined by frequency of ultrasound system and lateral resolution is restricted by aperture size of ultrasound transducer. In addition, the transformational information of the ultrasound probe enable to obtain tracked ultrasound images, which have various potential applications for medical diagnosis. An example for image guided surgery is that virtual ultrasound image overly provide depth penetration view to surgeon with non-invasive and in real-time.

At the same time, synthetic aperture ultrasound imaging (SAUI) is an idea to utilize wider aperture size to improve the resolution. While general ultrasound imaging system transmits several arrays and receives the signals using the same aperture size, SAUI uses more number of elements to have wider aperture size. As the consequence, the resolution restricted by both frequency of transducer and aperture size can be improved by reconstruct received signals through SAUI algorithm.

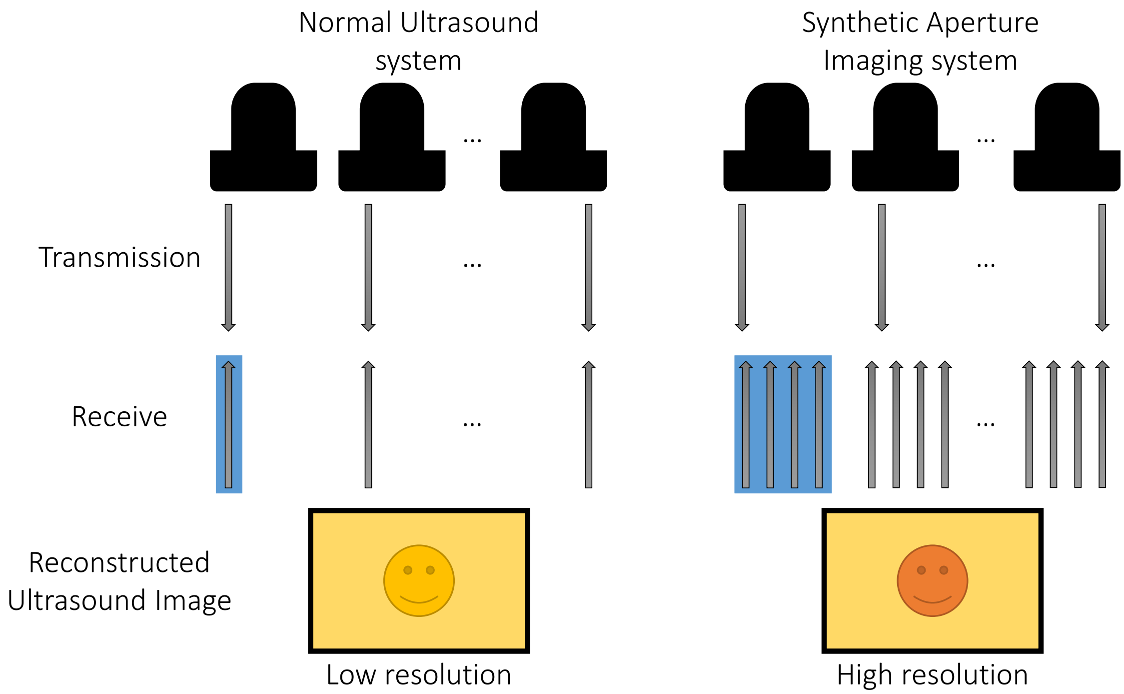

Figure: General idea of synthetic aperture imaging system.

Motivation/Relevance

The motivation of the research is to overcome the resolution image limitation in the deep sight. Although the image resolution improves corresponding to the center frequency of transmission, it is not possible to set the frequency as high as possible because the attenuation also increases as the center frequency do. Thus, generally low frequency such as 2.5MHz is used, so that the resolution is limited to around 600 µs.

Visualizing precise structure of fetus in early stage helps early disease detection as well as correct diagnosis. SAUI is a solution for the problem, but the performance is still restricted by physical limitation of the number of elements. Therefore, the approach of this project is to take away the limitation of aperture size by tracking the ultrasound transducer.

The performance of reconstructed synthetic aperture images is depending on the accuracy of the transformation calibrated, and tracking accuracy and the accuracy of the transformation between images and to the probe is important. In order to move the probe for a designated position, or to know the location of the origin of ultrasound image, unknown rigid-body transformation on the transducer from sensor to image is needed to be calibrated. Process to identify this unknown transformation is called ultrasound (US) calibration. The strategy taken to get the transformation between the tracking device and image is solving the hand-eye calibration problem also known as AX=XB problem, where A and B are relative motions connected by the unknown rigid body transformation X. Assuming B is computed from homogeneous transformation of robot arm, A is computed by the transformation between each image and the phantom. We aims to improve the tracking accuracy using robot and create a new ultrasound calibration method to utilize accurate transformation from probe to image.

Technical Approach

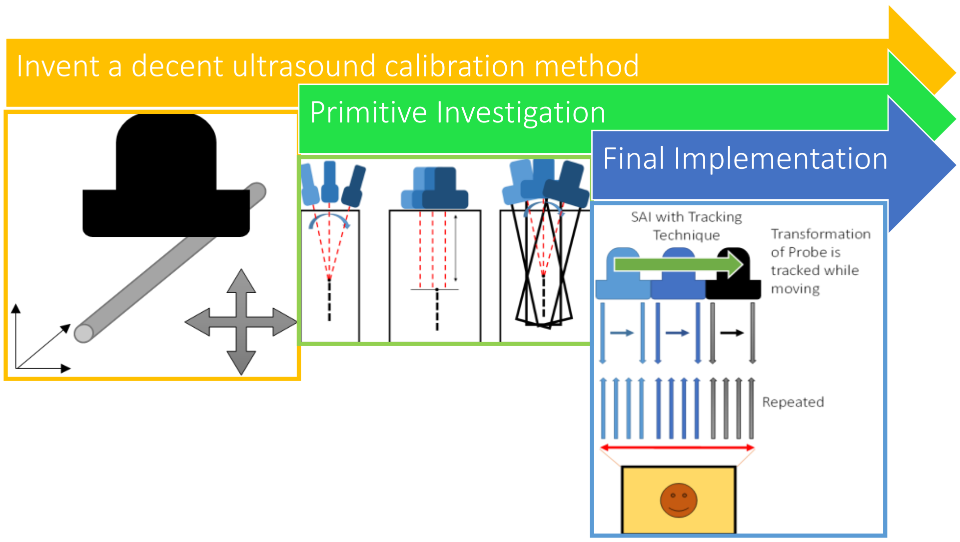

Figure: A flowchart to show the technical approach

1. *Invent a decent ultrasound calibration method*
   The problem of conventional approach based on segmentation is that the accuracy of points picking is severely depending on the image quality and the point spread function of the phantom. The accuracy is directly related to the range of potential applications. The accuracy of US calibration based on segmentation is about 1.5 mm~ although various compensation method is applied [1]. On the other hand, the accuracy required to SAUI is sub-wavelength (616 µm for 2.5MHz transducer), which cannot be achieved in segmentation based approach. Therefore, a simple and accurate calibration technique is necessary.

   We propose a new ultrasound calibration method, which not relying on segmentation but utilized the trajectory of moved phantom. While fixing the position of ultrasound probe, a line phantom is moved in designated distance in x and y direction from the coordinate of phantom. The amount of displacement of a target appearing in the image compared to the actual displacement. Compared to the segmentation method, normalized cross-correlation involves the information of entire characteristic of the acoustic response including the shape and amplitude, and it is possible to obtain accurate displacement of the target. At the same time, robotic tracking system is also implemented to further improve the accuracy of reconstructed transformation.

STEP 1

$$^{\mathrm{USimage}}p = R_i \cdot {}^{\mathrm{Model}}p$$

STEP 2

$$^{\mathrm{Model}}I_i(x,y,0) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \cdot {}^{\mathrm{Model}}I_i(x,y,z).$$

$$\Delta t^{ij}(x,y) = {}^{\mathrm{Model}}I_i(x,y) - {}^{\mathrm{Model}}I_j(x,y)$$

STEP 3

$$\Delta t^{ij} = \begin{bmatrix} x \\ y \\ Z \end{bmatrix}$$

$$^{A}R^{ij}\,{}^{X}R = {}^{X}R\,{}^{B}R^{ij},$$

$$^{A}R^{ij}\,{}^{X}\boldsymbol{T} + \begin{bmatrix} R_i^T(1,1)x + R_i^T(1,2)y + R_i^T(1,3)\boldsymbol{Z} \\ R_i^T(2,1)x + R_i^T(2,2)y + R_i^T(2,3)\boldsymbol{Z} \\ R_i^T(3,1)x + R_i^T(3,2)y + R_i^T(3,3)\boldsymbol{Z} \end{bmatrix} = {}^{X}R\,{}^{B}P^{ij} + {}^{X}\boldsymbol{T}$$

Figure: Mathematical approach. STEP1 drives rotational component of a pose. Points indicate relative position of the phantom. Points of model is based on the displacement of stage, and points of US image represent the appeared displacement calculated by normalized cross correlation. STEP2 calculate translational component of relative poses. STEP3 gets the final transformation of X. Red indicates unknown, so that the equation can be solved as a least square problem.

Quick validation of the proposed method is conducted through simulations and experiment. In simulation, the noise of NCC was defined as 50 µm, which is the number confirmed though an preliminary experiment, and the tracking system accuracy of 100 µm was set based on the accuracy of the robot (Universal Robot, UR5) used in experimental. The result depicts that the rotational error compared to the grand truth was 0.15±0.10 degree and the translational error was 0.48±0.32 mm for 60 ultrasound poses simulation. In experiment, L14-5W/60 linear array transducer were calibrated, and as a primitive investigation, 10 ultrasound probe poses data were acquired to show the improvement compared to segmentation based approach. As a result, the repeatability of reconstructed rotation was 3.98 degree, which was better than the repeatability using segmentation (4.80 degree). To confirm the translational accuracy and achieve the level required to our goal, further experimental validation and algorithmic improvement is necessary.

2. *Primitive investigation using active-echo element*

Without US calibration, primitive confirmation of the potential of the technique is available using precise tracking system and accurate location indicator. Active echo element is a strong candidate for the test due to its accurate sensitivity for ultrasound transducer center detection (50 um). Since active echo element can be a reliable distance indicator from the ultrasound transducer, multiple images keeps same distance to the element can be generated, so that SAUI algorithm can be applied. Here, SAUI algorithm is understood and optimized for our application.

3. *Final implementation*

The final process is to combine two components explained in this section. To be specific, we track the calibrated ultrasound transducer, and taking images when moving robots to multiple directions. The relation of image is connected by tracked information and SAUI algorithm is used for reconstruction.

Deliverables

Minimum

- Experimentally confirm the new calibration method is superior to segmentation based calibration.
- Construct the design for SAUI w/ robotic tracking using active-echo system.

Expected

In addition to minimum,

- Confirm SAUI w/ robotic tracking using active-echo system.

Maximum

In addition to expected,

- Implement SAUI w/ robotic tracking using calibrated transducer
- Confirm the resolution improvement through phantom experiment

Milestones

1. Confirm the performance of new US calibration utilizing moved phantom trajectory.
   Date: Feb 28

2. Confirm the accuracy error of the new calibration method is better than segmentation based method.
   Date: March 7

3. Achieve the accuracy error of the new calibration method in sub-millimeter.
   Date: March 14
   Comment: This is possible to cause delay. The backup plan is using US calibration using active-echo element. Xiaoyu is working on the project.

4. Understand synthetic aperture algorithm.
   Date: Feb 24

5. Construct a simulation to test synthetic aperture imaging
   Date: Feb 28

6. Build a connector to connect phased array probe and ultrasound machine
   Date: March 7
   Comment: the parts has already ordered.

7. Make an attachment for hold the probe with robot
   Date: March 7
   Comment:

8. Connect probe to ultrasound machine
   Date: March 14

9. Learn how to use active echo element
   Date: Feb 28

10. Initial Test of SAUI using active element
    Date: March 14
    Comment: confirm SAUI can be applied. If the phased array probe is not ready to use, we will use 6cm linear probe instead.

11. Confirm resolution improvement by SAUI using active element
    Date: March 21

12. Try generate SAUI using calibrated probe
    Date: April 11

13. Confirm resolution improvement by SAUI using calibrated probe
    Date: April 18

Dependencies

- Funding
  - ✓ Tools necessary for the project will be provided by MUSiiC Lab

- Ultrasound imaging system
  - ✓ MUSiiC Lab

- Low frequency ultrasound probe
  - ✓ Got a 2.5MHz phased array transducer
  - ✓ Need to make a connector to available US machine
    Discuss with Xiaoyu
  - ✓ Need to make an attachment to robot
    Print in 3D or using silicon lubber

- Tracking system: Robot
  - ✓ Universal Robot is available
  - ✓ Need to figure out control system
    Learn from Rishabh and Fereshteh

- Meeting as the team
  - ✓ Team mate meet twice a week after each class
  - ✓ Meeting with Dr. Boctor : every Friday
  - ✓ Take appointments to other mentors when needed

Management plan

Both members have their specialized tasks for the project.
Haichong: US calibration and robotic control system
Ezgi: Synthetic aperture imaging algorithm

Reading List

Nock, L.P., Trahey, G.E., “Synthetic receive aperture imaging with phase correction for motion and for tissue inhomogeneities. I. Basic principles”, IEEE TUFFC, 1992
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Jørgen Arendt Jensen, Svetoslav Ivanov Nikolov, Kim Løkke Gammelmark, Morten Høgholm Pedersen, “Synthetic aperture ultrasound imaging”, Ultrasonics, 2006
Karaman, Mustafa,Pai-Chi Li, O'Donnell, M., “Synthetic aperture imaging for small scale systems”, IEEE TUFFC, 1995

References

[1] Alexis Cheng et al., “Design and development of an ultrasound calibration phantom and system”, Proc. SPIE Medical Imaging, 9036-76, 2014