CIS II: Project No. 2
Synthetic Aperture Ultrasound Imaging with Robotic Tracking Technique

Team: Haichong “Kai” Zhang, Ezgi Ergun

Mentors: Dr. Emad M. Boctor, Xiaoyu Guo, Alexis Cheng

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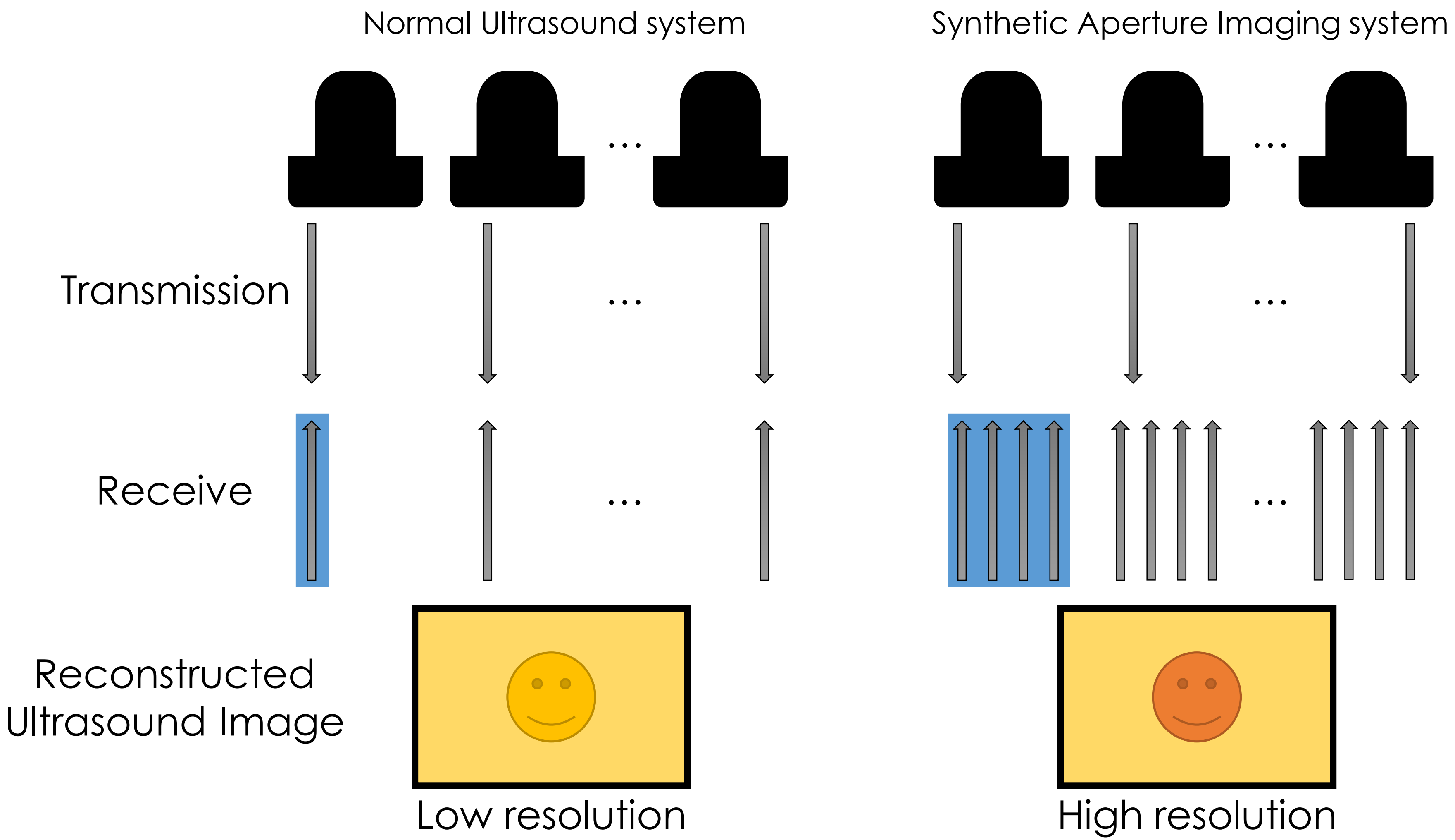
LABORATORY FOR
Computational Sensing + Robotics
THE JOHNS HOPKINS UNIVERSITY

MUSiiC
Research Laboratory

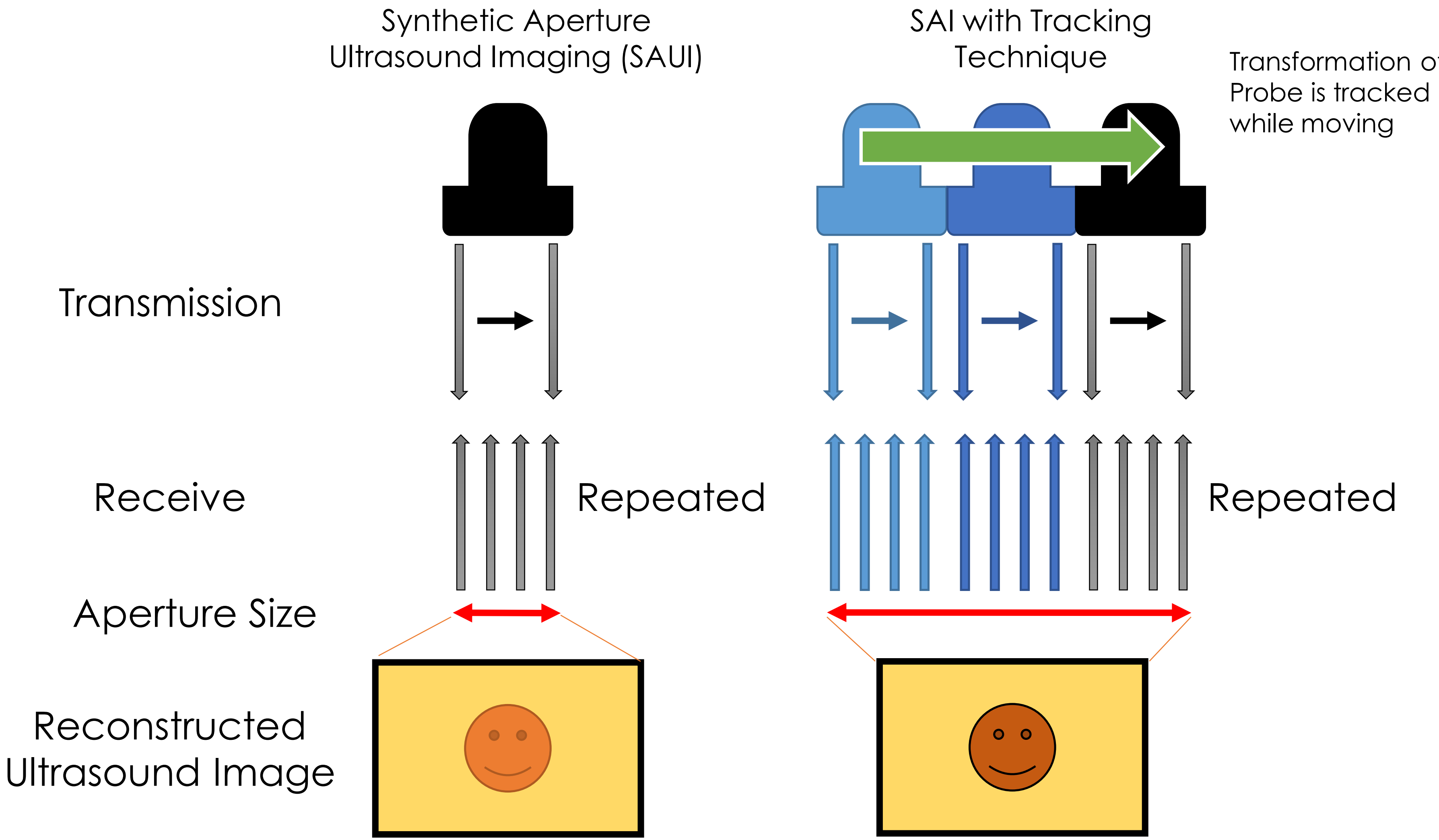
Overview

1. Background
   - Synthetic aperture ultrasound imaging
   - Combination with robotic tracking
2. Technical summary of approach
3. Ultrasound calibration
4. Short-cut confirmation using active-echo
5. Deliverable
6. Milestones

Synthetic Aperture Ultrasound Imaging



Combination with robotic tracking



Higher resolution can be achieved by expanding the aperture size.

Technical Summary of Approach

Development of a new ultrasound calibration technique

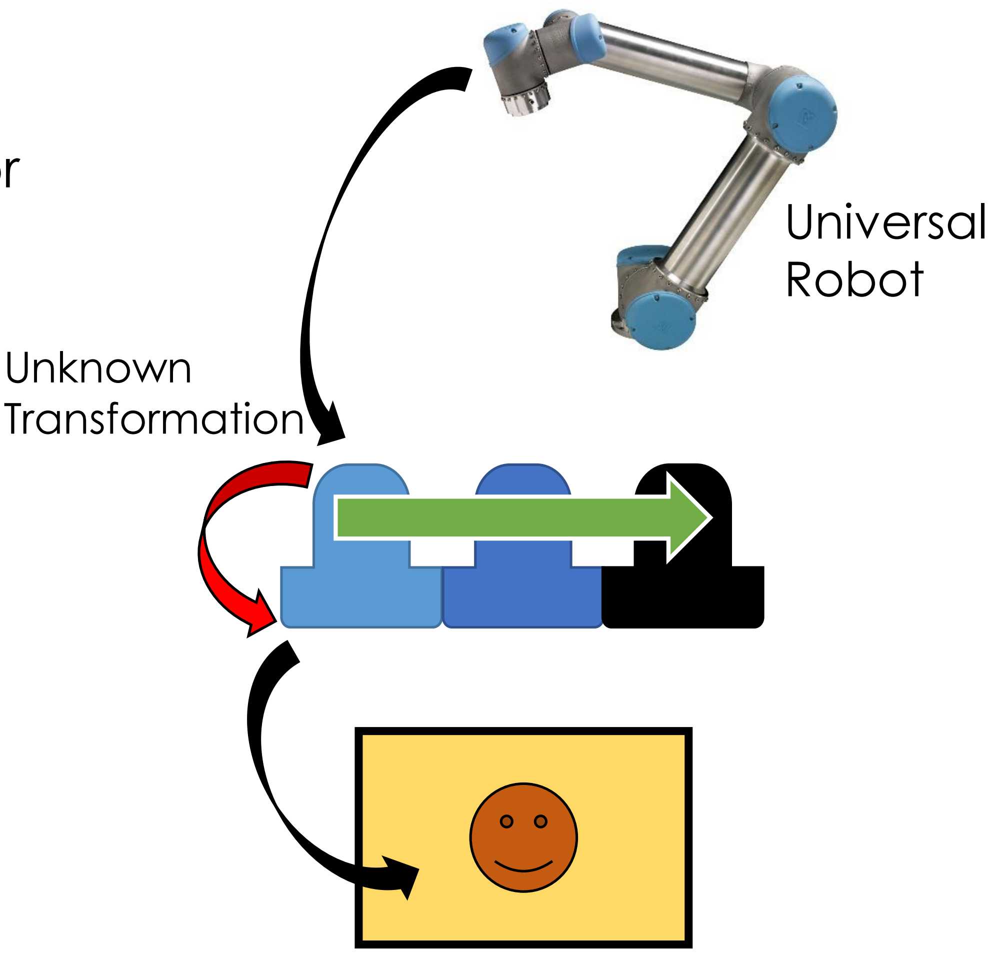
- Ultrasound calibration utilizing trajectory of moved phantom
- Active echo ultrasound calibration

Short-cut confirmation using active-echo

Final combination:
Synthetic aperture using tracked transducer

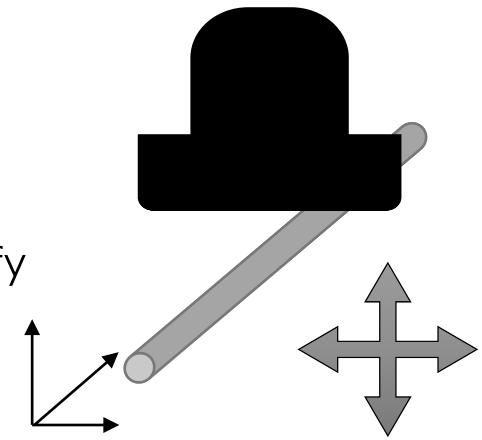
Ultrasound calibration

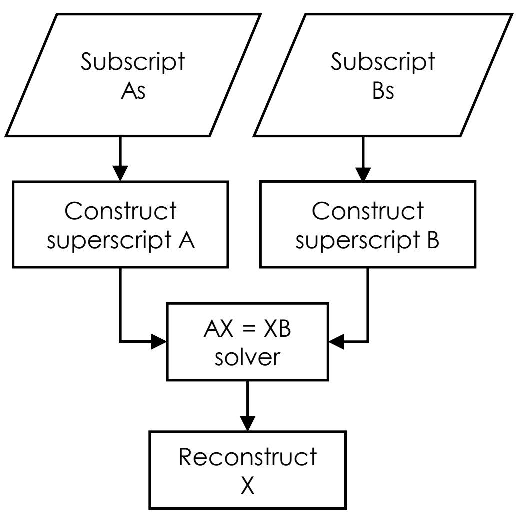
- In order to move the probe for a designated position, or to know the location of the origin of ultrasound image, unknown rigid-body transformation on the transducer from sensor to image is needed to be calibrated.
- Process to identify this unknown transformation is called ultrasound (US) calibration.



Ultrasound calibration utilizing trajectory of moved phantom

- Moving phantom toward x and y axis, from the coordinate of phantom.
- Normalized cross correlation (NCC) is used to identify the displacement of phantom in image.
- The goal of this project is to reconstruct X only using moving information.





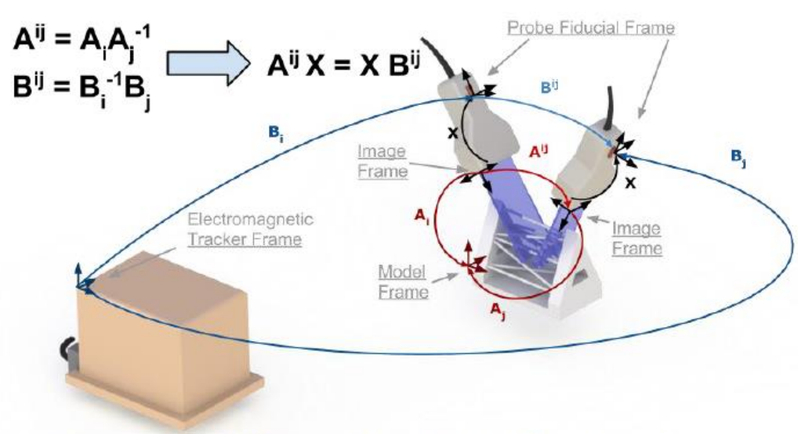
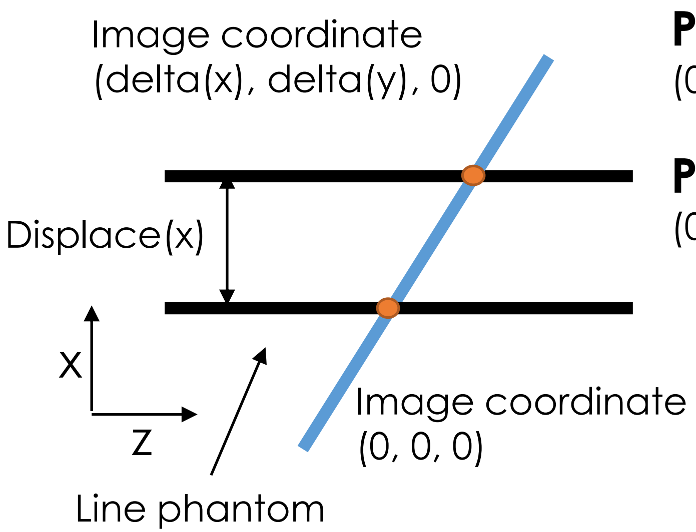


Figure 1. $AX = XB$ formulation with labeled coordinate frames

STEP1 – Rotation

Ultrasound calibration utilizing trajectory of moved phantom

- The rotation (of subscript A) is reconstructed through point cloud registration between three points on model coordinate and image coordinate.



Points in model coordinate

(0,0,0), (displace(x), 0, ±sqrt(norm(delta)^2 – displace(x)^2))

Poinsts in image coordinate

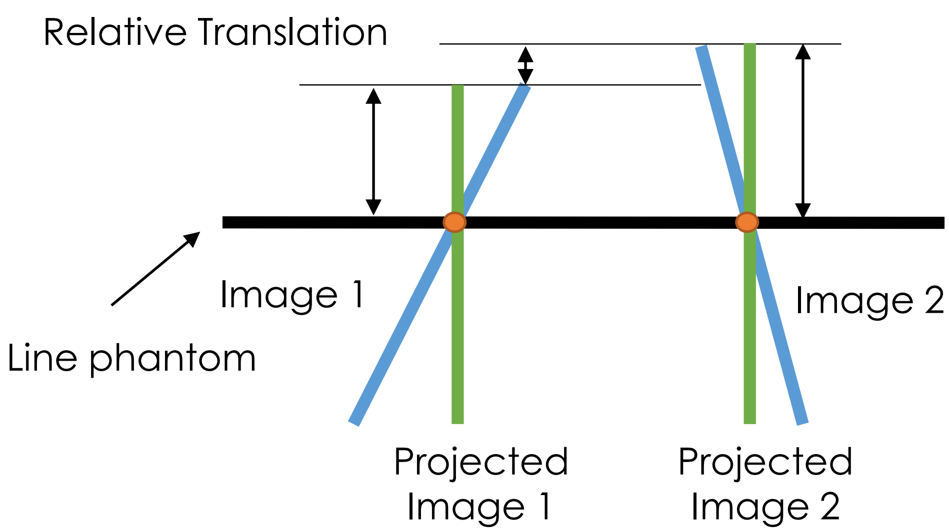
(0,0,0), (delta(x), delta(y), 0)

STEP 1 $${}^{\text{USimage}}p = R_i \cdot {}^{\text{Model}}p$$

STEP2 – Translation (partial)

Ultrasound calibration utilizing trajectory of moved phantom

- Translation of two images from the coordinate of model can be obtained by getting displacement of points in the images which is projected to the model coordinate.



STEP 2

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

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

STEP3 – Reconstruction of X

Ultrasound calibration utilizing trajectory of moved phantom

STEP 3

Rotation

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

Translation

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

- Three equations and four unknowns for one relative pose
- Nine equations for six unknowns for three relative poses

Simulation result

Ultrasound Calibration utilizing moving phantom trajectory

Rotation (degree)	Error from GT	STD	Translation (mm)	Error from GT	STD	Repeatability
Yaw	0.0924	0.0578	X	0.3722	0.2612	0.4619
Pitch	0.0966	0.0734	Y	0.2099	0.12	0.217
Roll	0.0712	0.0399	Z	0.1646	0.1467	0.2142
Norm	0.15	0.101589	Norm	0.46	0.322717	0.553464

1. Error form GT = closeness to the grand truth
   Subtract each result with grand truth and took the average of absolute value. STD is also calculated
2. Repeatability: repeat reconstructing X loop times and see the stability of result

Experimental Result

Ultrasound Calibration utilizing moving phantom trajectory

Moved phantom (MF) algorithm

-0.085	0.996	-0.007
0.049	0.011	0.999
0.995	0.084	-0.049

X from segmentation

-0.118	-0.986	0.121
-0.067	-0.113	-0.991
0.991	-0.125	-0.052

X from active-echo

0.061	0.998	0.027
0.025	-0.028	0.999
0.998	-0.060	-0.026

- Rotation of unknown X is calculated
- 45 poses with 2.54 mm displacement was used

Problem

- The alignment of stage to the model is difficult
- Attachment was built, but it was not sufficient

Ultrasound calibration using active echo

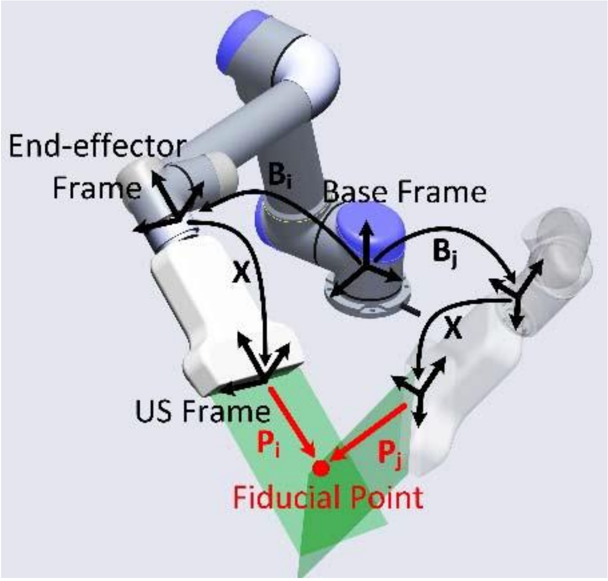
- Based on optimization problem to minimize *BXp*.

Table 2. Repeatability for Xs computed with segmented AE and CW points

Type of Points	Corner (Lateral, Axial)	Repeatability
Active Echo	0 mm, 0 mm	0.37 mm
Active Echo	0 mm, 90 mm	0.60 mm
Active Echo	58.5 mm, 0 mm	0.48 mm
Active Echo	58.5 mm, 90 mm	0.71 mm
Crosswire	0 mm, 0 mm	1.66 mm
Crosswire	0 mm, 90 mm	2.82 mm
Crosswire	58.5 mm, 0 mm	1.55 mm
Crosswire	58.5 mm, 90 mm	3.11 mm

Table 3. Best reconstruction precision for Xs computed with segmented AE and CW points

Type of Points	Reconstruction Precision
Active Echo	1.05 mm
Crosswire	2.36 mm



Guo, X et al., "Active Echo: A new Paradigm for Ultrasound Calibration", MICCAI 2014, under revision

Technical Summary of Approach

Development of a new ultrasound calibration technique

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- Active echo ultrasound calibration

<u>Short-cut confirmation using active-echo</u>

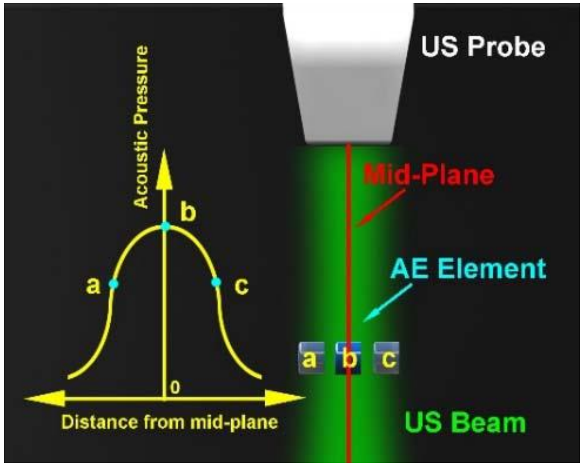
Final combination:
Synthetic aperture using tracked transducer

Short-cut confirmation using active-echo

Without US calibration, primitive confirmation of the potential of the technique is available using precise tracking system and accurate location indicator.

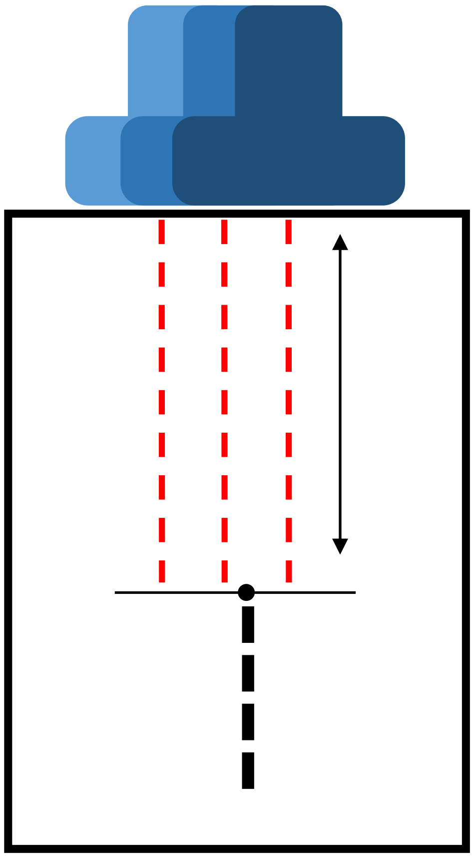
Active echo element is a strong candidate for the test due to its accurate sensitivity for ultrasound transducer center detection (50 um).

Learn SAUI algorithm and optimize it for this approach.



Guo, X et al., "Photoacoustic Active Ultrasound Element for Catheter Tracking", SPIE Photonics West 2014

Short-cut confirmation using active-echo



Scan a probe by keeping the length of red line same

Figure: the synthetic aperture test

Purpose

- Knowing rotation through try and error
- Align rotation to be same as rotation of robot base

Advantage

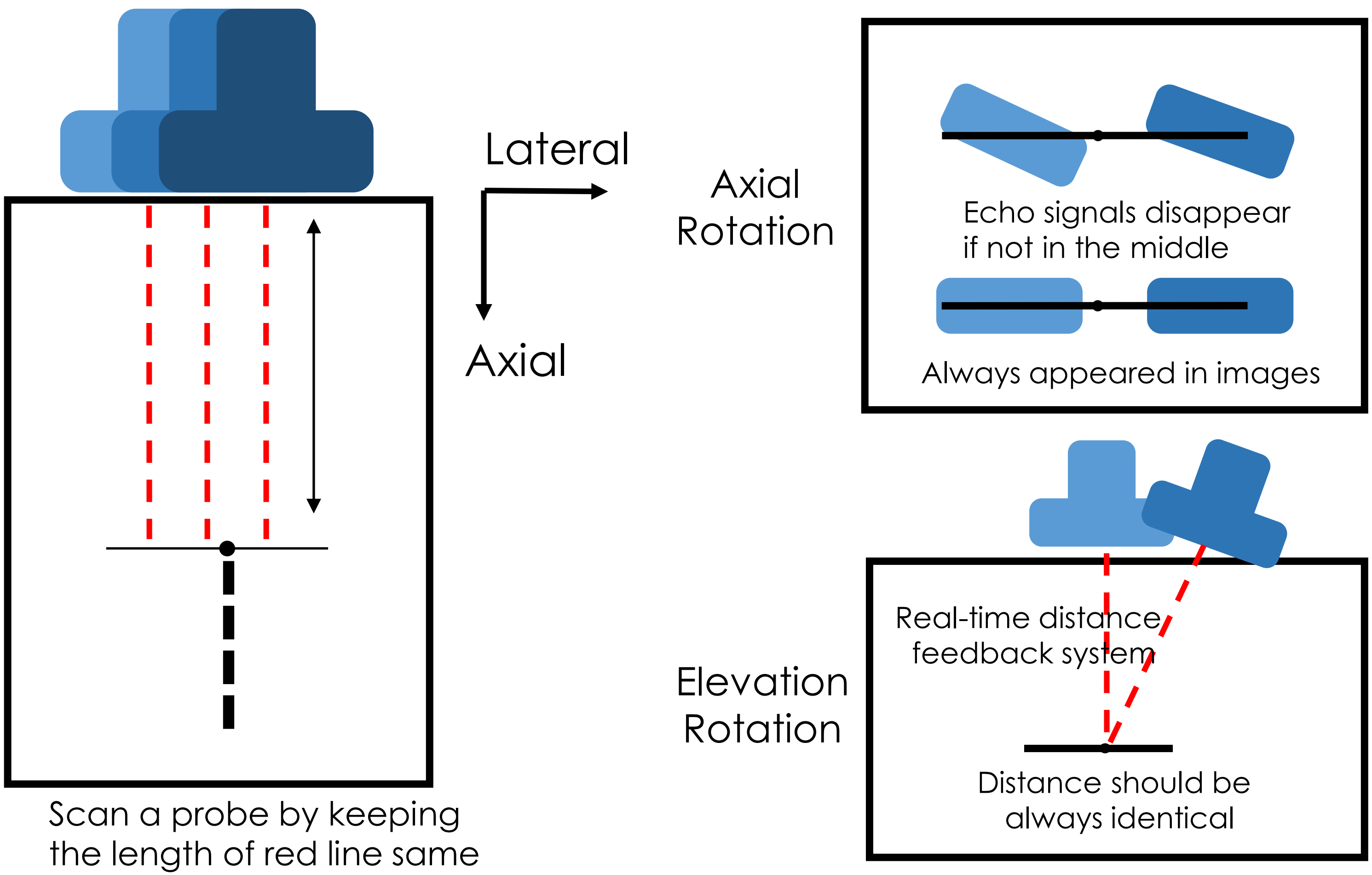
- One directional displacement is available by aligning two degrees of rotations

Limitation

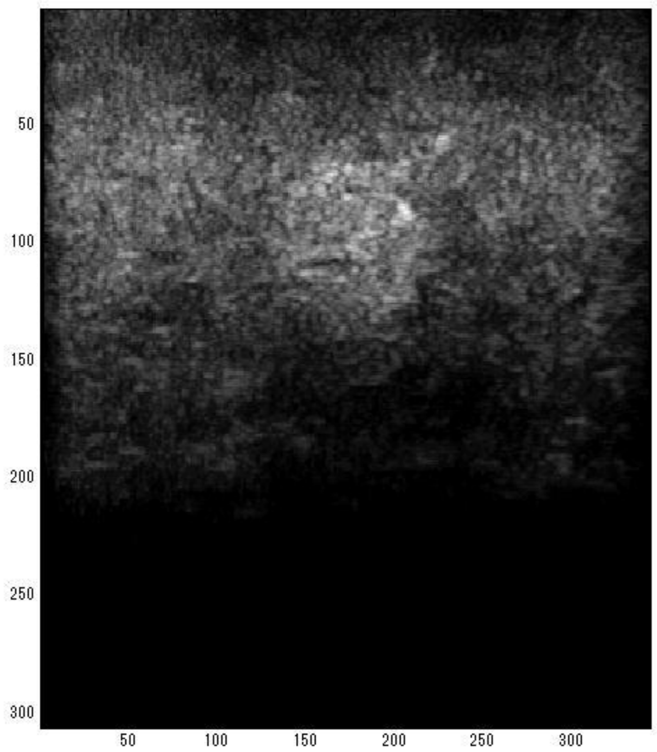
- Hard to implement movements with rotation
- Impossible to move at absolute position because absolute translation of X is unknown

Experiment setup

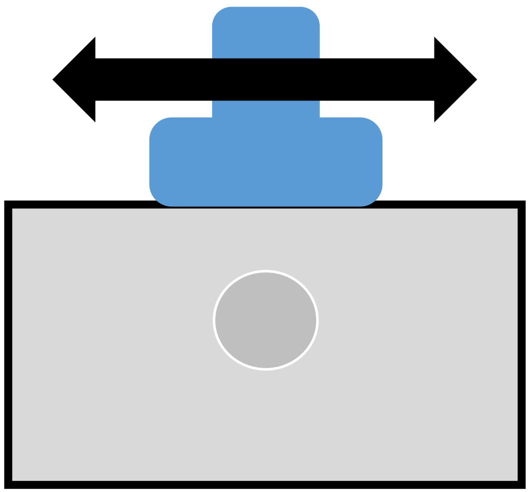
Rotational alignments



Experiment setup

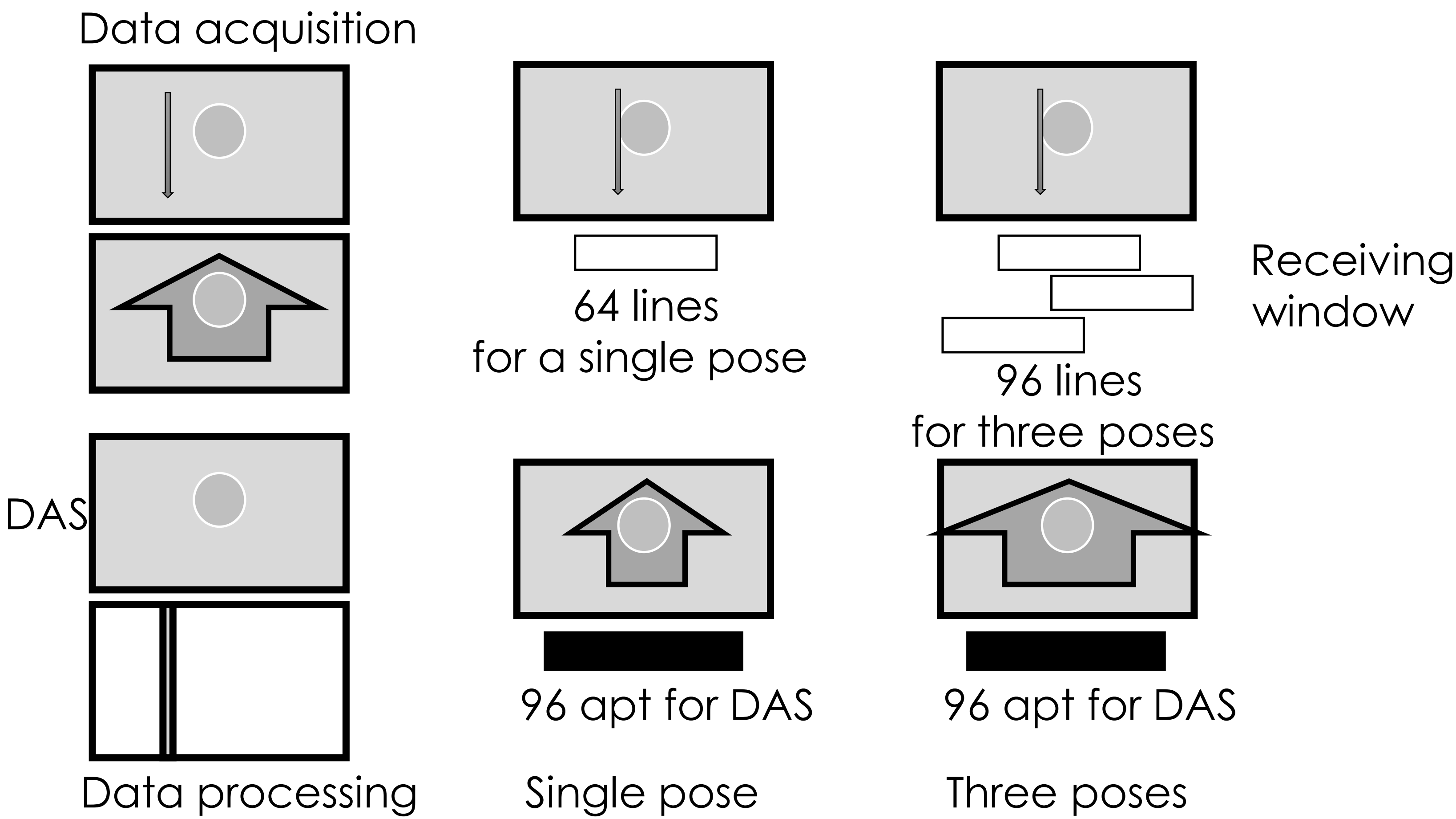


Demo of elastography phantom
with transmission and receiving forcusing

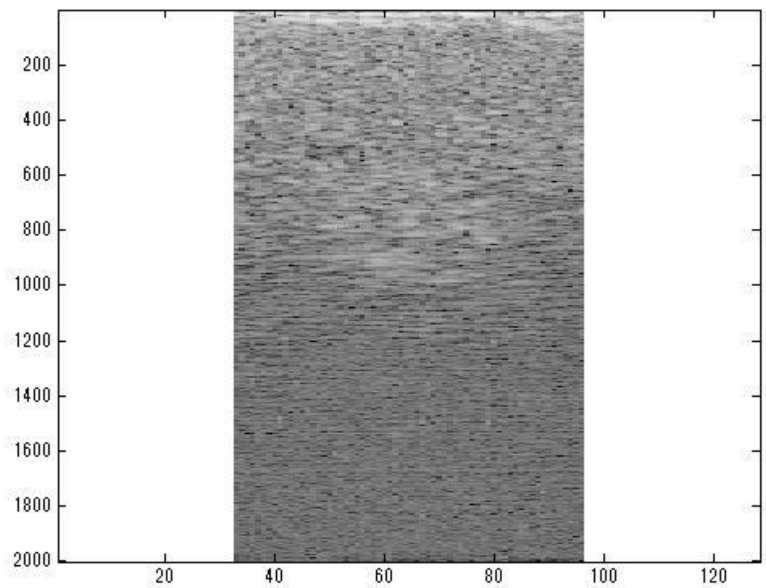


Criteria	Parameter
Probe width	38.4 mm
Probe pitch	0.3 mm
Scan	Linear
Element	128 maximum
Depth	77 mm (40MHz, 2000)
Transmission	8 elements
Probe motion	±4.8 mm, ±9.6 mm

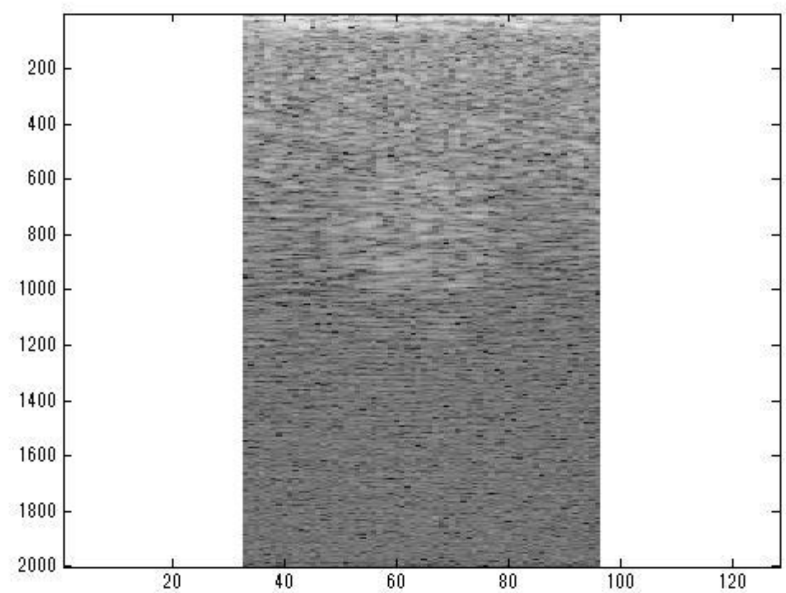
Data processing



Experimental result



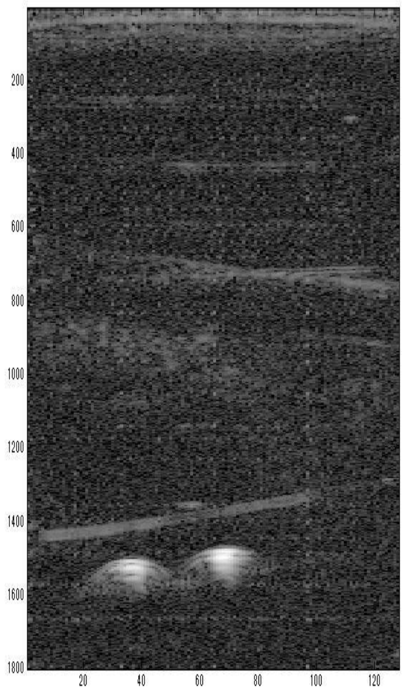
Single pose



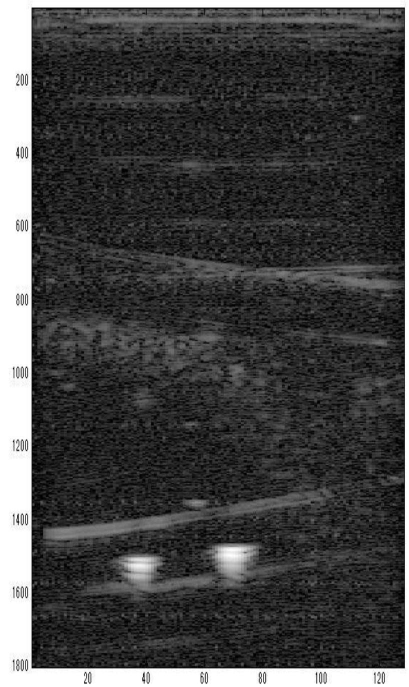
Three poses

- Structure inside phantom became clearer using three poses. (edges)
- 2/3 lateral resolution improvement was hard to confirm.
- **Combined three poses successfully generated a enhanced image**

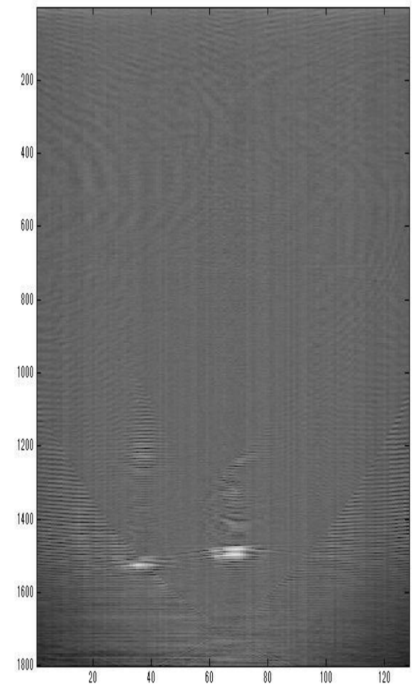
Synthetic aperture reconstruction algorithm



Prebeamformed



Delay and sum



Synthetic Aperture

$$S(\vec{r}_p) = \sum_{m=1}^{M} \sum_{n=1}^{N} w_m(\vec{r}_p) w_n(\vec{r}_p) g_{n,m} \left(\frac{\left|\vec{r}_n - \vec{r}_p\right| + \left|\vec{r}_p - \vec{r}_m\right|}{c} \right)$$

K. Gammelmark, Improving the Image Quality of Synthetic Transmit Aperture Ultrasound Images, PhD Thesis, Ørsted. DTU, Technical University of Denmark, 2800, Lyngby, Denmark, 2004.

Short-cut confirmation using active-echo - Summary

What we did

- Generate 3 synthetized aperture image using phantom with DAS
- SA algorithm is under construction

Problem and next step

- Having solid SA algorithm
- Test image effect using rotation gotten from ultrasound calibration

Deliverables

Minimum: Expected by March 14 → Achieved March 19

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

Expected: Expected by April 1

- Confirm SAUI w/ robotic tracking using active-echo system.
  Almost achieved
- Field II simulation of SAUI w/ robotic tracking

Maximum: Expected by May 1

- Implement SAUI w/ robotic tracking using calibrated transducer
- Confirm the resolution improvement through phantom experiment
- Finalized ultrasound calibration utilizing trajectory of moved phantom

Milestones (1/2)

1. Confirm the performance of new US calibration utilizing moved phantom trajectory.
   Planned Date: Feb 28, Finished Date: Feb 28
2. Confirm the accuracy error of the new calibration method is better than segmentation based method.
   Planned Date: March 7, Finished Date: March 1
3. Achieve the accuracy error of the new calibration method in sub-millimeter.
   Planned Date: March 14, Expected Date: April 1
4. Understand synthetic aperture algorithm
   Planned Date: Feb 24, Finished Date: March 11
5. Construct a simulation to test synthetic aperture imaging
   Planned Date: Feb 28, Expected Date: April 1
6. Build a connector to connect phased array probe and ultrasound machine
   Planned Date: March 1, Expected Date: April 5, Status: attachment will be arrived in this week
7. Make an attachment for hold the probe with robot
   Planned Date: March 7, Expected Date: April 12
8. Connect probe to ultrasound machine
   Planned Date: March 14, Expected Date: April 5

Milestones (2/2)

9. Learn how to use active echo element
   Planned Date: Feb 28, Finished Date: Feb 28
10. Initial Test of SAUI using active element
    Planned Date: March 14, Finished Date: March 19
11. Confirm resolution improvement by SAUI using active element
    Planned Date: March 21, Expected Date: April 1
12. Try generate SAUI using calibrated probe
    Planned Date: April 11, Expected Date: April 11
13. Confirm resolution improvement by SAUI using calibrated probe
    Planned Date: April 18, Expected Date: April 18

Thank you for your attention.