Enabling Technologies for Robot Assisted Ultrasound Tomography

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JOHNS HOPKINS UNIVERSITY

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MUSiiC Research Laboratory

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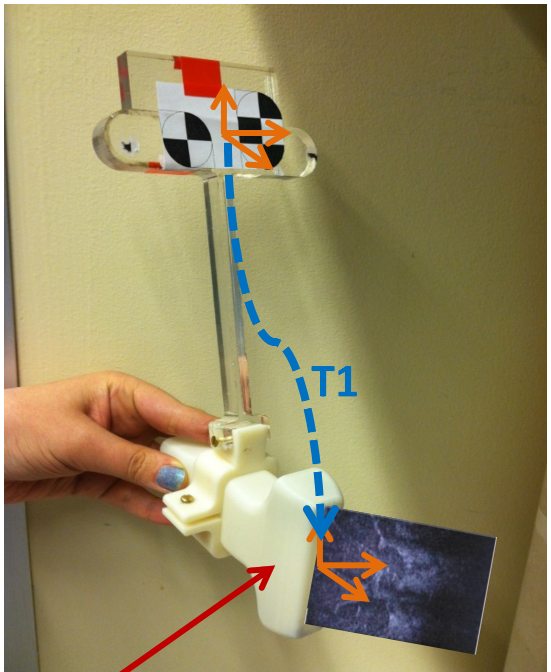
Summary of Project

- Developing a prototype for robot assisted ultrasound tomography
- Free hand ultrasound probe + robot operated tracking each other
- Ultrasound tomography

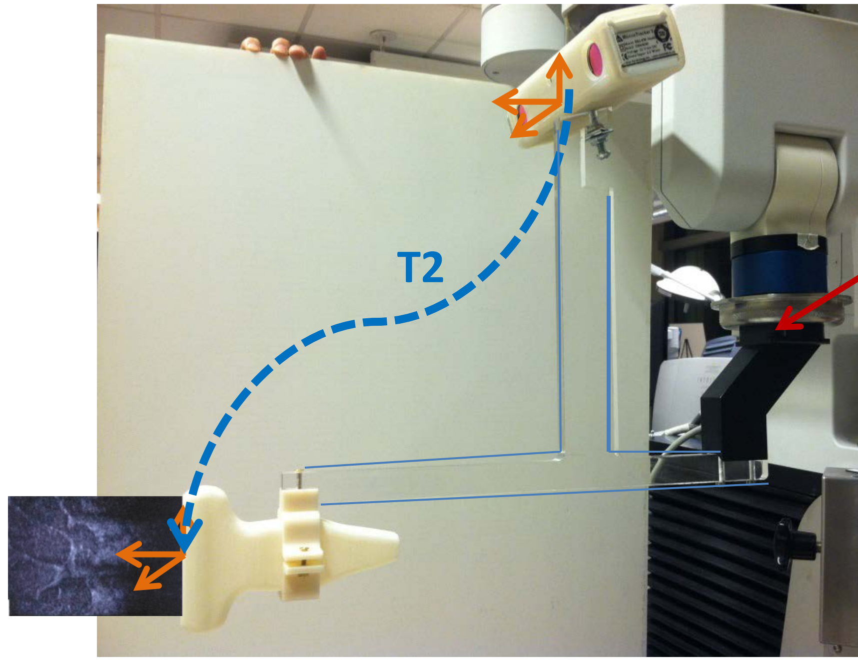
Summary of Problem

- In 3D ultrasound, the goal is to reconstruct 3D volumes from 2D ultrasound images.
- Four techniques to construct a 3D ultrasound volume:
  - Constrained sweeping
  - 3D probe
  - Sensorless techniques
  - Tracked 2D probe
- The fourth method is more commonly used but the transformation between the tracking system and the 2D image needs to be found: ultrasound calibration techniques

Our Project Schematics



Freehand Probe



Robot Endeffector

Require two ultrasound (US) calibrations T1 and T2

Project Summary | Summary of problem | Paper selection | Technical details | Application to project | References

Selected Paper:

Ultrasound in Med. & Biol., Vol. 31, No. 2, pp. 143–165, 2005

0301-5629/05/$–see front matter

ELSEVIER

doi:10.1016/j.ultrasmedbio.2004.11.001

- *Review*

A REVIEW OF CALIBRATION TECHNIQUES FOR FREEHAND 3-D ULTRASOUND SYSTEMS

LAURENCE MERCIER,* THOMAS LANGØ,† FRANK LINDSETH,† and LOUIS D. COLLINS*
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(*Received* 8 *June* 2004, *revised* 5 *November* 2004, *accepted* 11 *November* 2004)

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Why this paper?

- Require two ultrasound calibrations in our project:
  - On the free-hand probe, find the transformation between the marker and 2D ultrasound image
  - On the robot-operated probe, find the transformation between the Optical Tracking cameras and 2D ultrasound image
- This paper: Recent review on calibration techniques for 3D ultrasound
- Become familiar with basic and advanced concepts
- Have a list of important issues in ultrasound tracking field

Significance & Background

- Significance:
  - the comprehensive review and classification of ultrasound calibration techniques published between 1994-2004
- Background:
  - The paper is very well written and
  - covers almost all the required background
- Familiarity with ultrasound imaging and calibration techniques can be helpful to better appreciate the significance of this paper.

Summary of Paper

- This paper covers:
  - Tracking technologies x
  - US image acquisition x
  - Phantom design and comparisons √
  - Speed of sound issues √
  - Feature extraction x
  - Least square minimization x
  - Temporal calibration x
  - Calibration evaluation techniques √

Main steps toward US calibration

Choose
- Choose US machine parameters and imaging mode
- Choose an appropriate calibration method and, if needed, a calibration phantom.

Collect data
- Put phantom or targets inside a water tank and take images;
- Extract features.

Analyze
- Adjust measurements if needed based on medium's speed of sound.
- Find sensor-world and world-phantom transformation.
- Use least squares method to find the image to sensor transformation.

Evaluate
- Evaluate the calibration results

Calibration Phantoms

- **Single point target:** spherical point or crossing of two wires
- **Multiple point targets:** cross-wires, triangular wires, collinear points, Z- fiducial phantoms, etc.
- **2D shaped phantoms:** align points of interest of a **solid 2D geometric object** in the ultrasound image.
- **Three wire phantoms:** the wires are **orthogonal** and their intersection is the origin of the phantom coordinate system and each **wire represents one axis**.
- **Wall phantoms:** In this phantom, a **line** from the wall is present in the image making segmentation **easier** than when the feature is a **point**.

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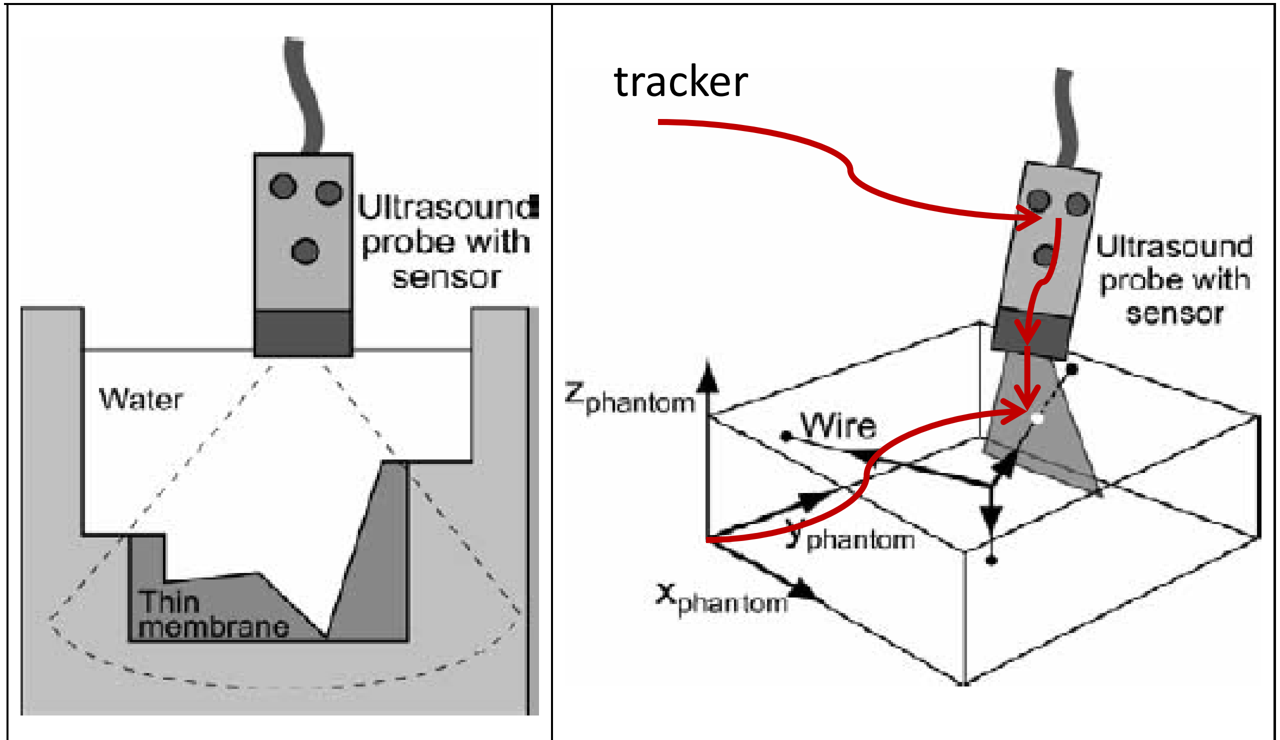
Examples



(a) (b)

Image from: L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound

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Speed of sound Issue

- Speed of sound is assumed 1540 m/s (speed of sound in human tissue)

$$d_{measured} = propagation\ time \times \frac{1540}{2}$$

- US calibration coupling medium (Eg. Water)

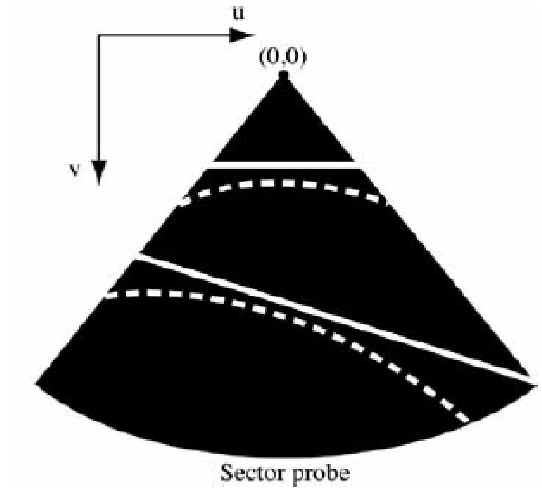

Image from: L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound

Speed of sound Ratio

Speech of sound in human tissue

Speech of sound in coupling medium

$$R = \frac{1540}{S_{medium}}$$

True distance

measured distance

$$d = d_{measured} \times R$$

Calibration Parameters

- Coordinate systems:
  - image,
  - sensor,
  - tracker (or world), and
  - Phantom
- (u_k, v_k): position of feature point extracted from the image
- (x_k, y_k, z_k): the position of the point in the phantom coordinates
- s_x and s_y are scale factors
- The top center point of image is usually considered as origin

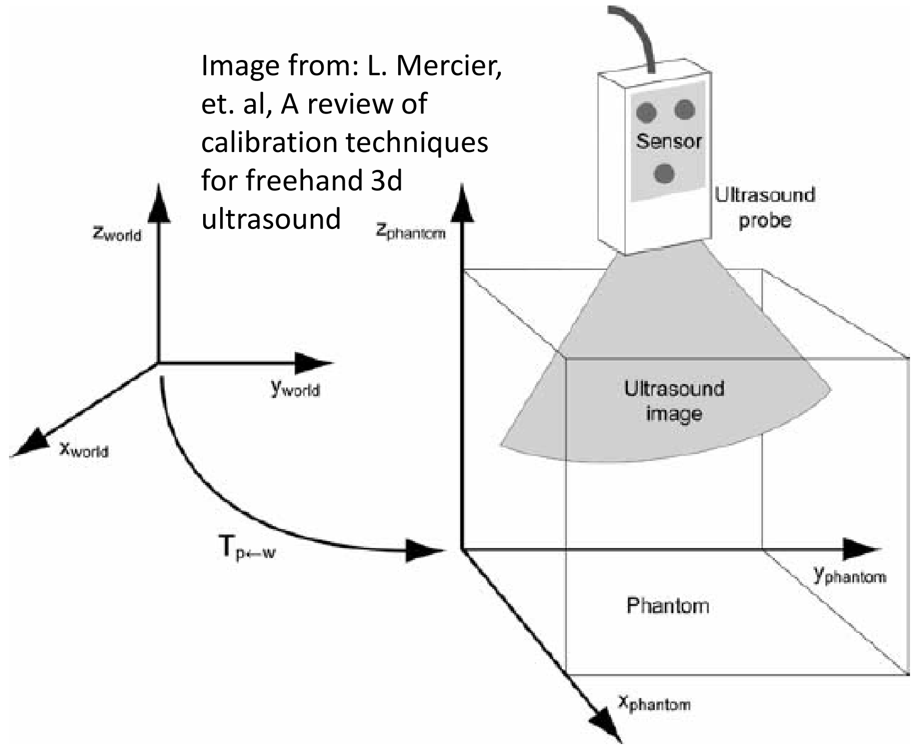

Image from: L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound

$$\begin{pmatrix} x_k \\ y_k \\ z_k \\ 1 \end{pmatrix} = T_{p\leftarrow w} . T_{p\leftarrow w} . T_{p\leftarrow w} . \begin{pmatrix} s_x . u_k \\ s_y . v_k \\ 0 \\ 1 \end{pmatrix}$$

LSQR Minimization

- **Closed form:** is used when we know the position of features in world's coordinate system
  - E.g. in single or multiple point targets

- **Iterative approach:** Iterative approach is used when we do not know the position of features in world's coordinate system
  - E.g. in three wire or wall phantoms

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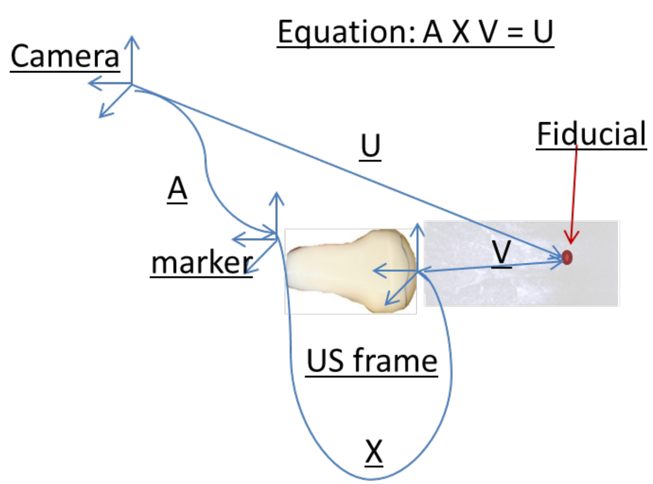
Comparison of Methods

- Criteria:
  - precision
  - accuracy
  - required time to perform calibration
  - complexity
  - price of the required software and hardware
  - …
- Depends on application

How to measure precision?

Reconstruction Precision:
Proposed by Detmer et al. (1994) involves:

- Imaging a target point (fiducial) from multiple viewing angles
- Extract the fiducial from image
- Map it to camra space (U)
- ✓ Forming a cloud of points.



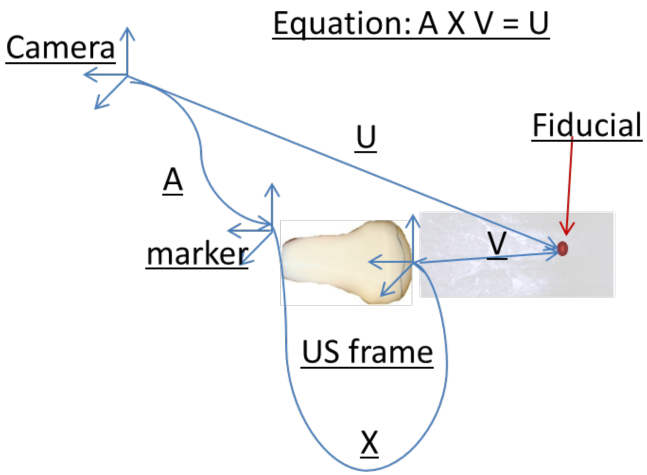
Note: Pos. of fiducial in camera space needs not be known

The standard deviation of this cloud: reconstruction precision

How to measure accuracy?

Reconstruction accuracy:
Similar to reconstruction precision except for:

- The position of fiducial in camera space is known with a good accuracy



The deviation from each point in the cloud of points from the real position of fiducial in camera space is used to measure accuracy.

My evaluation of paper

- Plus:
  - The first review paper with description of almost all existing (before 2004) calibration methods
  - Provides mathematics only if necessary and gives references for further details
  - Provides comprehensive comparison tables
  - Covers almost every important topic in the field
- Minus:
  - Could have given some example applications appropriate for each method
- Possible Future work:
  - More recent advances in the field of ultrasound calibration can be reviewed. (After 2004)

Our method of choice

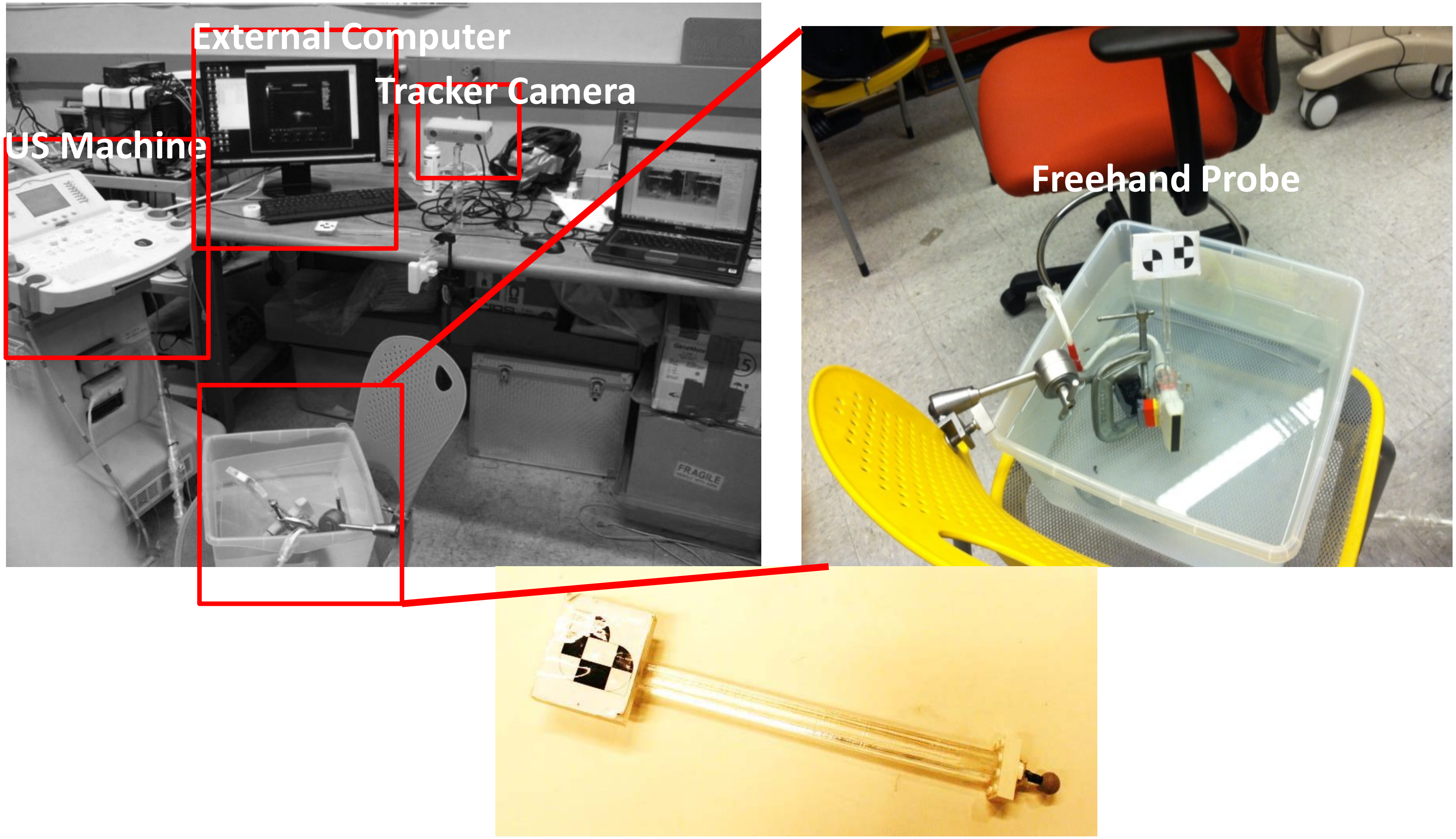
- Single point target: Pointer calibration
- Pros:
  - Does not require phantom
  - Do not need to worry about tracker’s FOV and line of sight
  - Fast, less complex, data collection can be done in several hours
  - Fast calculation and experiment setup preparation
- Cons:
  - Less accuracy due to hand movement
  - Not a large set of data can be acquired in reasonable time
  - Image thickness affects accuracy:
    - Possible solution: Novel active echo pointer

Our method of choice

Reproducibility   accuracy

		r.m.s. error	Mean calibration reproducibility	Mean point reconstruction precision	Mean point reconstruction accuracy	Mean reconstruction accuracy (distances)
Prager et al. (1998b)	Cross-wire	0.56	1.47	0.04	–	0.04 ± 1.12
	Three-wire	1.04	5.37	−0.15	–	−0.15 ± 2.18
	Single-wall	0.48	3.27	0.14	–	0.14 ± 1.63
	Cambridge	0.34	0.92	0.23	–	0.23 ± 1.33
Blackall et al. (2000)	Cross-wire	–	1.05 ± 0.43	0.80 ± 0.46	1.15 ± 0.40	−0.00019 ± 0.60
	Registration phantom	–	1.84 ± 1.26	1.15 ± 0.62	1.16 ± 0.45	−0.025 ± 0.69
Boctor et al. (2003)	Cross-wire	–	–	0.62 ± 0.29*	–	0.25 ± 1.78*
	Hopkins	–	–	0.72 ± 0.343*	–	0.15 ± 1.63*
Kowal et al. (2003)	Three-wire	0.221	3.2 ± 1.94	2.3 ± 1.23	–	0.3 ± 0.49
	Cambridge	0.160	2.2 ± 2.74	2.4 ± 1.38	–	0.3 ± 0.53
	Pin cage	0.135	2.7 ± 1.59	2.5 ± 1.36	–	0.3 ± 0.58
	Wedge cage	0.151	1.9 ± 1.23	2.2 ± 1.28	–	0.3 ± 0.51
Lindseth et al. (2003c)[†]	Single-point target	–	0.63 ± 0.39 (P)	–	2-D: 0.79 ± 0.39 (P)	
			0.62 ± 0.38 (L)		2-D: 0.73 ± 0.41 (L)	
					3-D: 1.00 ± 0.39 (P)	3-D: 0.15 ± 0.30 (P)
					3-D: 1.48 ± 0.35 (L)	3-D: 0.23 ± 0.51 (L)
	Diagonal phantom	–	0.38 ± 0.17 (P)	–	2-D: 0.86 ± 0.46 (P)	
			0.44 ± 0.25 (L)		2-D: 0.77 ± 0.43 (L)	
					3-D: 0.84 ± 0.36 (P)	3-D: 0.10 ± 0.30 (P)
					3-D: 1.24 ± 0.71 (L)	3-D: 0.26 ± 0.46 (L)
	Z-fiducials	–	0.55 ± 0.29 (P)	–	2-D: 1.52 ± 1.35 (P)	
			0.63 ± 0.36 (L)		2-D: 1.03 ± 0.84 (L)	
					3-D: 0.81 ± 0.43 (P)	3-D: 0.16 ± 0.33 (P)
					3-D: 1.15 ± 0.43 (L)	3-D: 0.25 ± 0.45 (L)
Leotta (2004)	Single-point target	–	–	0.94	–	−0.10 ± 0.70
	Multiple point target	–	–	0.96*	–	−0.10 ± 0.68*

Collect data: Experiment Setup



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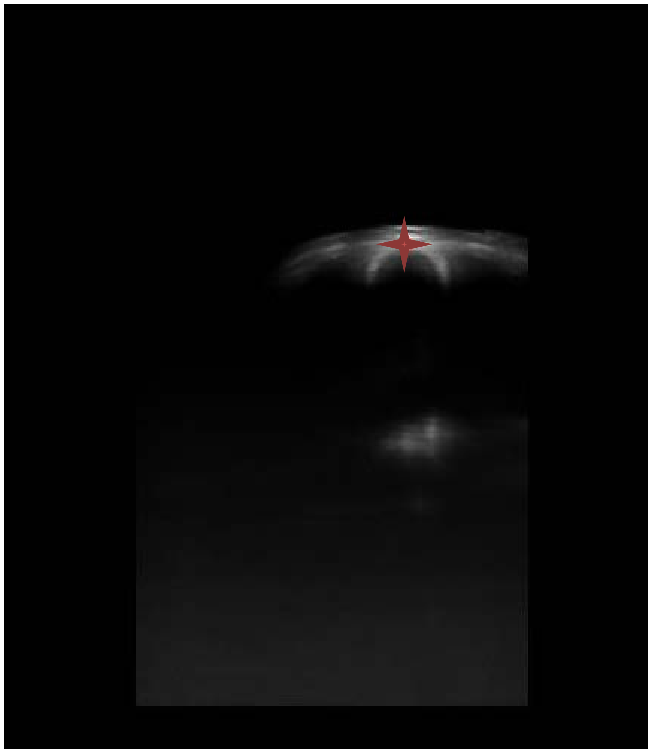
Collect data: Some Example Images



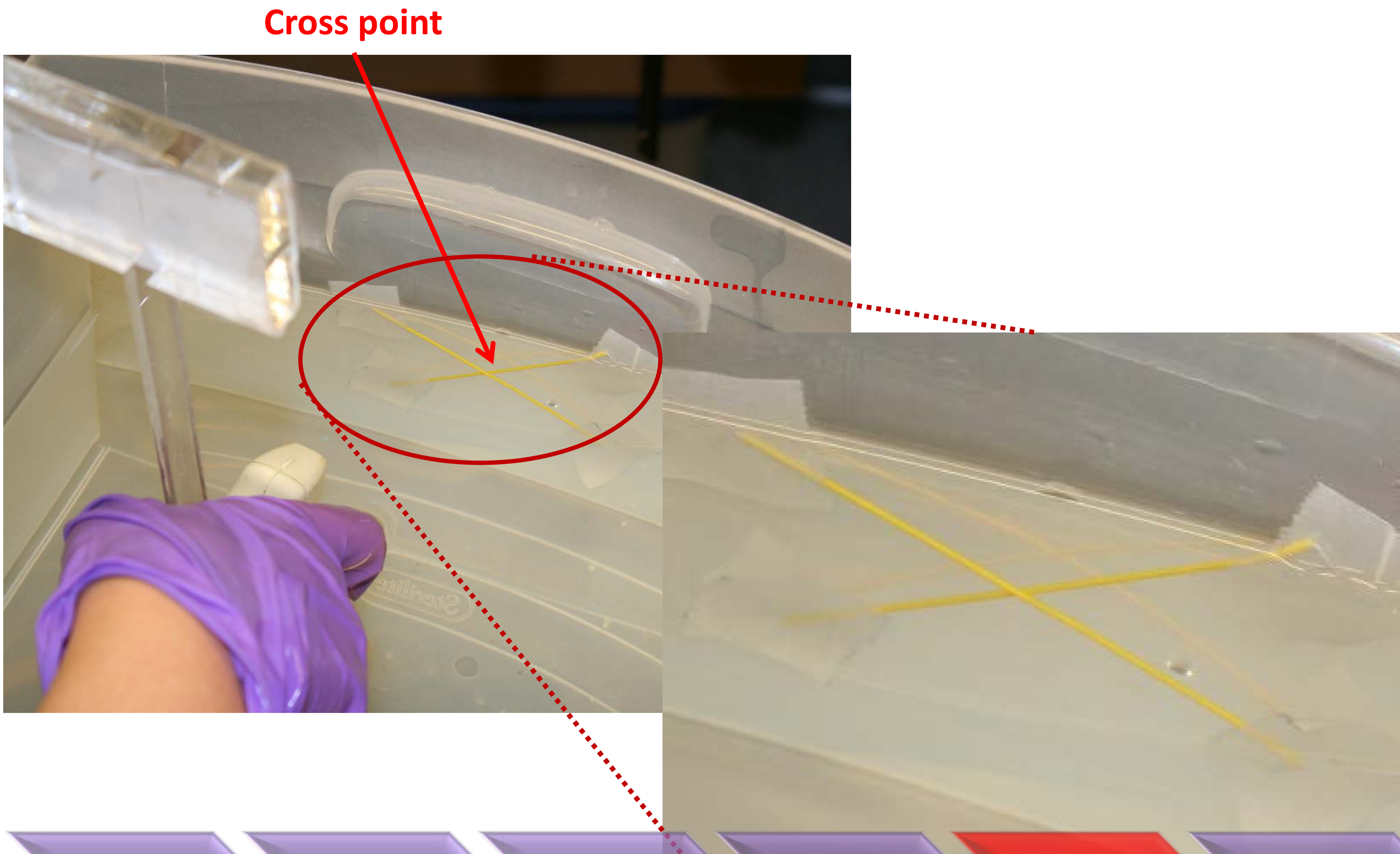
Analyze: Result

```
Scroll C:\WINDOWS\system32\cmd.exe

C:\cis2FR\US_Calibration\lsqrsource\examples\build\Release>pointerUSCalibration
markerziv.txt outUS.txt pointerziv.txt outputziv.txt
vnl_least_squares_function: WARNING: unknowns(8) > residuals(7)
..\..\..\..\vxlsource\core\vnl\algo\vnl_levenberg_marquardt.cxx: Number of unkno
wns(8) greater than number of data (7)
FAILED CALIBRATION, possibly degenerate configuration


C:\cis2FR\US_Calibration\lsqrsource\examples\build\Release>pointerUSCalibration
markerziv.txt outUS.txt pointerziv.txt outputziv.txt
Percentage of data used in estimate: 0.133333
t3[x,y,z]:
        [-18.6233, 187.732, -38.2771]
omega[z,y,x]:
        [-1.55332, 0.271969, -1.67711]
m[x,y]:
        [1.10744, 1.03291]
sum of squared errors: 17.1022
max, min, mean error: 1.93173, 0.593321, 1.39118


C:\cis2FR\US_Calibration\lsqrsource\examples\build\Release>po_
```

T1

0.0186	-0.1144	0.9937	-18.6233
-1.0666	0.2739	0.0459	187.7318
-0.2975	-0.9893	-0.1022	-38.2771
0	0	0	1.0000

Evaluation: Reconstruction Precision



More References

- More details in the following papers:
  - **Beam Calibration without a Phantom for Creating a 3-D Freehand Ultrasound System, 2001**
  - By: D. M. Murator and R. L. Galloway, Jr.
  - **A Novel Phantom-Less Spatial and Temporal Ultrasound Calibration Method, 2005**
  - By: Ali Khamene and Frank Sauer
- Implementation of method on IGSTK:
  - **Ultrasound Calibration Framework for the Image-Guided Surgery Toolkit (IGSTK), 2009**
  - By: Ziv Yaniv, Pezhman Foroughi, Hyun-Jae Kang, and Emad Boctor

Thanks!

QUESTIONS?

US Image Acquisition

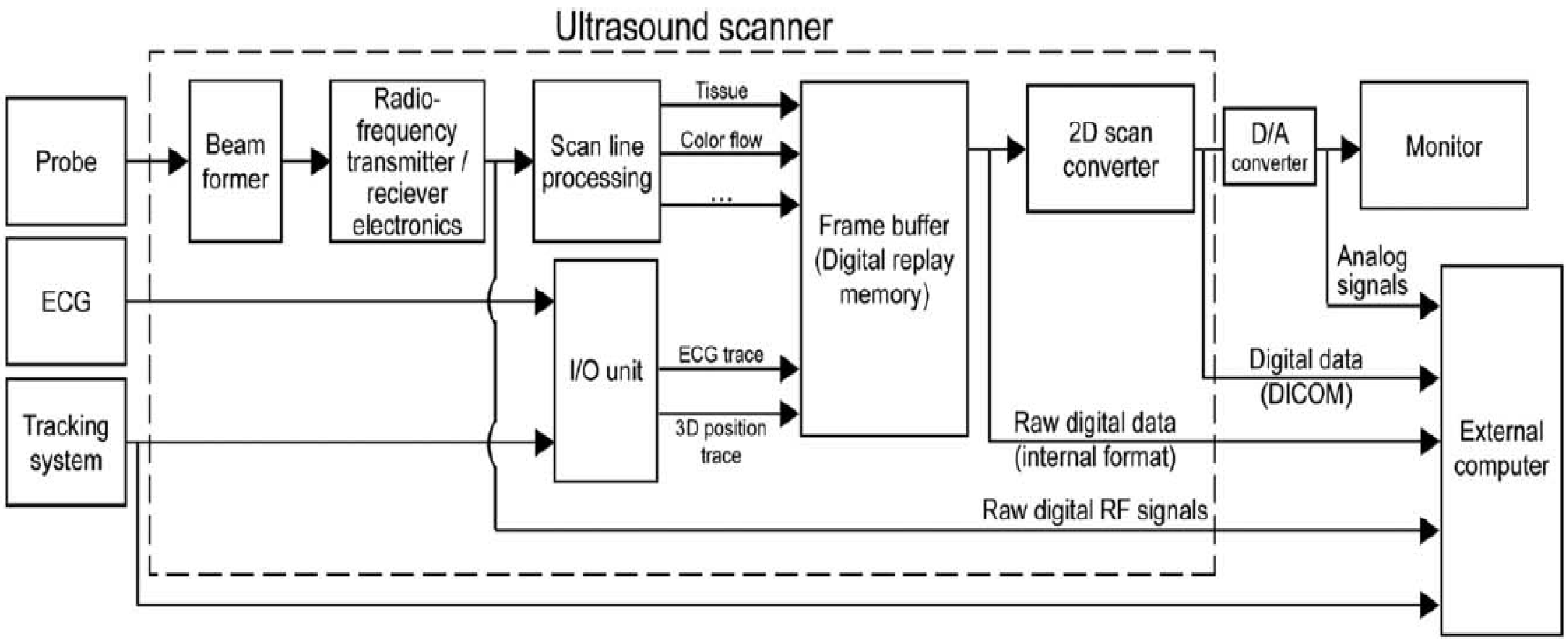


Image from: L. Mercier, et. al, A review of calibration techniques for freehand 3d ultrasound

US Image Acquisition