Enabling technologies for robot assisted ultrasound tomography: system setup and calibration

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ABSTRACT

In this study, we are proposing a robot-assisted ultrasound tomography system that can offer soft tissue tomographic imaging and deeper or faster scan of the anatomy. This system consists of a robot-held ultrasound probe that tracks the position of another freehand probe, trying to align with it. One of the major challenges is achieving proper alignment of the two ultrasound probes. To enable proper alignment, two ultrasound calibrations and one hand-eye calibration are required. However, the system functionality and design is such that the ultrasound calibrations have become a challenge. In this paper, after providing an overview of the proposed robotic ultrasound tomography system, we focus on the calibrations problem. The results of the calibrations show a point reconstruction precision of a few millimeters for the current prototype, and the two images have at least 50% overlap visually; confirming the feasibility of such a system relying on accurate probe alignments.

Keywords: ultrasound tomography, robotic ultrasound, ultrasound calibration, tracked ultrasound

1. INTRODUCTION

The ultrasound machine is relatively inexpensive, portable, and more importantly, does not produce ionizing radiation. The ultrasound penetration depth typically ranges up to 15 cm. The thicker the tissue, the more attenuation is caused, and consequently, the noisier the images obtained. This is why ultrasound imaging cannot be used for thick tissues or obese patients. One of the techniques to overcome this limitation is called transmission ultrasound or ultrasound tomography. In this technique, unlike the conventional method in which both the transmitter and receiver are placed at the same location, one transducer is used as the transmitter and one is used as the receiver, while the imaged tissue is placed in the middle. Therefore, the penetration depth is doubled. Marmarelis *et al.* [1] for instance propose an ultrasound computed tomography prototype where a tank of water with many identical transducers in the wall of the tank is considered for acquiring tomographic imaging. Khoei [2] has covered many such systems. Even though promising results have been reported using the ultrasound transmission tomography systems, more development is needed in this field to enhance the spatial resolution and speed up the process [2]. Furthermore, requiring the scanned area to be inside the water is inconvenient and limits possible areas to be scanned. In addition, using vast number of transducers instead of the existing ultrasonic imaging systems to enable this technology is another disadvantage. Consequently, this technique has not gained significant attention so far. In this paper, we aim to develop a system that uses two conventional ultrasound probes: a combination of human operated probe and a robot operated probe, which can be used to offer higher imaging depth and can enable ultrasound tomography imaging. The advantages of having a robot in the loop include precise alignment and ease of operation.

Using robotics in ultrasound image acquisition has also been reported in the literature. For example, Abolmaesumi *et al.* [3] developed a robotic ultrasound system for the neck in which the operator, a developed image-guided software tool, and the robot controller share control of one ultrasound probe. Najafi and Sepehri [4] proposed a similar tele-operated system for abdominal ultrasonography. However, none of the previous work has reported use of robotics for tomography purposes. To the best of our knowledge, this is the first time a robotic ultrasound tomography system has been presented. In robotic ultrasound tomography, one of the major challenges is achieving proper alignment of the two probes. At the minimum, two ultrasound calibrations and one hand-eye calibration are required to enable tracking. The nature of this system has made ultrasound calibration challenging.

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Ultrasound calibration is used to find the transformation from (a typically) tracked sensor, which is rigidly attached to an ultrasound probe, to the ultrasound image coordinate system. Usually, a fiducial marker is imaged by the ultrasound probe from different angles while, at the same time, the position and orientation of the tracked sensor is measured. The relationship between these two data sets is used to find the unknown transformation. It is possible to use only a point as the fiducial, or a line, several points, a pointer, or more complicated calibration phantoms consisting of several points, lines or planes. Mercier *et al.* [5] provide an extensive summary and comparison of different methods of ultrasound calibration. In this paper, after providing an overview of the system, the focus will be placed on the ultrasound calibrations.

In section 2, an overview of the overall system and details of each component are explained. Section 3 provides the methodology including simulation study for camera and rigid body positions, used ultrasound calibration method, required hardware, and software. Section 4 describes the experiment setups for the calibrations, the data collection procedure, and system evaluation results.

2. SYSTEM OVERVIEW

In this section, an overview of the system is provided and system components are described. Figure 1 shows an overview of the robot assisted ultrasound tomography system. The freehand probe is operated by a sonographer or a technician and is tracked by a tracking system installed on the robot side. The appropriate movement of the robot-held probe can be calculated and sent to the robot such that the robot-held probe moves in compliance with the freehand probe. Below, the Components of this system are explained in more detail.

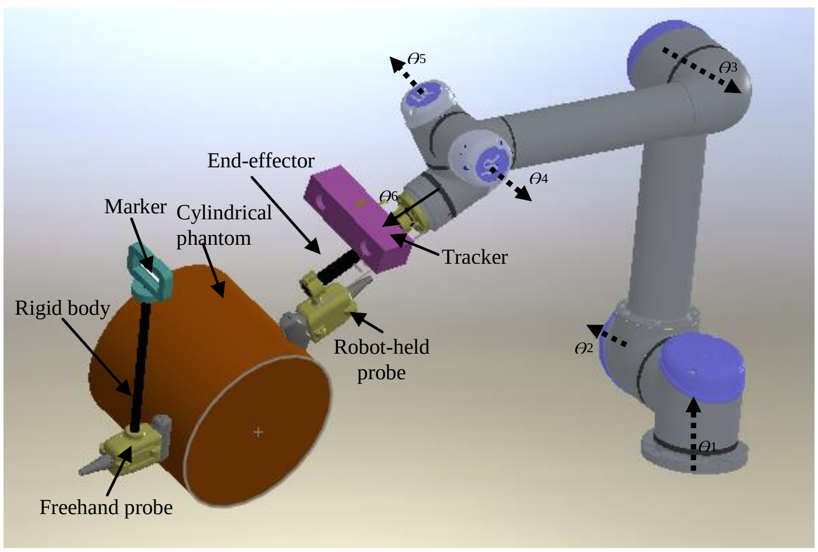


Figure 1. System overview and components

2.1 Ultrasound system

Two ultrasound machines are required to facilitate simultaneous operation of both probes. Two Ultrasonix machines (Ultrasonix Inc., Richmond, British Columbia, Canada) are used. Two identical 60 mm linear array probes are used. One of the probes called freehand probe will be operated by the technician; the other one called robot-held probe is attached to the robotic arm to track and mimic he motion of the freehand probe.

2.2 Tracking system

For tracking, an external tracking system is required. The first consideration for the external tracker is finding an appropriate place for it in the system's workspace. We chose to put the tracker on the robot arm. This arrangement has the following advantages: 1) there is no limitation in workspace due to the tracker's limited field of view (FOV); 2) it can provide tomographic images from the tracker to compensate for truncated tomography caused by small FOV of ultrasound image; and 3) the system will be more easily portable.

We selected the MicronTracker SX60 (Claron Technology Inc., Toronto, ON, Canada), which provides real-time images of the scene (visible light functionality), has a small footprint, and is ultra-light (camera + case < 500 grams), has passive, easily printable markers and low cost stereo cameras. The camera's range of measurement is 115 x 70 x 55 cm, and the maximum measurement rate is 48 Hz. The camera's calibration accuracy is 0.25 mm. The tracker is connected to a PC through IEEE1394b (Firewire) with a speed of 800 Mb/s. In its range of measurement, MicronTracker can detect the 3D position of Xpoints that are at least 2.5 mm in diameter.

2.3 Robotic arm

A robotic arm that can precisely reach every point of the workspace and can provide all the orientations is required. A low-noise flexible and lightweight robot is also preferred for this application. As shown in Figure 1 we used UR5 robotic arm (Universal Robots Inc., Odense, Denmark) which is a lightweight (18.4 kg) and noiseless robot with 6 degrees of freedom. All the six joints have a range of rotation of ±360 degrees. The robot tooltip can reach 850 mm from the center of the base with a repeatability of ±0.1 mm and with a speed of up to 1 m/s [6].

The robot comes with a controller and a teach pendant (or control panel). The control panel has a software tool called Polyscope from which the robot can be controlled by the user. In general, the robot can be controlled in 3 modes: GUI, URscript, and C API: 1) The GUI is available through the polyscope software on the control panel and gives direct access to control the joints' angles or the tooltip position. It is also possible to save the positions as a program and run it automatically. 2) The URscript is the language provided by the company with built in variables and functions. 3) It is also possible to control the robot using the low level C-API. However, the users need to provide their own robot controller and specify all the parameters, such as each joint's position, speed, and acceleration.

UR5 also comes with its own simulator called URsim. In addition, the experimental version of the Universal Robots ROS simulator has been recently implemented [7].

3. METHODOLOGY

3.1 Simulation study for mechanical designs

To enable the tracking and also robot-held probe operation, two mechanical interfaces are designed and manufactured.

The marker should be rigidly attached on top of the probe so that it is always visible in the tracker's range of measurement. We desire to have the camera looking at the same scene that the ultrasound probe is imaging; hence we shall put the camera at the end-effector just before the robot-held probe. However, we also should consider that the area that is scanned should not obstruct the camera's view of the marker on the freehand probe. Hence it should be placed at a distance with respect to the robot-held probe that is in contact with the tissue. When the rough desired camera position is determined, we need to design the freehand rigid body such that it ensures that: 1) The marker is always in the range of measurement of the camera, 2) The marker is always in the camera's line of sight.

At this stage, it is assumed that the area that is scanned is cylindrical with a maximum diameter of 30 cm. Based on this assumption and considering the camera's range of measurement volume, the camera's position and angle on the end-effector and the marker position on the freehand probe are determined based on a sample simulation study shown in Figure 2.

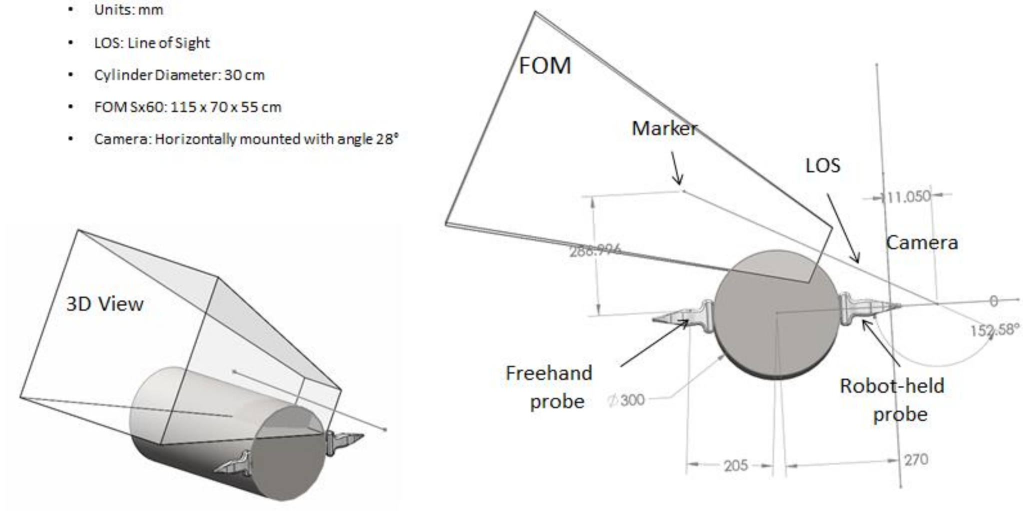
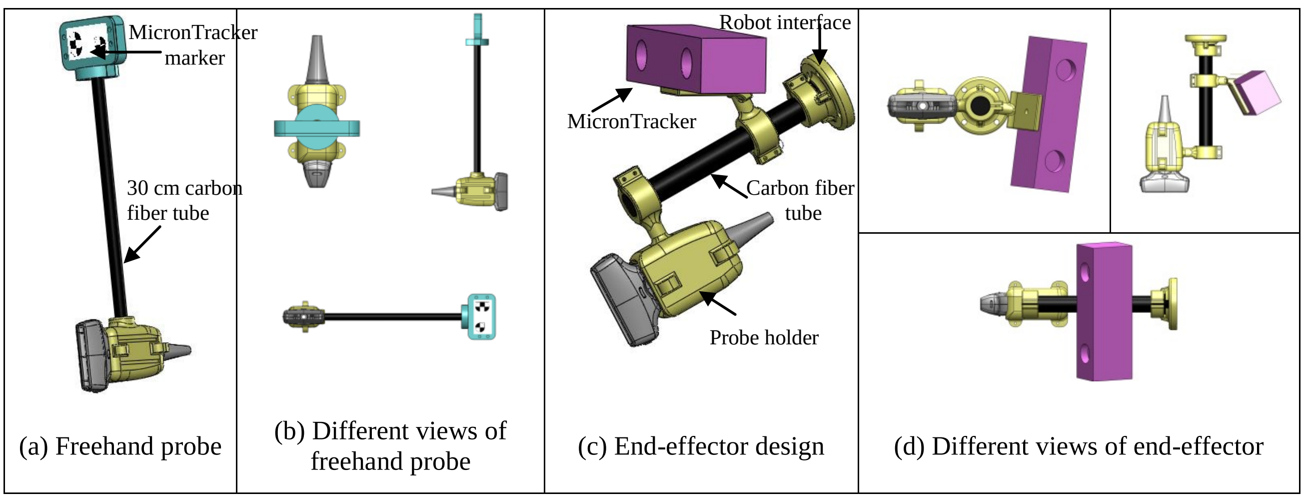


Figure 2. Simulation study of camera and rigid body positions

Freehand probe rigid body

Firstly, a probe holder is designed and built using ABS material and solid 3D printing. A hole is designed on top of the probe holder to insert a 30 cm rod complying with the design shown in Figure 2. To ensure both rigidity and lightness we used carbon fiber tube with 0.5 inch inside diameter. The marker is attached to the top of the tube as shown in Figure 3 (a) and (b).



(a) Freehand probe
(b) Different views of freehand probe
(c) End-effector design
(d) Different views of end-effector

Figure 3. Freehand rigid body and end-effector current design

End-effector rigid body

In order to attach the tracker's camera and robot-held probe, we designed a separate end-effector that could be mounted on the robot arm. Figure 3 (c) and (d) shows its components. Since the camera's weight should be tolerated on the end-effector, the carbon fiber tube, used for the end-effector, has a larger diameter (0.75 inch), in comparison with the freehand rigid body, to ensure more rigidity. The whole end-effector weights around 1 kg and is less than the maximum possible payload on the robot, which is 5 kg.

3.2 System calibration

Two ultrasound calibrations are required to enable the tracking: the transformation from the freehand probe marker coordinate system to its ultrasound image coordinate system, X1, and the transformation from the tracker's camera coordinate system to the robot-held probe ultrasound image, X2, as shown in Figure 4. In addition to the ultrasound calibrations, another calibration is required (not in the focus of this paper). It is called hand-eye calibration, which will determine the transformation from the robot tooltip to the MicronTracker's coordinate system, X3. The hand-eye calibration is required for the operation of the overall system.

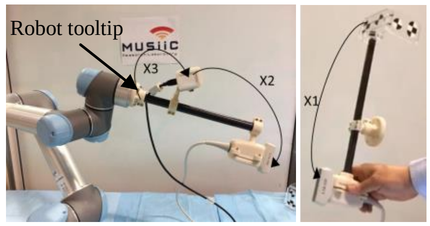


Figure 4. Unknown transformations found through ultrasound calibrations

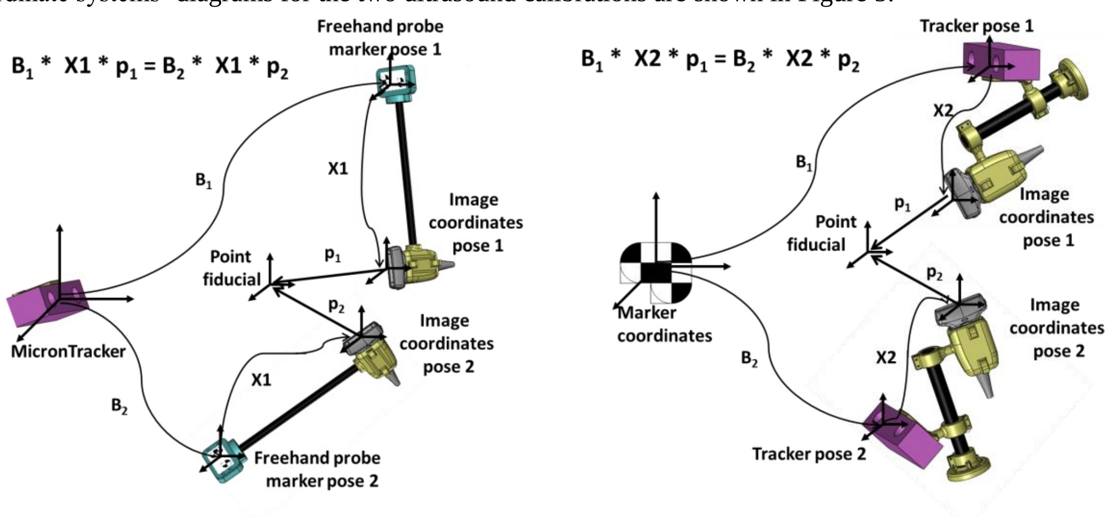
The ultrasound calibration method should be chosen carefully for such a system due to several limitations: 1) The camera has a small range of measurement; 2) the marker is attached at a height relative to the probe's position; 3) the marker is attached at a distance relative to the probe's position. Limitations 2 and 3 infer that, when the probe rotates a certain degree, the observed rotation from the marker or camera's points of view is larger, i.e., the probe's range of motion during calibration is limited. We chose the point calibration method, as it is more straightforward than other types of ultrasound calibration and can more easily alleviate the limitations on the system.

Point calibration

In the point calibration, the following equation holds for two instances of time:

$$B_i X p_i = B_j X p_j \quad (1)$$

Where B_i and B_j are the transformations from tracker to the tracked sensor at times i and j; X is the transformation from tracked sensor to ultrasound image coordinate system; and p_i is the position of point element in the ultrasound image. The coordinate systems' diagrams for the two ultrasound calibrations are shown in Figure 5.



(a) Freehand ultrasound calibration diagram (b) Robot-held ultrasound calibration diagram

Figure 5. Point calibration coordinate systems in the two ultrasound calibrations

Gradient decent solver

To solve equation 1 for X, a gradient descent solver is used which is presented in [8]. In summary, an initial X is given to the algorithm; the algorithm finds the cloud of points based on current X, then finds the corresponding cost function, based on which a new X is calculated using gradient descent. The above procedure is repeated and consequently, the cloud of points shrinks iteratively until convergence. To determine convergence, two thresholds for translation and rotation are set. The algorithm converges when the difference between the two consecutive X's is less than the thresholds. Please refer to [8] for more details.

4. EXPERIMENTS AND RESULTS

In this section, the experiment setups, data collection procedures, and evaluation results for the two ultrasound calibrations are provided. The procedure to find *X1* is called freehand calibration, and the one for *X2* is called robot-held calibration.

Since the ultrasound machine and the PC that records tracker poses are not synchronized, either a temporal calibration needs to be done, or data collection should be done when all the components are at a fixed position. We chose the latter, and the robotic arm is used to fix the probes' positions in both calibrations.

4.1 Freehand calibration

Figure 6 shows the experiment setup for the freehand ultrasound calibration. An extra light is placed beside MicronTracker to increase the accuracy of tracker readings.

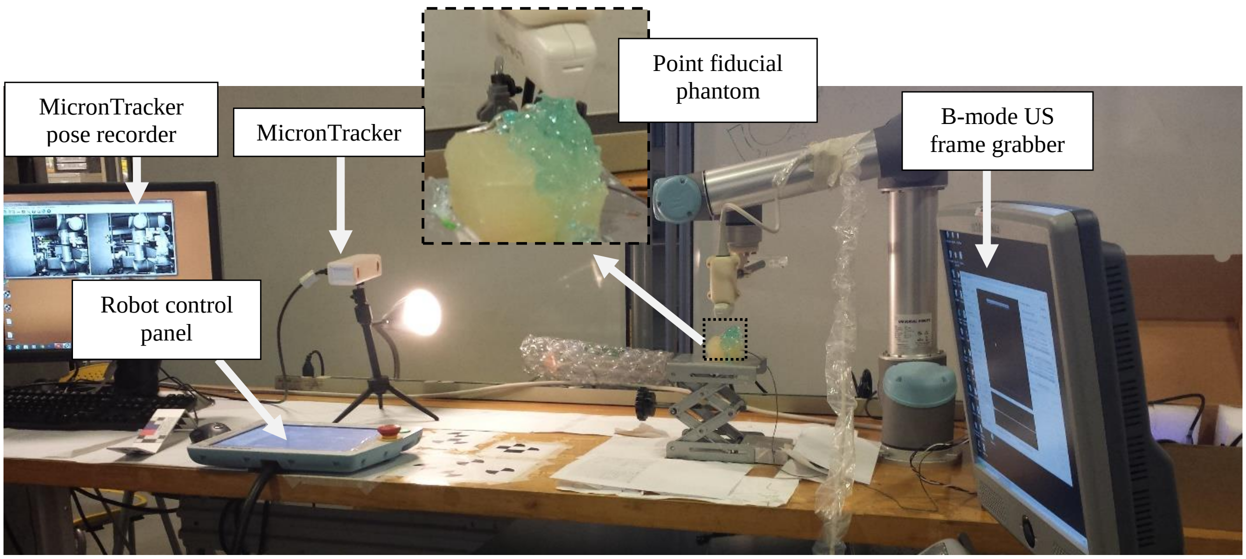


Figure 6. Freehand ultrasound calibration setup

Data collection procedure

To collect data, the point fiducial is inserted into a gel phantom and fixed on a stage at a height of about 8 inches with respect to the table. Ultrasound gel is used to avoid contact with the gel phantom so that the point fiducial does not move due to phantom's deformation. The reason for using gel instead of a water tank is that, due to the tube that comes out of the probe holder, the range of motion would be limited inside a water tank. An extra marker is attached perpendicular to the original marker to cover more ranges of motion. These two single markers are registered in the MicronTracker software as a multi-facet marker. After the calibration is complete, the extra marker is detached. The following explains the setup in more details:

1. The camera is fixed at the side at a distance of about 60 cm from the point fiducial, and its software tool can record a stream of rotation matrices and the positions of the probe's marker in the camera coordinates.
2. The ultrasound machine has a frame grabber software tool that records B-mode images. The depth is set to 7 cm; the focus is adjusted at each data collection to acquire the best image. Frequency is set to 5 MHz and

ultrasound images are stored at a rate of 17 Hz. The ultrasound machine is in B-mode Harmonic Resolution mode, and the TCG is set to a low value.

3. When the optimal position of the probe is achieved, while the robot is stationary, 20 frames are recorded on both the ultrasound machine and MicronTracker pose recorder. Later, the average of these 20 frames are taken to analyze each data set. Hence, each data set includes 20 ultrasound frames and 20 transformation matrices from camera to the probe's marker.
4. The above is repeated 60 times to get 60 data sets.

The average of the 20 points in each data set is taken to produce 1 ultrasound image and 1 transformation matrix for each set. The position of the point fiducial is segmented manually in all images and then converted to millimeters. Gradient solver is used to find X1.

4.2 Robot-held ultrasound calibration

Figure 7 shows the experiment setup for the Robot-held ultrasound calibration.

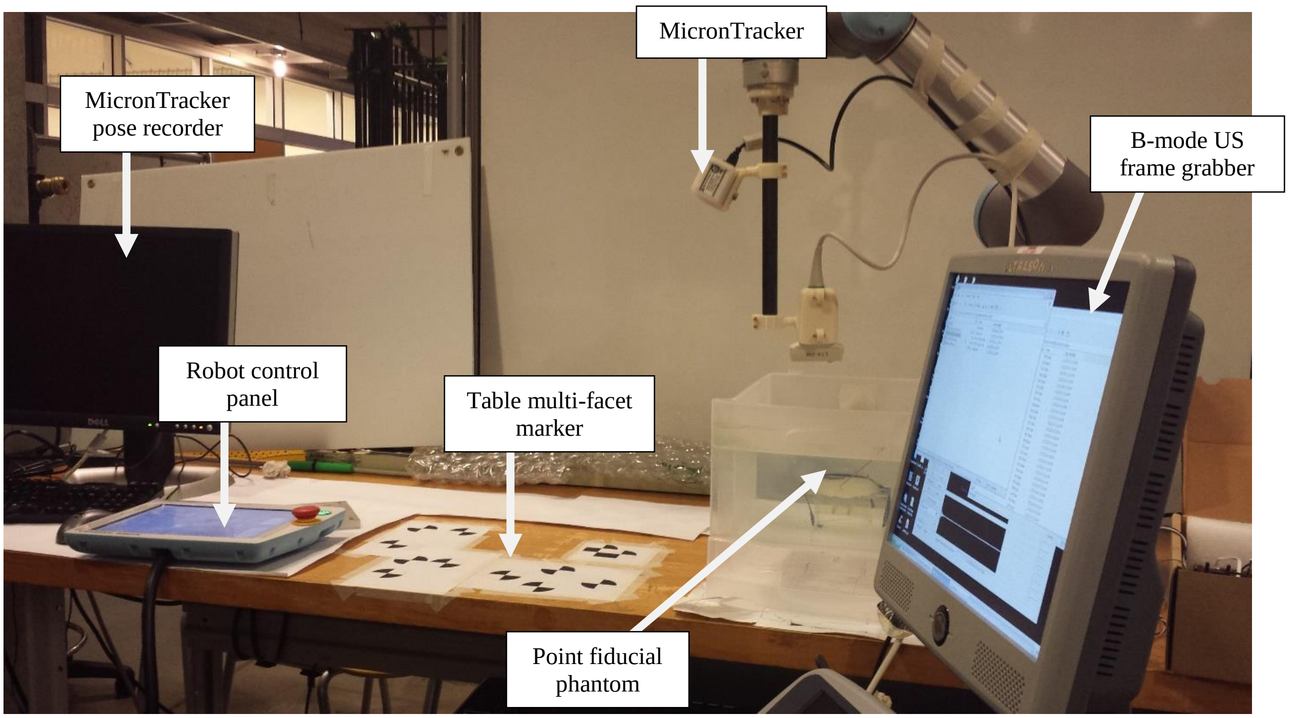


Figure 7. Robot-held ultrasound calibration setup

Data collection procedure

The data collection procedure for the robot-held ultrasound calibration is similar to the freehand calibration with the following exceptions: 1) the point fiducial is inserted into a gel and fixed inside the water tank. The water tank is used here because it provides more convenience, and no extra gel is required; in addition, the end-effector design is such that the range of motion will not be limited by the water tank. 2) A multi-facet marker is attached to the table, and this marker is fixed with respect to the robot base. This time the tracker is moving and the marker is fixed; hence the transformation matrix is inversed.

4.3 Ultrasound calibrations evaluation

The reconstruction precision is used to evaluate the calibrations. For the freehand calibration, 3 data sets were discarded due to empty reading from MicronTracker and hence 57 data sets are used. 45 sets are used to find X1 and 12 points are used to evaluate the reconstruction precision. For the robot-held ultrasound calibration, 4 data sets were discarded and hence 56 sets were used in total. 44 data points are used to find X2 and 12 are used to evaluate the reconstruction precision. Table 1 shows the reconstruction precision along axes together with the norm of the precisions.

Table 1. Ultrasound calibrations reconstruction precision

	Precision (STD in mm)			
	Norm	**X**	**Y**	**Z**
Freehand	4.30	1.20	0.97	3.99
Robot-held	1.79	0.69	1.25	1.05

The low accuracy observed for the freehand ultrasound calibration can be due to limited range of motion that is imposed by the rigid body. It can also be because of the auxiliary marker that is registered to the first marker and creates more error in the tracker's readings. We believe that the accuracies can be improved either by further analysis, rejecting appropriate outlier data sets, or improving the reading accuracies.

4.4 Overall system performance

As mentioned before, in order to evaluate overall system performance, an extra calibration is done called hand-eye calibration. This calibration is done by fixing a marker on the table, and moving the camera, while attached to the end-effector, to different viewing angles of the marker, similar to what is done for the robot-held ultrasound calibration. Similar data analysis is done and the norm reconstruction precision for the current calibration is 2.52 mm.

Overall system performance is evaluated by fixing the freehand probe and running the system so that the robot-held gets aligned with the freehand one; this is done with different initial positions for the robot-held probe, and the repeatability is measured. The results are shown in Figure 8 and Table 2. Figure 6 shows that the image planes are visually aligned and have at least 50% overlap.

Figure 8. Probes alignment

Table 2. Repeatability of robot-held US image corners for a fixed freehand probe

	Repeatability (mm)
corner 1	5.87
corner 2	5.16
corner 3	4.97
corner 4	5.73

5. DISCUSSIONS AND CONCLUSIONS

There are other ways of choosing calibrations for the system. For example, an alternative way of finding X2 is to calibrate the ultrasound image to the Robot tooltip, i.e., find the transformation from the robot tooltip to the robot-held probe ultrasound image, and then use X3 to recover X2. The advantage of this alternative method is that we can benefit from the higher accuracy of the robot (in comparison with the MicronTracker); and the disadvantage is that it is required to calibrate the robot and perform X3 first. A future step of this project can be to combine the transformations recovered with the two methods to achieve a better accuracy.

In this paper, in summary, an ultrasound tomography system is proposed that can be used for soft tissue tomographic imaging, deep ultrasonic scanning, and faster scanning of the anatomy. The use of robot-held probe in this application improves accuracy and ease of operation for the two tracking probes. An overview of the system's prototype and components is provided. A challenging problem in this system is ultrasound calibration. A point target ultrasound calibration is delivered which shows a reconstruction precision of few millimeters. This can be improved benefiting from other methods of calibrations or more extensive data collections and processing. However, the achieved results validate the feasibility of tracking in such system. This paper is the first publication on the proposed robot assisted ultrasound tomography system.

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