DUAL ROBOTICS ULTRASOUND TOMOGRAPHY

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I. Introduction

A. Goals

We aim to study new quantitative ultrasound parameters to prostate cancer detection and biopsy guidance, such as speed of sound and attenuation provided by ultrasound tomography. Prostate USCT (Ultrasound Computed Tomography) is anatomically challenging due to the deep anatomy of prostate and surrounding bones. Thus, water gantry is infeasible, and we aim to use a dual robotic system with an aligned TRUS (Transrectal Ultrasound Scan) receiver and an abdominal transducer that have been successfully applied in pelvic region imaging. In detail, the TRUS probe will be inserted to phantom or patient body, and the abdominal probe should be in close contact with the phantom surface. During a scan, the TRUS probe needs to rotate, and the abdominal probe needs to follow that rotation while maintaining co-linear with the TRUS probe, to ensure the needs of ultrasound tomography, Further, we will apply the virtual fixture to control the force to ensure the safety of the system.

B. Background & Significance

Prostate cancer is the most dominant than other cancers (180,890, 21% in total cancer diagnosis) and the second leading cause of cancer-related deaths in men (26,120, 8%)[1], and early detection is crucial for effective treatment. However, current diagnostic methods have their limitations. The prostate-specific antigen (PSA) test can be helpful in identifying prostate cancer, it is not accurate enough, as they sometimes detect non-aggressive cancers that may never cause harm, which lead to overdiagnosis and overtreatment.

Although multi-parametric prostate MRI is an effective detection method, its high cost limits its availability. Therefore, a practical and effective detection method is needed, and ultrasound computed tomography (USCT) technology presents a promising alternative.

USCT offers several advantages over other traditional methods, including real-time imaging, non-invasiveness, and high-resolution images. Moreover, USCT provides quantitative ultrasound transmission data, such as sound velocity and attenuation, which can aid in cancer staging.

Traditional hardware for USCT is cylindrical water tanks, however, the deep physiological structure of the prostate poses a challenge to obtaining high-resolution images. To address this challenge, the study employs a dual-robotic system, where a transrectal ultrasound (TRUS) probe is inserted into the patient's body, allowing close proximity to the prostate and reducing acoustic impedance mismatch. This approach can yield high-quality images that are suitable for cancer detection.

Instead of using dual-robotic arm, the study uses a rotatory stage for the TRUS probe, to replaces one robotic arm. Because the industrial robotic arms cost around 30k each. This is a way to reduce costs. Moreover, this method improves the efficiency, because in actual diagnosis situations, the robotic arm installed with TRUS probe will hinder the activities of patients and doctors, and will also affect the workspace of another robotic arm; on the contrary, because the small size of the rotatory stage, these limitations can be avoided.

Safety is the most important items that need to be considered, the study uses virtual fixture to control the force applied on the patients. The purpose of virtual fixture is to avoid exerting too much force on the patient and causing harm to the human body.

II. Technical Approach

A. Calibration

For the end-effector to ultrasound calibration, a cross-wire phantom fixed in a water tank was used, and it was imaged by two probes under thirty independent poses of each robot arm represented by $B_A^{(i)}$ and $B_T^{(i)}$. And then, they applied $BX\vec{p}$ calibration to obtain the end-effector to abdominal probe transformation X_A. For TRUS Probe X_T, since the second robot arm remain as a dependency, we used a step motor with encoder to obtain X_T. The Trus probe has only one degree of freedom(rotation). The transformation are shown in Figure 1 was modified, $X_T A$ now represents robot base frame to TRUS probe Frame. From which X_A and X_T were respectively optimized through an iterative gradient descent procedure after algorithm initialization.

The $BX\vec{p}$ problem could be solved with

$$\underset{X \in SE(3)}{\operatorname{argmin}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} ||B^{(i)} X p^{(i)} - B^{(j)} X p^{(j)}||_2^2 \quad (1)$$

We withheld one tenth of all the data samples to assess calibration accuracy by calculating standard deviation of the Euclidean distance between each calculated cross location and the average cross location:

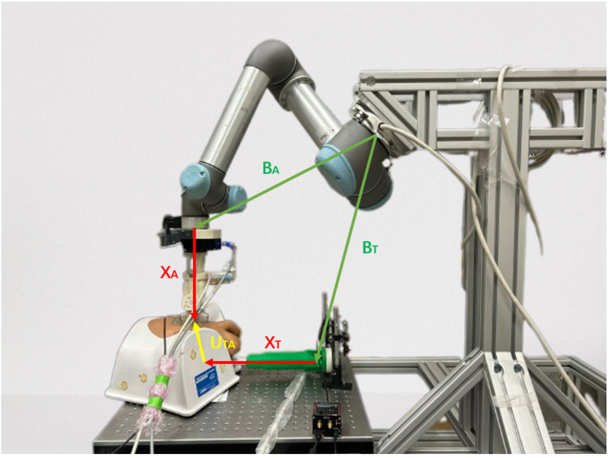

Fig. 1. Working Principle of the dual-robot system[2]

$$E^{(i)} = ||B^{(i)}Xp^{(i)} - \sum_{j} \frac{1}{n} B^{(j)}Xp^{(j)}||_2^2 \tag{2}$$

For the calibration between TRUS Probe and robot base inverse X_{TA} with B_T, the method is moving the cross-wire phantom to 7 different locations to form the point cloud of cross-wire, and X_{TA} is solved with ICP (Iterative Closest Point) method. Or, an alternative method could be use the abdominal probe to touch the TRUS probe, if X_A was accurate enough and two probes' frame centers are strictly attached, this method avoids propagates more error from point cloud registration.

And the accuracy was assessed again, by calculating standard deviation:

$$E^{(i)} = ||B_T^{(i)} X_T p_T^{(i)} - B_A^{(i)} X_A p_A^{(j)}||_2^2 \tag{3}$$

B. Motion Planning

For the motion planning part, the abdominal probe follows the rotation of the TRUS probe. We need to calculate the location and the orientation of the abdominal probe after each step of movement of the TRUS probe to make two probes colinear.

As shown in the Figure2. P_I (P_{goal}) is the position where the abdominal probe should move after each step of the TRUS probe rotation. After calibration, we can obtain all robot rigid transformation. But since we lacked a robotic arm, so we used a rotatory stage for the TRUS probe and simplified the transformation from the TRUS to end-effector (X_T) , end-effector to base (B_T) and base to base (X_{TA}) to the transformation from the TRUS to the base of robot arm with abdominal probe (X_{trus}).

P_I is solved with

$$\vec{p_A} = \mathit{translation}(X_{trus}^{-1} B_A F_A X_A) \tag{4}$$

$$\vec{n_A} = \mathit{rotation}(X_{trus}^{-1} B_A F_A X_A) * \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{5}$$

$$\vec{p_T} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \qquad \vec{n_T} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{6}$$

$$t = \frac{\vec{n_A} \cdot \vec{p_A} - \vec{n_A} \cdot \vec{p_T}}{\vec{n_A} \cdot \vec{n_T}} \tag{7}$$

$$P_I = (\vec{p_T} + t \cdot \vec{n_T}) * X_{trus} \tag{8}$$

P_T and n_T are position and the orientation of the TRUS probe relative to TRUS frame, so the position is a zero-vector and the orientation points towards y-axis. P_A and n_A are position and the orientation of the abdominal probe relative to TRUS frame. We can obtain the distance from P_{goal} to TRUS probe by calculating t.

Due to P_{goal} is always a point along the y direction relative to TRUS probe, we can obtain the representation of P_{goal} under TRUS frame. Finally, we transfer P_{goal} to the base frame by multiplying X_{trus}. After the abdominal probe reaches to P_{goal}, all transformation will be recalculated to update P_{goal}.

In this method, the distance between P_{goal} and TRUS frame in z-axis is constant, so the desired motion planning is that P_{goal} is updated following the rotation of TRUS frame, and the orientation of the abdominal probe is the same as the z-axis of TRUS frame, and all P_{goal} points form a contour of circle.

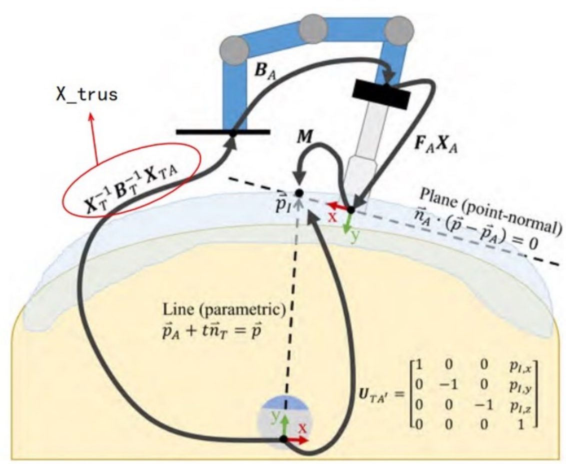

Fig. 2. P goal calculation[3]

After obtaining the desired frame of the abdominal probe, we need to transfer the frame to the end-effector of the robot arm, and then used it as the input for virtual fixture algorithm.

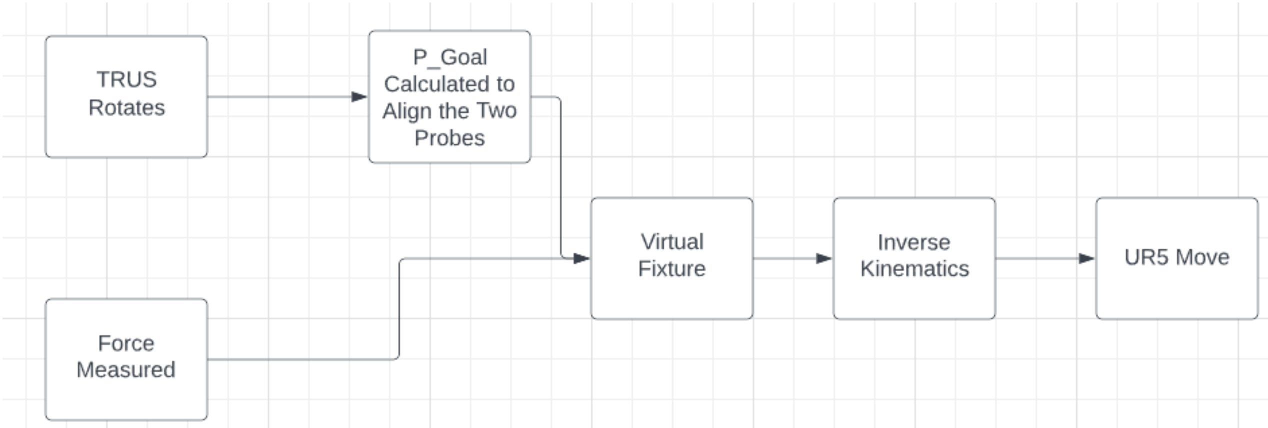

Fig. 3. Control Diagram

C. Virtual Fixture

Virtual Fixture is a constrained quadratic optimization problem, as shown in equation 9

$$\text{argmin}_{\Delta x} ||W_{tip} \cdot (\Delta x/\Delta t) - (\Delta x_d/\Delta t) - k \cdot (f - f_d)||^2, \quad subject\ to\ H\Delta x/\Delta t \geq h \tag{9}$$

where Δx is a six by one vector for the change of $\{x,\ y,\ z,\ roll,\ pitch,\ yaw\}$ in Cartesian frame for the abdominal probe relative to world frame; Δx_d is the desired change in Cartesian frame for the abdominal probe relative to the world frame; Δt is a constant time step; W_{tip} is a weight matrix; k is a constant factor; f is the measured force; f_d is the desired force; $H\ and\ h$ are geometry constraints. The original formula is in the paper [4], we modified it for our own usage.

To begin with, for the objective equation, as mentioned above, there are six elements in both $\Delta x_d\ and\ \Delta x$. The first three elements of Δx_d, which are $\{x,\ y,\ z\}$, come from the the P_{goal} discussed in section II-B. The $\{roll,\ pitch,\ yaw\}$ is simply the orientation of the TRUS probe, as we aim to have the two probes to be co-linear all the time. For Δx, all six elements come from readings of the robot driver. The $k \cdot (f - f_d)$ term is a feedback of the force. What we aim is to maintain a constant force between the probe and the phantom or the patient body. For instance, for a specific P_{goal}, if the force measured f is exactly the same as the desired force f_d, then the abdominal probe should reach the exact P_{goal} position. On the other hand, if the measured force is greater than the desired force, we pursue the abdominal probe to lift up along the contact direction (y direction of the TRUS probe and abdominal probe, the direction we are aligning the two probes) proportional to the term $k \cdot (f - f_d)$ to reduce the reaction force instead of aiming for the P_{goal}. (only the contact direction force is considered here)

A control diagram is shown in figure 3

Subsequently, for the subjective function, we used two geometric constraints, which means 2 sets of $H\ and\ h$. The first one is to stay around a point. The idea is to fix the tip of the abdominal probe to a desired point within a sphere with radius $\epsilon 1$, as shown in equation below.

$$H = \begin{bmatrix} -c_{\alpha 1}c_{\beta 1}, & -c_{\alpha 1}s_{\beta 1}, & -s_{\alpha 1}, 0, 0, 0 \\ & \cdots & \\ -c_{\alpha 1}c_{\beta m}, & -c_{\alpha 1}s_{\beta m}, & -s_{\alpha 1}, 0, 0, 0 \\ & \cdots & \\ -c_{\alpha n}c_{\beta 1}, & -c_{\alpha n}s_{\beta 1}, & -s_{\alpha n}, 0, 0, 0 \\ & \cdots & \\ -c_{\alpha n}c_{\beta m}, & -c_{\alpha n}s_{\beta m}, & -s_{\alpha n}, 0, 0, 0 \end{bmatrix}, \quad \vec{h} = \begin{bmatrix} -\epsilon_1 \\ \vdots \\ -\epsilon_1 \end{bmatrix} - H\vec{\delta}$$

Fig. 4. Stay at a Point [4]

The second one is to maintain a given direction with a tolerance $\epsilon 2$.

$$H = \begin{bmatrix} 0, 0, 0, & -c_{\alpha 1}c_{\beta 1}, & -c_{\alpha 1}s_{\beta 1}, & -s_{\alpha 1} \\ & \cdots & \\ 0, 0, 0, & -c_{\alpha 1}c_{\beta m}, & -c_{\alpha 1}s_{\beta m}, & -s_{\alpha 1} \\ & \cdots & \\ 0, 0, 0, & -c_{\alpha n}c_{\beta 1}, & -c_{\alpha n}s_{\beta 1}, & -s_{\alpha n} \\ & \cdots & \\ 0, 0, 0, & -c_{\alpha n}c_{\beta m}, & -c_{\alpha n}s_{\beta m}, & -s_{\alpha n} \end{bmatrix}, \quad \vec{h} = \begin{bmatrix} -\epsilon_1 \\ \vdots \\ -\epsilon_1 \end{bmatrix} - H\vec{\delta}$$

Fig. 5. Maintain in a Direction [4]

With the two geometric constraints and our objective equation, we could make sure the optimized Δx would have the same orientation and a nice offset of position due to force feedback compared with our Δx_d.

In addition, virtual fixture has a very nice advantage on force feedback control. The constraints $H\ and\ h$ are geometric constraints, so when the optimization is performed, even if the force is very large (in both positive or negative direction), the Δx calculated would not exceed the geometric constraints, which would be very safe for the phantom or the patient.

III. Experimental Setup

List of Instruments

1) KDC101 Motor Controller
2) Two laptops
3) UR5 CB2
4) Two Ultrasonix machine
5) Abdominal Probe
6) TRUS probe

7) Robotiq FT300-S Force Sensor
8) Multi-Modality Pelvic Phantom model 048A

We used a rotary stage for the TRUS probe with the KDC101 controller. One laptop with windows operating system and LabVIEW is used for this controller. The TRUS probe is mounted on the rotary stage. The force sensor and the Abdominal probe are mounted on the UR5 robot arm, which are all connected with another laptop with Ubuntu 18.04. The two laptops would connect to the same ROS master and communicate with each other. The two Ultrasonix machine are each connected with one probe respectively.

During each iteration of the scan, the Ubuntu Laptop would tell the windows laptop how the rotary stage should rotate. A P_{goal} will be calculated based on the current position and orientation as well as the orientation of the TRUS probe. The virtual fixture function would take the P_{goal} and current position and orientation to calculate a Δx_d. Combining with a measured contact force by using Robotiq FT300-S Force Sensor, the virtual fixture would calculate where the robot should move (Δx). After that, we combine our current position and orientation and the calculated change Δx to get a position and orientation in world frame ("base_link" frame in robot description). The inverse kinematics [5] would then convert the desired position and orientation into joint angles. There are eight solutions from inverse kinematics, and we would choose the one closest to the current configuration. The joint angle will be fed to the robot arm. The abdominal probe would then move accordingly. This would be an iterative process until a scan is fully finished.

IV. Results

A. Calibration

The BXp Calibration error calculated for three different x,y and z translation are x=3.295mm.±0.7mm y=2.541mm.±0.5mm z=1.049mm.±1mm .

If We assume the encoder for the step motor is accuate, so the only error that propagates into Point Cloud Registration (Or touch calibration introduced in Technical Approach) will be X_A. Since we used motors instead of another robotic arm, the Trus probe had to be inserted into the bottom of the calibration water tank, which made collecting point cloud data points difficult and unstable. Because in the process of collecting points, we must constantly switch the probes on the ultrasonic machine, and the water tank leaks during the switching process, which may cause the position of the points in the water tank to change during the process of switching probes. And 7 sample points, if not accurate enough, would be insufficient for point cloud registration.

There for, the touch calibration was used to obtain the transformation between the robot base and the TRUS probe. And the error for three different x,y and z translation are: From 90 degree to 135 degree:

$$\begin{aligned} x &= 3.2558mm \pm 1.7mm \\ y &= 3.9472mm \pm 0.5mm \\ z &= 1.8060mm \pm 0.6mm. \end{aligned} \tag{10}$$

From 45 degree to 90 degree:

$$\begin{aligned} x &= 6.3640mm \pm 1.3mm \\ y &= 9.1934mm \pm 0.5mm \\ z &= 1.1505mm \pm 1.6mm. \end{aligned} \tag{11}$$

The imaging parameters for Ultrasound machine: Speed of Sound:1480m/S, Power:-11(4dB), Gain:50 %, Depth:3.8cm.

B. Robot Motion Framework

For the motion planning part, we simulate the position and the orientation of P_{goal} in Matlab and Rviz, and observe the abdominal probe was able to track the motion of the TRUS probe. The MATLAB simulation is to prove the idea, so we aim to test motion planning and virtual fixture alone while not considering about calibration and registration errors. Thereby, we set all the necessary transformations with reasonable values. The TRUS probe (The green one in figure 6 is placed at the origin of the world frame and rotates with respect to the $x-axis$ of the world frame. Ideally, the abdominal probe (The red shapes in figure 6) should follow the rotation of the TRUS probe while maintaining a constant distance between, which means it would draw a circle if the TRUS probe rotates 360 degrees. In figure 6, we rotates the TRUS probe 90 degrees totally, so the abdominal probe should draw a quarter of a circle. Each red shape shows the position and orientation of the abdominal probe at one time. We also draw a half circle in blue to make the relationship more clear. In figure 6, we could clearly see the red shapes are exactly on the half circle with correct orientation each time.

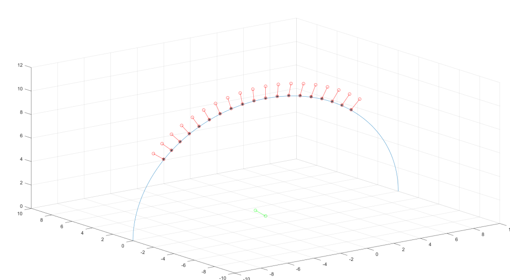

Fig. 6. Motion Planning MATLAB Simulation

For the Rviz simulation, this is where we put things together. The reason for this simulation is to do a last check before using the real robot. The programming for this simulation compared with controlling a real robot would be very similar. In other words, the code using for this simulation could be used on the real robot with simply connecting the robot to the computer. We used the

.urdf and .xacro file provided from the ROS package *ur_modern_driver*, along with the standard ROS package *robot_state_publisher* and *rviz* to make a simulation of the real robot, as shown in figure 7.

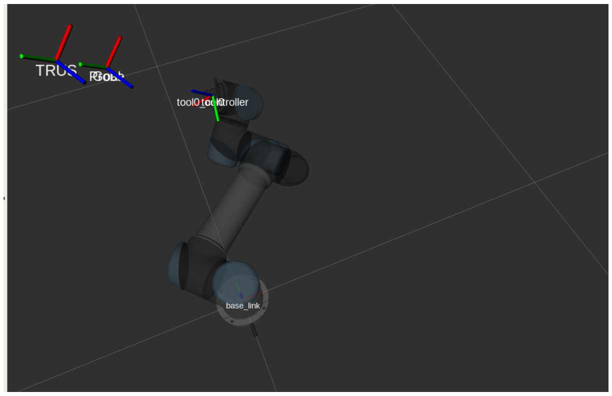

Fig. 7. Motion Planning Rviz Simulation

The frame at the top right is the TRUS probe frame (the transformation comes from our registration), and the one on its right is the *Goal* frame. The *Goal* frame is where the abdominal probe should be located at according to our motion planning calculation. The one coincides with the *Goal* frame is the *Abdominal Probe* frame. (This transformation comes from our BXp calibration) The reason they are coincided is the virtual fixture calculated the movement Δx, which is converted to joint angles by inverse kinematics then fed to the robot. Although hard to tell from the picture, we also simulated a force sensor to further test our virtual fixture. Instead of moving to a position 100 percent coincided with the *Goal* frame, the *Abdominal Probe* frame would leave an offset with the *Goal* frame according to the simulated force. When the simulation works perfectly, we then moved to the real robot.

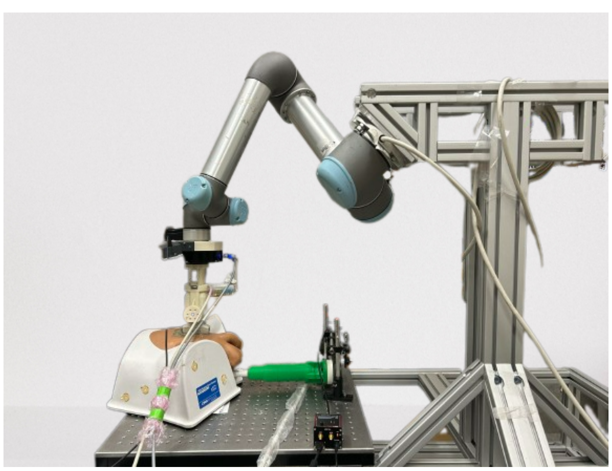

Fig. 8. Working Enviroment

The setup is shown in figure 8. We use the two probes to scan a pelvic phantom. During the scan, we keep tracking of the magnitude of reaction force between the abdominal probe and the phantom from the force sensor. For the virtual fixture, we set the $\epsilon 1$ to be 0.1 $meters$. With the $k(f - f_d)$ term in the objective equation (only consider the contact direction force), the abdominal probe would consider both the desired force as well as the desired position P_{goal} calculated by our motion planning method. The 0.1 $meters$ for $\epsilon 1$ is used to keep the abdominal probe in a close contact with the phantom surface. Just for clarification, if the abdominal probe is in air, then the force sensor would give a zero; we set our desired force to be -3 N, so in such a situation, the abdominal probe would move accordingly in the direction of y-axis of the TRUS probe. (The green axis in figure 7). The k is set as 0.001, and the force during the whole process is shown in figure 9.

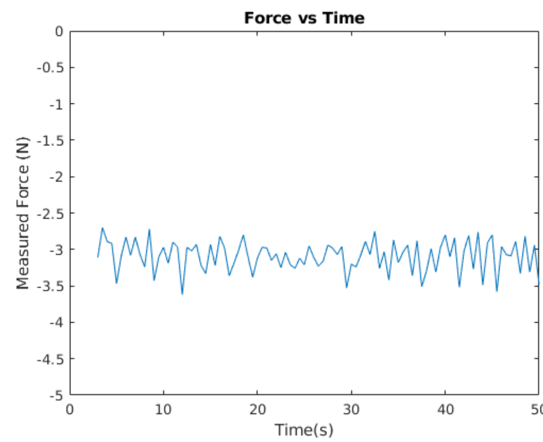

Fig. 9. Force vs Time

The force magnitude is mostly within -3 ± 0.5 N, which is good enough to keep a close contact with the phantom surface. This figure also shows that the process is working nicely as desired.

C. Imaging

As shown in figure 10, we could clearly see some noise in both images. The reason for the noise is that the two ultrasound probes are well aligned, so each probe would receive the signal (or interference) from other probe, which forms the noise in the figure.

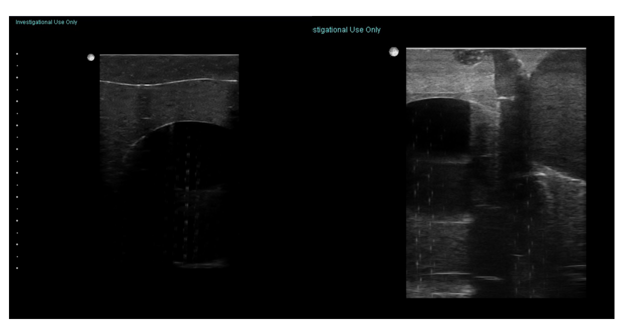

Fig. 10. Ultrasound image for Abdominal Probe(left) and Trus Probe

V. Management Summary

A. Deliverable

- Minimum (Completed)
  - A demonstration of proper dual-robotic setup and equipment connectivity
  - Robot base-to-base registration and end-effector-to-ultrasound calibration
  - Real-time motion planning of dual arms for ultrasound image acquisition where two ultrasound transducers are automatically aligned.
- Expected (Completed)
  - Integration of virtual fixture to limit robot arms' workspace to ensure the safety for in vivo imaging (for Abdominal probe)
  - Enhanced path planning to achieve smoother and steadier motion.
- Maximum
  - A real-time demo on a speed of sound phantom in preparation for the validation of ultrasound tomography reconstruction methods. (Completed)
  - A real-time demo on a realistic pelvis phantom to show the automaticity and safety of the framework. (Completed)
  - Integration of virtual fixture for the TRUS probe. (In progress)

What we have done is to achieve perfect alignment of the dual-robotic arms to ensure the needs of ultrasound tomography. Moreover, we made the dual robotic arm safer when moving by applying virtual fixture. In detail, We determined each transformation of the dual robotic arm system through $Bx\vec{p}$ calibration and point-cloud registration, and then do motion planning for the robotic arm. After that, we constrained the force for the robots by applying virtual fixture. Finally, we implemented a real-time demo to show the automaticity and safety of the framework.

In terms of deliverable, we completed all of our minimum and expected deliverable, as well as the first two of our maximum deliverable.

B. Future Plans

In this semester, we did not have two robot arms for the project. The first step for future work would be moving the TRUS probe to a second robot arm, and redo all the calibrations and registration needed. After that, the force for a P_{goal} is currently approximated by the force measured at the current location, with the premise of each movement is very small, so the force measured before the movement or after is very similar.

After that, there are three more things we are planning to work on. We aim to implement a hand guided control to move the abdominal probe to a desired initial position. Also, we could work on the third maximum deliverable of the project, the virtual fixture of the TRUS probe. Finally, we would like to implement a hand-over-hand control mode for the scanning process.

C. Credits

- Zhenghao Li
  1) Bxp Calibration algorithm for Abdominal Probe
  2) Point Cloud Registration (ICP) Algorithm
  3) Transformation loop setup and frame definition
- Ziyi Wang
  1) Calculation of goal position and orientation of the abdominal probe
  2) Inverse kinematics of robot arm
  3) Find force sensors for hand-over-hand control
- Yunpu Zhang
  1) Communication with ROS between all components
  2) Control of the rotary stage for the TRUS probe
  3) Virtual Fixture
  4) Force sensor calibration improvement
  5) Main code

D. Lessons Learned

- Bxp Calibration method with gradient solver
- Point Cloud Registration
- Force sensor calibration
- Inverse Kinematics control of the robot
- Alignment motion planning
- ROS communication between different Operating System.
- Virtual Fixture
- Step motor control

VI. Technical Appendices and Reference

A. Documentation

All the documentation could be found on our Wiki Page. The code along with the instruction are in GitHub Repository.

References

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