CIS II Proporsal

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1 Goal

We will use a dual robotic system with an aligned abdominal and a TRUS probe for prostate cancer detection. What we need to do is to achieve perfect alignment of the dual-robotic arms to ensure the needs of ultrasound tomography. Moreover, we will make the dual robotic arm safer when moving. In detail, We will determine each transformation of the dual robotic arm system through hand-eye calibration and base-to-base calibration, and then do motion planning for the robotic arm. After that, we will manually guide the abdominal probe to the correct initial position by applying hand-over-hand control, then we will constrain the force, velocity and acceleration for the robots, as well as a virtual fixture to limit the workspace of it, to avoid the collision between two robotic arms. Finally, we will implement a real-time demo to show the automaticity and safety of the framework.

2 Statement of Relevance/Importance

The detection of prostate cancer is an important mission for physicians, as it is the second most common non-skin cancer and the fifth leading cause of cancer death in men worldwide in 2018. However, many detection methods have drawbacks. PSA, or prostate-specific antigen, which is measured through a blood test, can be helpful in detecting prostate cancer, but it is not a perfect test, and there can be false positives or false negatives; multi-parametric prostate MRI is a useful detection method, but the equipment is expensive so the penetration rate is insufficient. So we need another method that provides practical and effective detection results, and Ultrasound computed tomography (USCT) technology can be a choice.

USCT has several advantages over traditional ultrasound tomography. It is real-time, non-invasive and the images are of high resolution. Also, USCT provides quantitative ultrasound transmission: like the sound velocity and sound attenuation, and the quantitative data could help to detect the stage of cancer.

However, the physiological structure of the prostate is deep, so it is difficult to obtain high-resolution images by traditional methods. Therefore, we use the dual-robotic system, the transrectal ultrasound (TRUS) probe extends into the human body and the probe is very close to the Prostate, receiving the ultrasound inside the patient's body. It can reduce the acoustic impedance mismatch and could get high-quality images.The actual working principle is shown in the Figure 1.

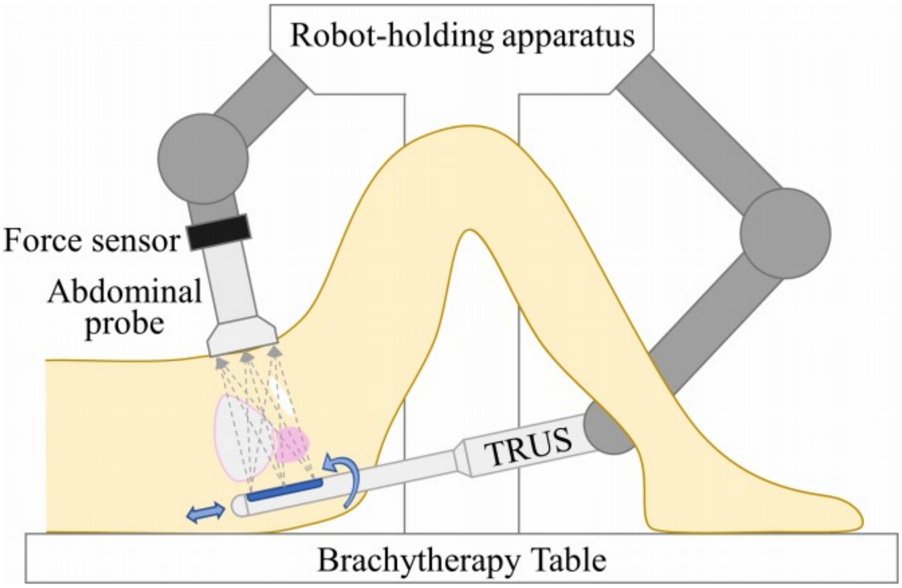

Figure 1: Working Principle of the dual-robot system[3]

3 Deliverables

- Minimum
  - 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
  - Hand Guide the robot arm to steer the abdominal probe to the correct initial position
  - 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.
  - A real-time demo on a realistic pelvis phantom to show the automaticity and safety of the framework
  - Integration of virtual fixture for the TRUS probe

4 Technical Summary of Approaches

4.1 Robot Arm Calibration & Motion Planning

All the variables we used in this section are defined below.

variables	definition
B_A	Transformation from the base to the end-effector of the left robot arm
B_T	Transformation from the base to the end-effector of the right robot arm
F_A	Rotational transformation of the end-effector of the right robot arm to the force/torque sensor
X_T	Transformation of the end-effector of the left robot arm to the TRUS probe
X_A	Transformation of the force/torque sensor to the abdominal probe
X_{TA}	Transformation between two bases
U_{TA}	Transformation between two probes

Table 1: Definition of Variables

The system is shown in Figure 2.

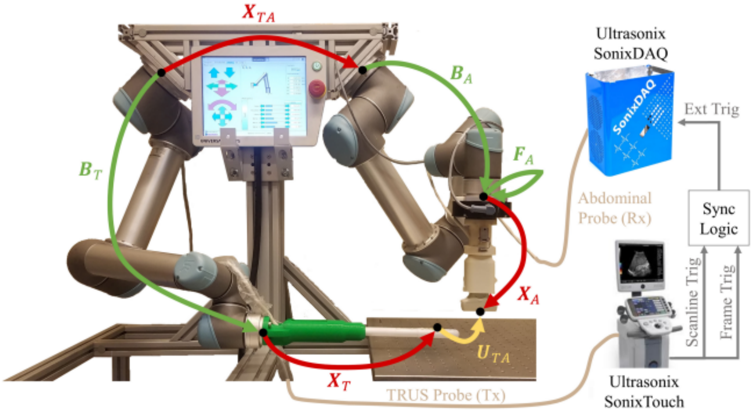

Figure 2: System Picture[4]

In the calibration part, we could obtain B_T *and* B_A from forward kinematics. F_A is the rotational transformation of the robot end-effector to the force sensor, which is also a known $SE(3)$ matrix. The first goal here is to apply $BX\vec{p}$ calibration to obtain X_T *and* X_A respectively: we would solve a $BX\vec{p}$ problem for each UR5 arm. After that, we would use *PointCloudRegistration* to obtain the transformation matrix between the two bases: X_{TA}.

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

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

In the motion planning part, we would use the position of the TRUS probe to calculate the velocity that the Abdominal probe should have to accomplish the desired motion. The velocity is defined as:

$$\mathbf{v} = \mathbf{v_{pose}} + \mathbf{v_{contact}} \tag{2}$$

$\mathbf{v_{pose}}$ *and* $\mathbf{v_{contact}}$ are defined in Figure 3.

For brevity, we would not expand the calculation for $\mathbf{v_{pose}}$ *and* $\mathbf{v_{contact}}$ in this **Short** technical summary of approaches, but the calculation for them could be found in [4].

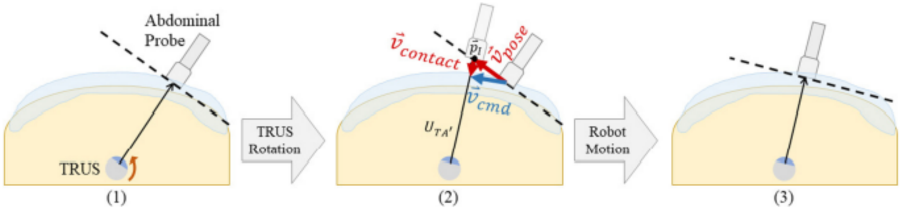

Figure 3: Velocity Components

4.2 Hand Guidance & Virtual Fixture & Smooth Motion

Hand Guidance is to move the robot to correct initial position with human hand, more information for this could be found in [4]. Virtual fixture should be a familiar concept; for smooth motion, it could also be defined as adding constraints to the robot, like maximum velocity, acceleration, etc.

The virtual fixture could be implemented with a number of different approaches. To limit the work space, we would like to accomplish this with RVIZ and MoveIt. Basically, we will have the robot in those simulation program imitating the behavior of the real robot. Then, we could add mesh files to illustrate obstacles or walls in the real world to the simulation. We would also implement a function to utilize our representation in the simulated world to determine if there is an obstacle in the path of a robot motion. Before trying to move the robot to any new position, the function would find out if the path is clean. The robot should only move when there is a clean path.

Another method of virtual fixture would be adding geometry constraints to the robot based on optimized constrained control. At this early stage, we are mostly considering about keeping the tip of the abdominal probe in a line. More specifically, when we do motion planning, we would move the probe from node to node. When the robot is executing the movement, we want its tip of the abdominal probe to stay in a line.[8]. From this paper, if we have a line $L(s) = \vec{L_0} + \hat{l} \cdot s$, where $\vec{L_0}$ is a point on the line and $\hat{l}$ is a unit vector indicating the direction, the system needs to correct the offset from the current position to the closest point on the line. To accomplish this goal, we first need a rotation matrix transforming the line to the world coordinate.

$$R = [\hat{v_1}\hat{v_2}\hat{l}],\ \hat{v_1} = \frac{\hat{l} \times \hat{l'}}{||\hat{l} \times \hat{l'}||},\ \hat{v_2} = \frac{\hat{v_1} \times \hat{l}}{||\hat{v_1} \times \hat{l}||} \tag{3}$$

where $\hat{l'}$ is a random unit vector not aligned with $\hat{l}$.

Then, if we approximate a cylinder around the line with radius $\vec{\epsilon_1}$ by a polygon with n vertices centered at origin, and we have:

$$[R][[c_{\alpha i}, s_{\alpha i}, 0]^t, 0, 0, 0] \cdot (\vec{\delta} + \Delta\vec{x}) \leq \vec{\epsilon_1}, i = 1, ..., n \tag{4}$$

Finally, we could set the H *and* h as follow. Again, more information could be found in [8]

$$H = \begin{bmatrix} -R_3[c_{\alpha i}, s_{\alpha i}, 0]^t, & 0, & 0, & 0 \\ & \dots & & \\ [R_3[c_{\alpha n}, s_{\alpha n}, 0]^t, & 0, & 0, & 0 \end{bmatrix}, \vec{h} = \begin{bmatrix} -\varepsilon_1 \\ -\varepsilon_1 \\ -\varepsilon_1 \end{bmatrix} - H\vec{\delta}$$

The idea of virtual fixture could be visualized in Figure 4 below. We would limit the workspace by virtual walls, as well as moving the tip of the abdominal probe in a line. (green dashed line in Figure)

The constraints are mainly three types in our plan: force, velocity, and acceleration, but before any constraints, we need to know the value for those properties at any time. The force part would come from the force measured from sensor. The acceleration part is also quite straightforward: the derivative of the velocity. The velocity part is calculated in section 4.1.

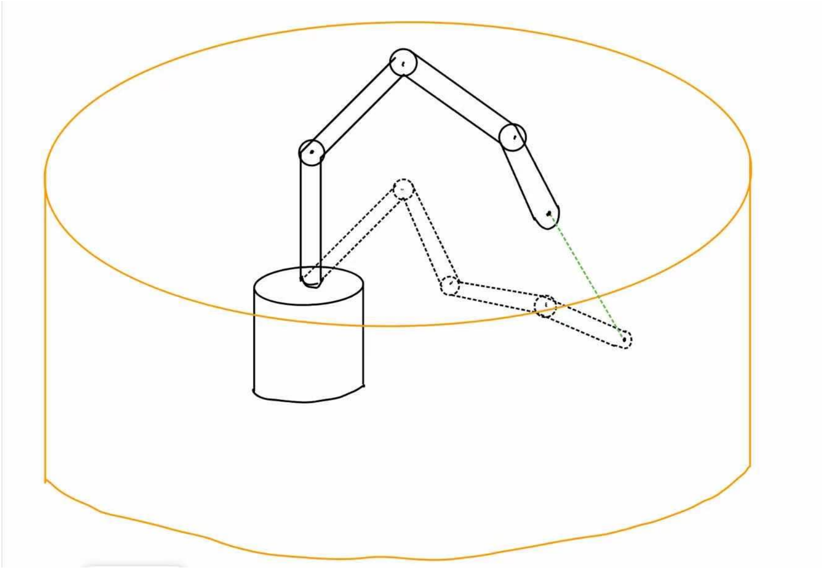

Figure 4: Virtual Fixture Visualization

After having those values, we could add constraints on them. For instance, we could limit the maximum acceleration; we could also set the speed inversely proportional to the distance from the abdominal probe to the phantom. Also, the translation part of the $U_{TA} \in SE3$ is not a constant value in expected, we need to calculate the speed and the location of the abdominal probe at any time considering the force, velocity and acceleration contacted with the phantom.

4.3 Automatic Image Acquisition System

The goal for the maximum part is to have an automatic image acquisition system. We would first use our dual robotic motion planning program to help validate an ultrasound image reconstruction algorithm from our mentor Yixuan. Then, we need to combine our program with the reconstruction algorithm to perform a demo on realistic phantoms to show the automaticity and safety of the framework. The phantom could be found here [7].

To do the virtual fixture of the TRUS probe, we would need to find out is the probe at correct orientation based on the image it obtain. We could apply computer vision techniques to resolve the information and correct the position of the TRUS probe.

5 Key Dates

Check Points	Dates	Status	Responsibility
Literature Review	02/10 - 02/17	Done	All
Familiar with CISST/SAW libraries and UR5 robot	02/16 - 02/23	In progress	All
Install Ubuntu 16.04 and ROS1 on lab laptop	02/16 - 02/17	Done	Yunpu
Understand Previous Code	02/16 - 03/09	In progress	All
Read Virtual Fixture and Path Planning literature	03/09-04/09	Waiting	All
Dual Robot installation	02/25 - 03/02	Waiting	All
UR5 Calibrations (end-effector to ultrasound probe)	03/03 - 03/17	Waiting	All (Mainly by Ziyi and Zhenghao)
Base-to-Base Calibration	03/17 - 03/27	Waiting	All (Mainly by Yunpu)
Real Time Motion Planning for Dual Arms	03/27 - 04/05	Waiting	All (Mainly by Ziyi and Yunpu)
Virtual Fixture	04/05 - 04/30	Waiting	All (Mainly by Yunpu and Ziyi)
Enhanced motion control and path planning	04/05 - 04/30	Waiting	All (Mainly by Zhenghao)
Maximum real time demo(If possible)	05/01 - 05/08	Waiting	All

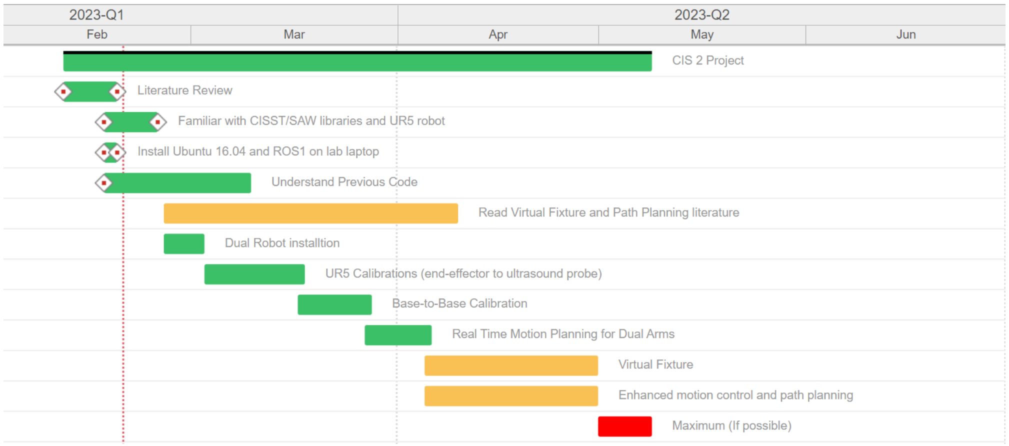

Figure 5: Timeline

Backup Plan:

1. If the other UR5 arrives later than the estimated date, then ”Dual Robot Installation” needs to be delayed and our group will perform end-effector to US probe Calibration and may start implementing Virtual Fixture Simulation towards one robot arm.
2. If can’t get the second force sensor, considering using only one sensor with Kalman Filtering.

6 List of Dependencies & Plan for Resolving

Type	Dependencies	Sources	Responsibility	Deadline	Status
General	Gain access to Emad lab pod.	Ashley	Zhenghao	2/13	Done
	Obtain previous code of Kevin.	Yixuan	Ziyi	2/16	Done
	Install ROS1 and Ubuntu 16.	Online website	Yunpu	2/23	In progress
	Install RVIZ and Moveit.	Online website	Yunpu	2/25	In progress
	Access to the CISST/SAW and cv2 libraries.	Anton Deguet and online website	Yunpu	2/24	In progress
Important	Abdominal and endoluminal ultrasound probes	Yixuan	Zhenghao	2/16	Done
	Realistic pelvic phantom	Yixuan	Ziyi	2/16	Done
	Exchange old laptop in the lab pod. (Also need a monitor)	Zhenghao	Zhenghao	2/27	Waiting
	Borrow another UR5 Robot	Dr.Taylor	Zhenghao	N/A	In progress
	Calibration marker (cross fishing wire)	Yixuan	Yunpu	3/01	Waiting
	First Force sensor test and remounting	Yixuan	Ziyi	3/05	Waiting
	Second Force sensor 3D printing and test	Yixuan	Ziyi	3/10	Waiting
	Yixuan’s reconstruction method	Yixuan	Yixuan	4/20	Waiting

7 Management Plan

- Documentation
  - Overleaf (latex)
  - Google Drive
  - Github Wiki (Markdown)
  - Course Website
- Communication
  - Meeting Time:Weekly meeting with mentors Yixuan Wu and Mohammad Salehizadeh at Wednesday 1:30 pm.
  - Two meetings per week by Students at Friday and Monday.
  - Communications Tools: e-mail, phone
- Interfaces

  - Each and every accomplishing of milestones and check points will be approved first by student meeting, then by mentor's meeting.
  - All the coding which requires combination and collaboration in the future will be written in a shared Github repository and be viewed on a weekly basis on student meeting to ensure project interfaces.

8 Reading List

1. ROBOTIC ULTRASOUND TOMOGRAPHY AND COLLABORATIVE CONTROL [4]
2. Dual-Robotic Ultrasound System for In Vivo Prostate Tomography [3]
3. Phantom with multiple active points for ultrasound calibration [9]
4. Global cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. [2]
5. Closed-form solution of absolute orientation using orthonormal matrices.[5]
6. Co-robotic ultrasound tomography: a new paradigm for quantitative ultrasound imaging.[1]
7. Correlation of ultrasound tomography to MRI and pathology for the detection of prostate cancer [6]

References

[1] F. Aalamifar. Co-robotic ultrasound tomography: a new paradigm for quantitative ultrasound imaging. *Ph.D. thesis, Johns Hopkins University*, October 2016.

[2] F. Bray, J. Ferlay, I. Soerjomataram, R.L. Siegel, L.A. Torre, and A. Jemal. Global cancer statistics 2018: Globocan estimates of incidence and mortality worldwide for 36 cancers in 185 countries. 68(6):394–424, 2018.

[3] Kevin M. Gilboy, Yixuan Wu, Bradford J. Wood, Emad M. Boctor, and Russell H. Taylor. *Dual-Robotic Ultrasound System for In Vivo Prostate Tomography*. The Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218 USA, 2020. URL: https://link.springer.com/chapter/10.1007/978-3-030-60334-2_16.

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[8] Weiqi Wang Ting-Yun Fang. *Co-Robotic Ultrasound Imaging System*. The Johns Hopkins University, 3400 North Charles Street, Baltimore, Maryland 21218 USA, 2017. URL: https://drive.google.com/file/d/16PvOlSm7f2qzwKBoGVO7q6Qlb2Tdtrwy/view?usp=sharing.

[9] Haichong K. Zhang, Alexis Cheng, Younsu Kim, Qianli Ma, Gregory S. Chirikjian, and Emad M. Boctor. Phantom with multiple active points for ultrasound calibration. *J. Med. Imag. 5(4), 045001 (2018), doi: 10.1117/1.JMI.5.4.045001.*, 2022b. URL: https://pubmed.ncbi.nlm.nih.gov/30525061/.