

# Dual-robotic Arm Prostate Ultrasound Tomography

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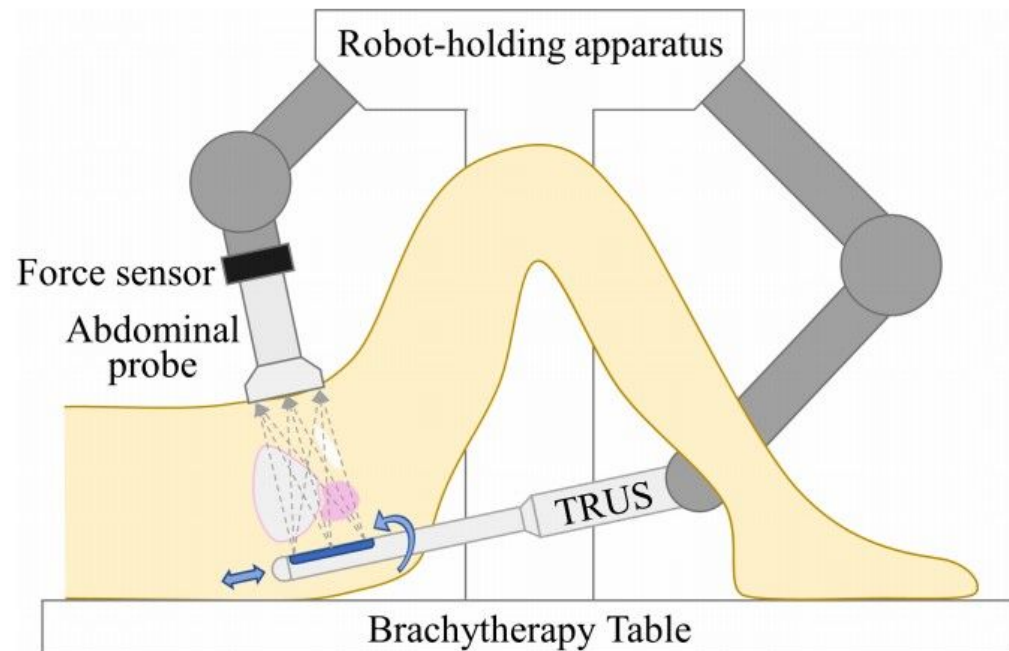


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## A dual robotic system with aligned abdominal and TRUS probes for prostate cancer detection



We need to do:

1. Determine each transformation of dual-robot arm using calibration.
2. Motion planning for the robotic arm.
3. Add constraints by applying the virtual fixture.
4. Implement a real-time demo.

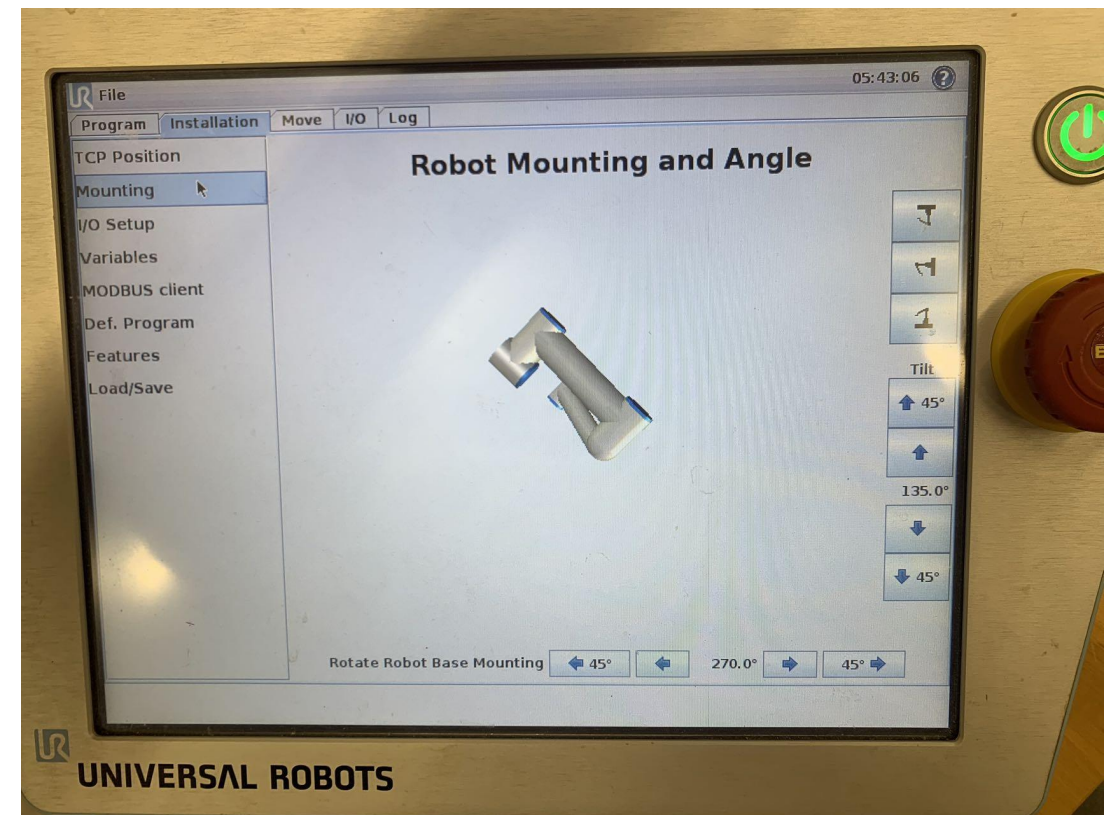
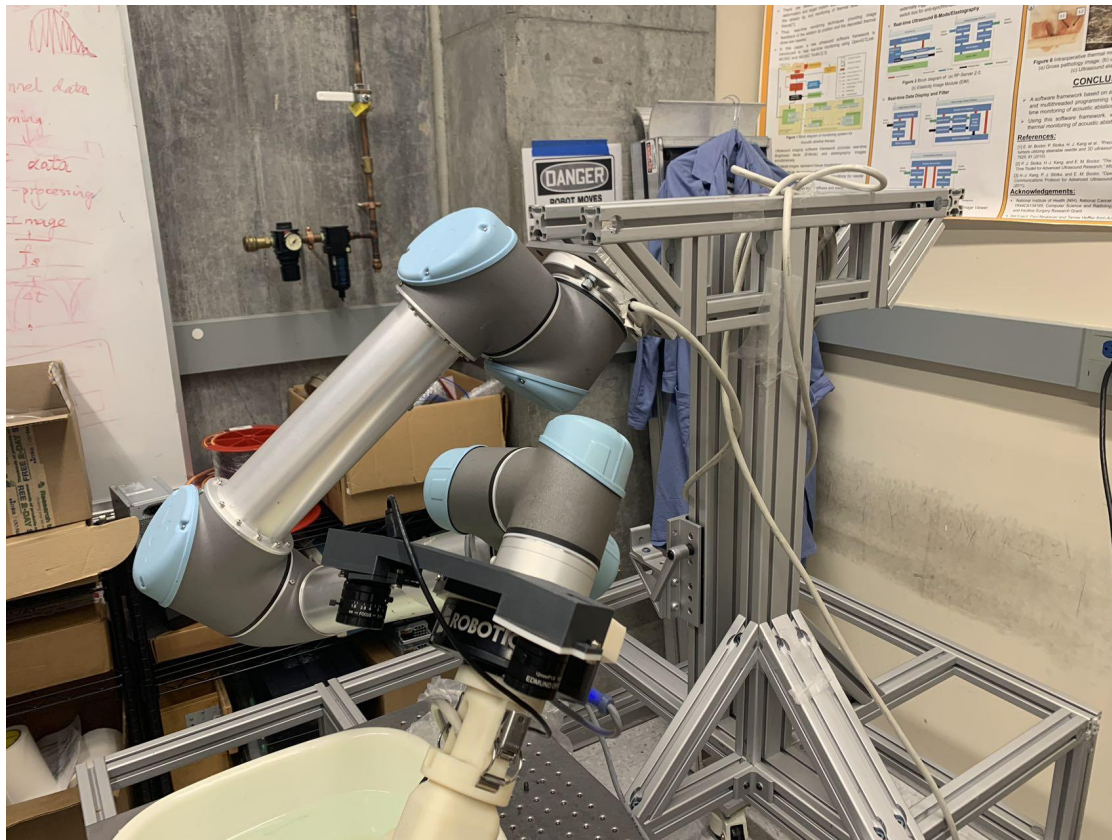
# DEPENDENCIES

Type	Dependencies	Sources	Responsibility	Deadline	Status
General	Gain access to Emad lab pod.	Ashley	Zhenghao	2/13	Done
	Access to the cv2 and CISST/SAW libraries.	online/Anton Deguet	Yunpu	2/25	Done
	Obtain previous code of Kevin.	Yixuan	Ziyi	2/16	Done
	Install ROS1 and Ubuntu 16, RVIZ, and Moveit.	Online website	Yunpu	2/27	Done
Important	Realistic pelvic phantom	Yixuan	Ziyi	2/16	Done
	abdominal and endoluminal ultrasound probes	Yixuan	Zhenghao	2/16	Done
	Exchange old laptop in the lab pod. (Also need a monitor)	Zhenghao	Zhenghao	2/27	Done
	Buy another UR5 Robot	Dr. Taylor	Zhenghao	N/A	Ordered
	Hand control Force sensor test and remounting	Yixuan	Ziyi	N/A	In progress
	Second Force sensor fixture 3D printing and test	Yixuan/ Robotiq FT 300-S FORCE TORQUE SENSOR	Zhenghao	3/10	Done
	Calibration marker (cross fishing wire)	Yixuan	Yunpu	3/10	Done
	Yixuan's reconstruction method	Yixuan	Yixuan	4/20	Waiting

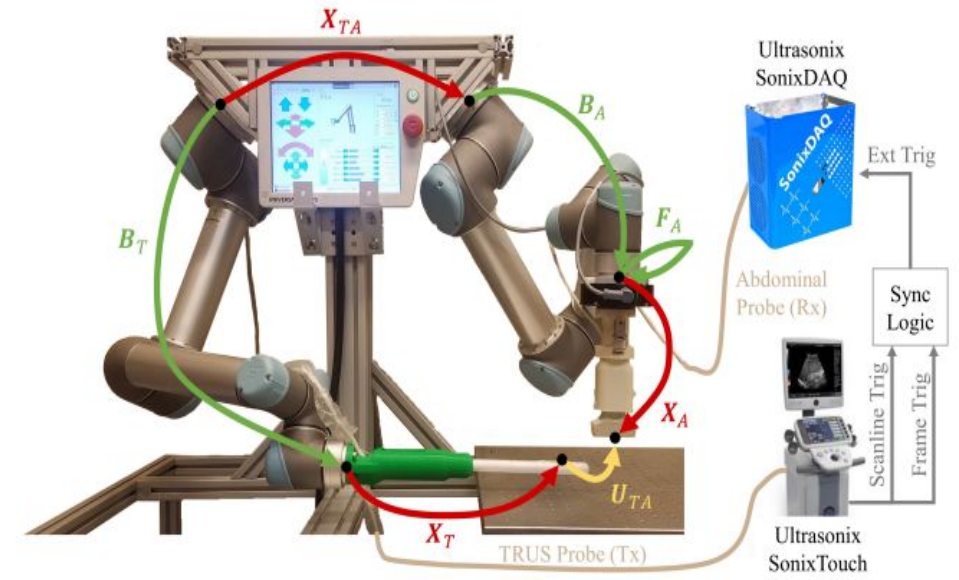
Activity	Current Result	Status
A demonstration of proper dual-robotic setup and equipment connectivity.	Mounting is finished, and required parameters is documented.	Done
Robot base-to-base registration and end-effector-to-ultrasound calibration.	Abdominal probe calibration is done, using a new method. Trus probe In Progress.	In Progress due to dependency
Real-time motion planning of dual arms for ultrasound image acquisition where two ultrasound transducers are automatically aligned.	Simulation in Man-made Test Cases	To Be Tested on a Real System

# Mounting of the Robot

- Mounting parameters: 135 degree, 315 degree/ 270 degree, Payload:3kg

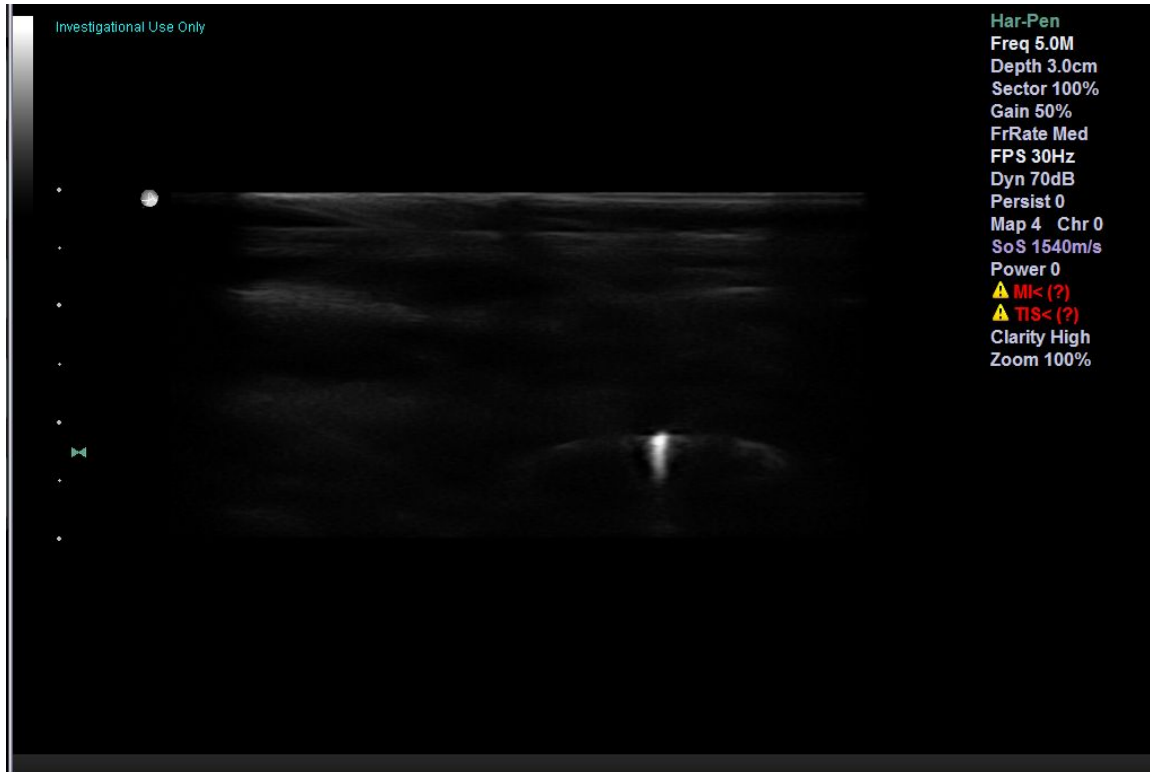


# BXP Calibration



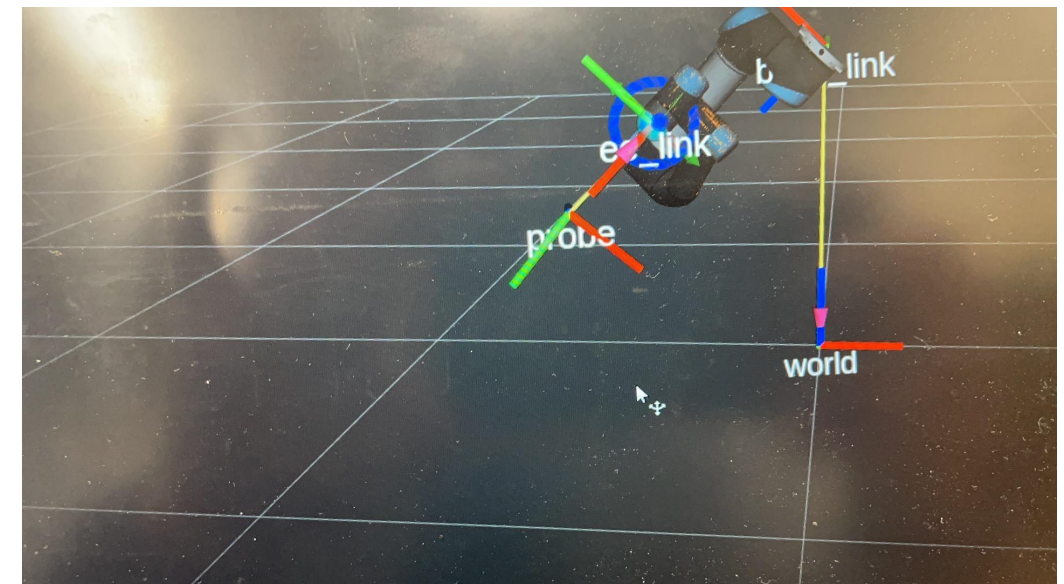
[4]Gilboy, Kevin M., et al. Dual-Robotic Ultrasound System for In Vivo Prostate Tomography. 2020

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



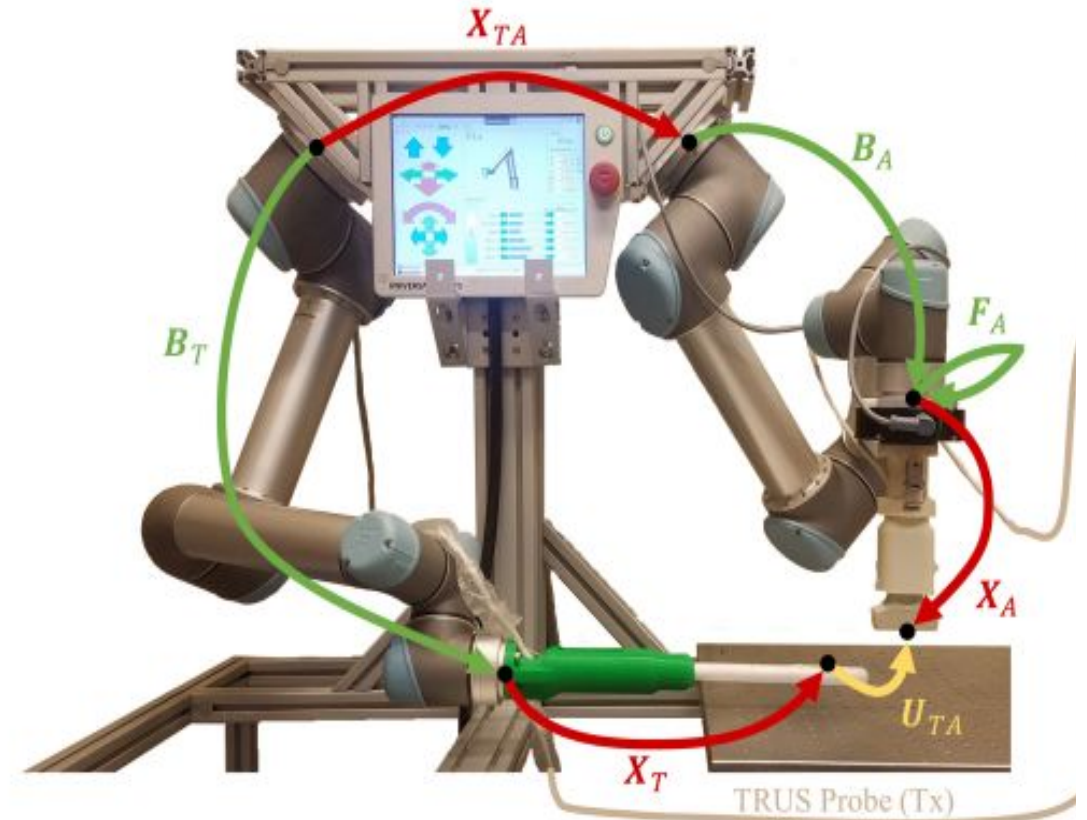
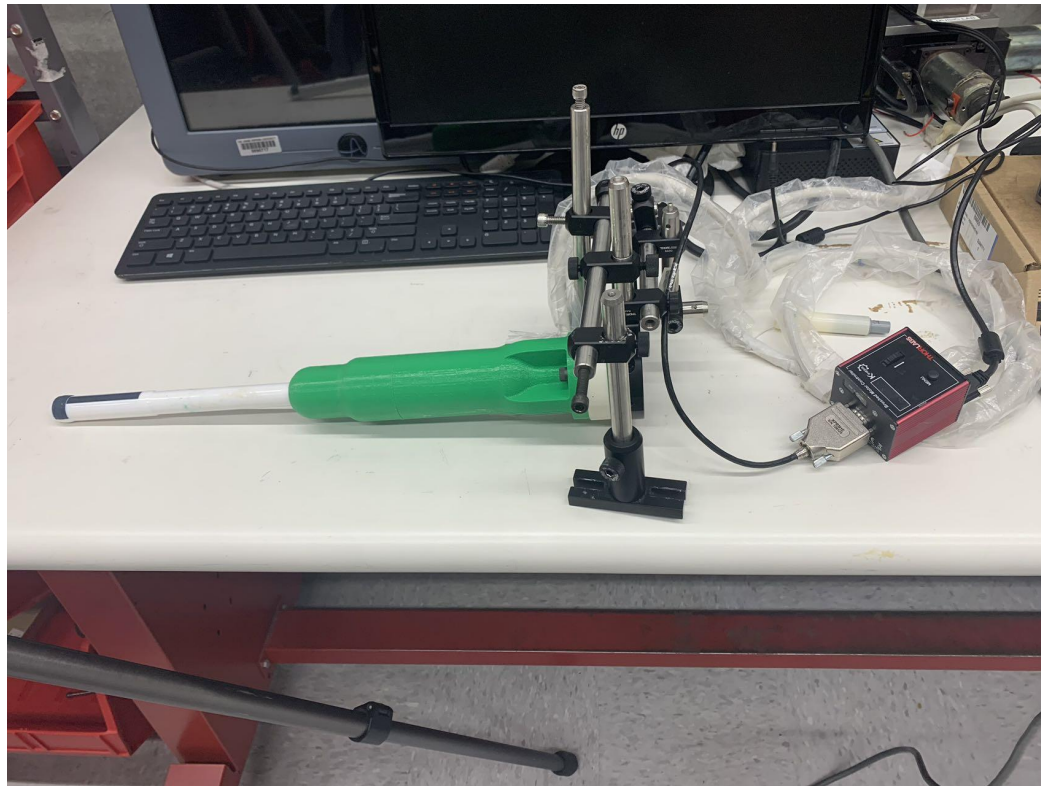
## RF data method

```
X=[-0.0428 -0.0756 -0.9963 -258.3383  
0.7164 0.6927 -0.0833 -30.4444;  
0.6964 -0.7173 0.0246 10.3143;  
0 0 0 1.0000]
```

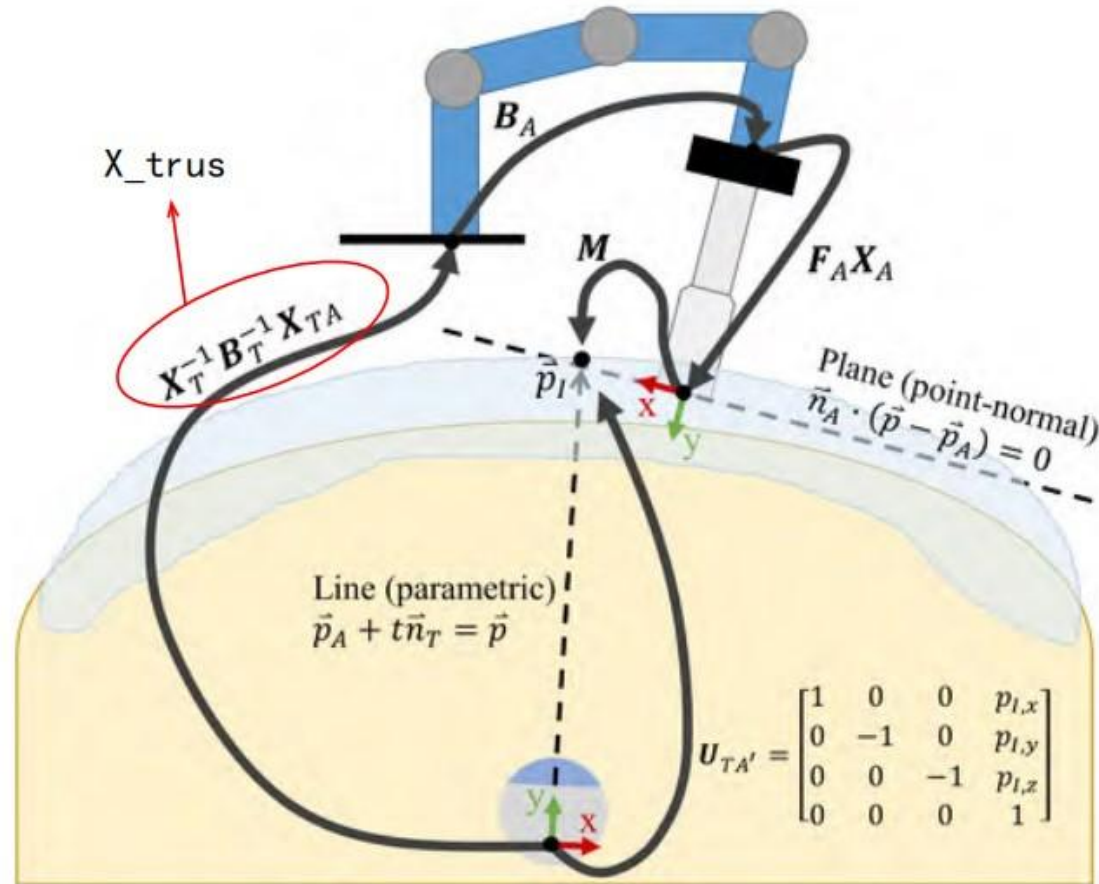


# Trus probe Calibration

May need to design a new phantom



[4]Gilboy, Kevin M., et al. Dual-Robotic Ultrasound System for In Vivo Prostate Tomography. 2020



In order to achieve alignment of the dual-robotic arms, we need to do the motion planning.

The abdominal probe will follow the rotation of the TRUS probe, so we need to determine the position and the direction of  $P_I$  ( $P_{goal}$ ).

## Calculation Approach:

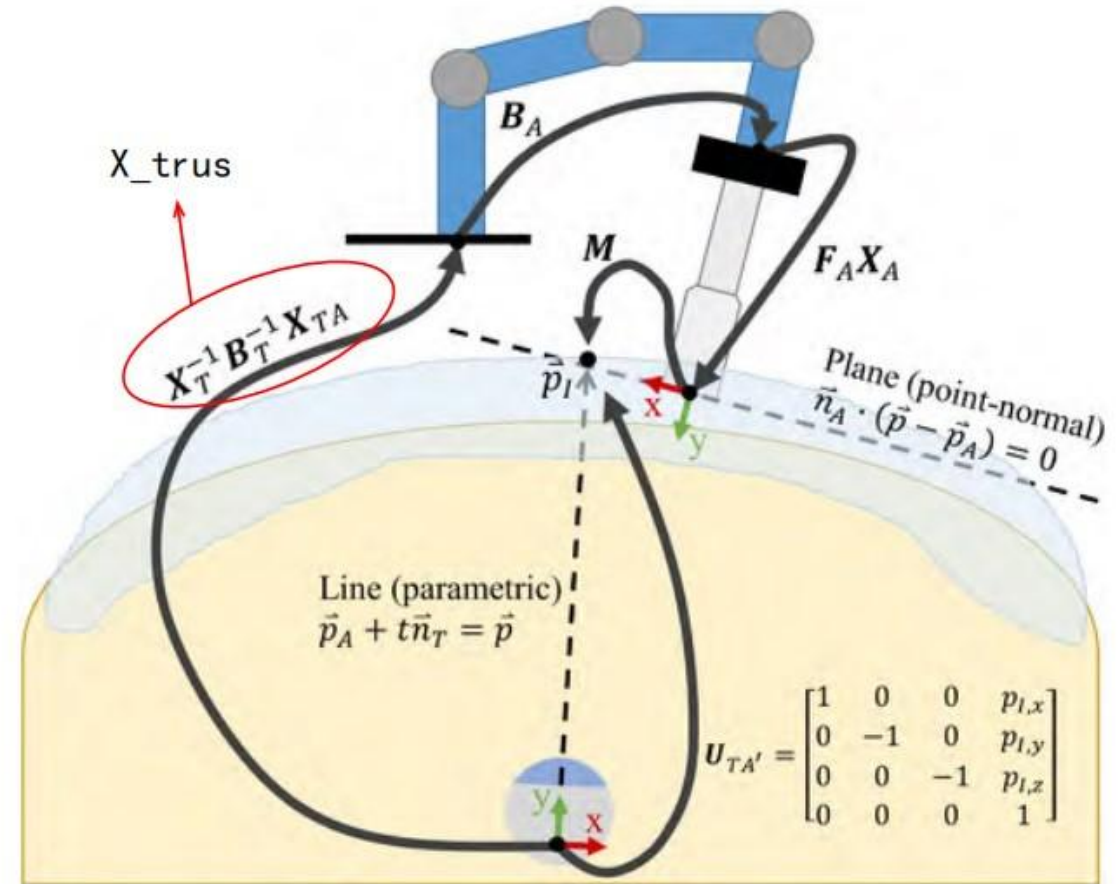
$$\vec{p}_A = \text{translation}(X_{trus}^{-1} B_A F_A X_A)$$

$$\vec{n}_A = \text{rotation}(X_{trus}^{-1} B_A F_A X_A) * \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

$$\vec{p}_T = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad \vec{n}_T = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

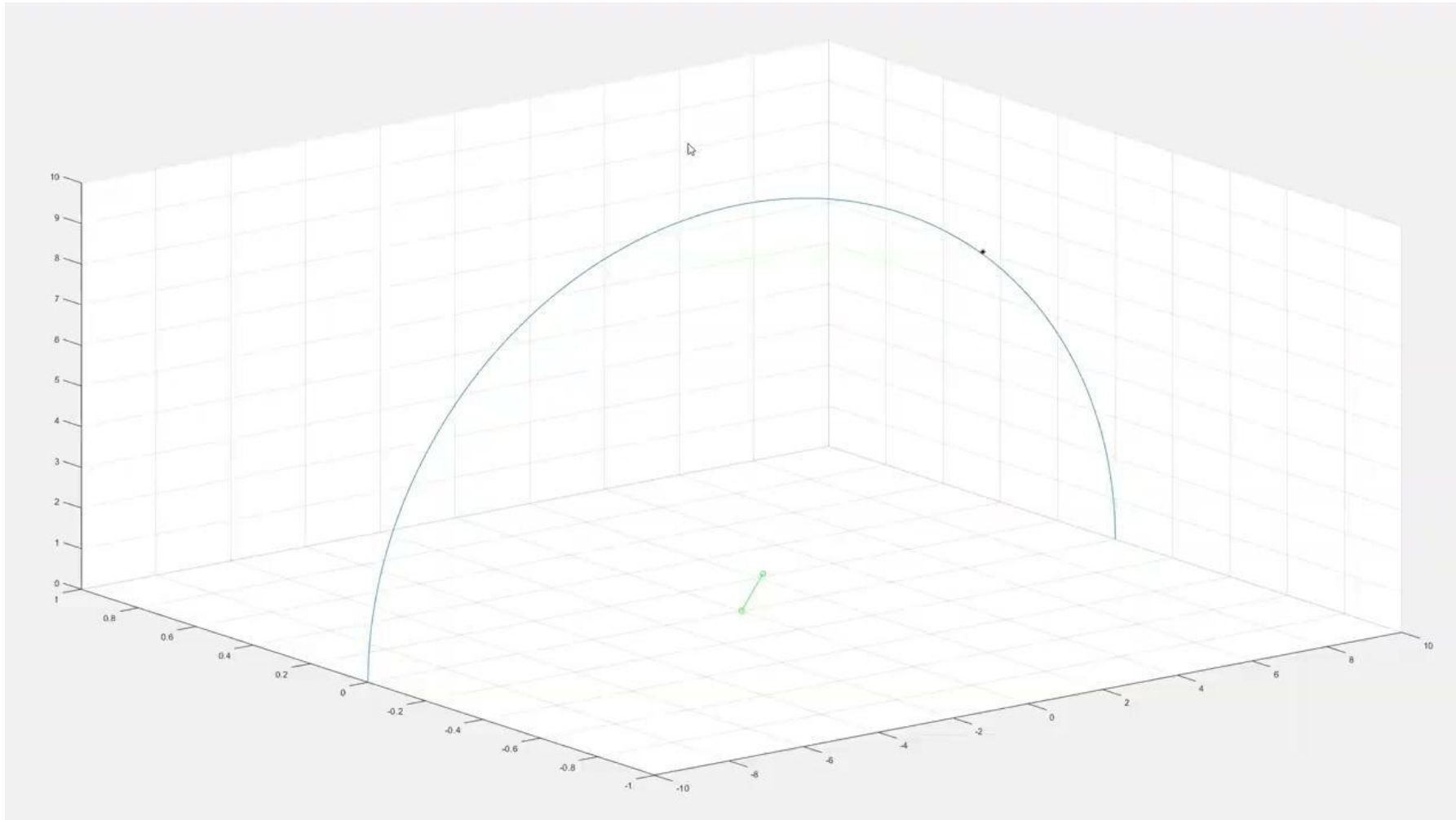
$$t = \frac{\vec{n}_A \cdot \vec{p}_A - \vec{n}_A \cdot \vec{p}_T}{\vec{n}_A \cdot \vec{n}_T}$$

$$\vec{p}_I = \begin{bmatrix} x_I \\ y_I \\ z_I \end{bmatrix} = \begin{bmatrix} \vec{p}_T + t \odot \vec{n}_T \end{bmatrix}$$



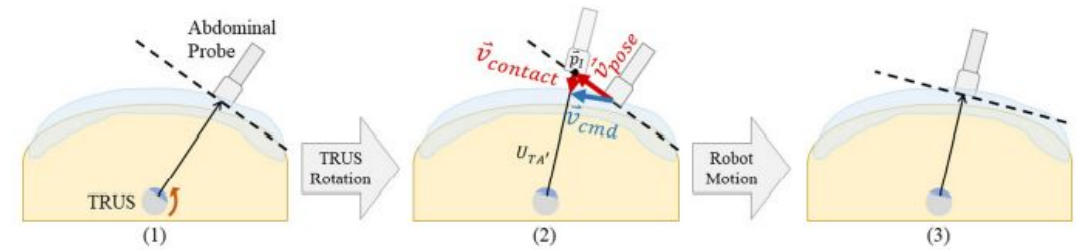
Gilboy, Kevin Michael. ROBOTIC ULTRASOUND TOMOGRAPHY AND COLLABORATIVE CONTROL. 2020, [https://drive.google.com/file/d/19cGn\\_ZnCLbUESI9dta3l0s9lQdg-DwQl/view?usp=sharing](https://drive.google.com/file/d/19cGn_ZnCLbUESI9dta3l0s9lQdg-DwQl/view?usp=sharing).

## Matlab Simulation



Activity	Current Result	Status
Hand Guide the robot arm to steer the abdominal probe to the correct initial position	Due to the lack of the force sensor, with the approval of mentor, this one was temporarily dropped	Removed
Integration of virtual fixture to limit robot arms' workspace to ensure the safety for in vivo imaging (for Abdominal probe)	Code works in Man-made Test Cases	To Be Tested on a Real System
Enhanced path planning to achieve smoother and steadier motion.	Code works in Man-made Test Cases	To Be Tested on a Real System

- Given Goal Point and Orientation



- Move to Goal Point while Maintaining the Orientation

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](https://link.springer.com/chapter/10.1007/978-3-030-60334-2_16)

## Definition

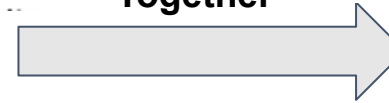
$$\begin{aligned} \arg \min_{\Delta \vec{q}/\Delta t} & \|W(\Delta \vec{x}/\Delta t - \Delta \vec{x}_d/\Delta t)\|, \\ \text{s.t.} & \quad H\Delta \vec{x}/\Delta t \geq \vec{h}, \\ & \quad \Delta \vec{x}/\Delta t = J\Delta \vec{q}/\Delta t \end{aligned}$$

Variable	Definition
$W$	Weight Matrix
$H, h$	Constraint Matrix
$J$	Manipulator Jacobian
$\Delta x, \Delta xd$	Actual and Desired Change of a 6 by 1 Position Vector in Cartesian Space
$\Delta q$	Change of the 6 Joints Value on a UR5 (6 × 1 Vector) in Configuration Space

- Two Components
  - Stay at a Point

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

Together



$$\operatorname{argmin}_{\Delta \vec{q}} \|W \cdot (J(\vec{q}) \cdot \Delta \vec{q} - \Delta x_d)\|$$

or

$$\operatorname{argmin}_{\Delta \vec{q}} \|W \cdot (J(\vec{q}) \cdot \Delta \vec{q} - \Delta x_d - F)\|$$

- Maintain a Direction

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

$$\text{s.t.} \quad \begin{bmatrix} H_P \\ H_D \end{bmatrix} \cdot J(\vec{q}) \cdot \Delta \vec{q} \geq \begin{bmatrix} \vec{h}_p \\ \vec{h}_d \end{bmatrix}$$

Ming Li, A. Kapoor, and R.H. Taylor. A constrained optimization approach to virtual fixtures. In 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 1408–1413, 2005. doi:10.1109/IROS.2005.1545420

# VIRTUAL FIXTURE



Activity	Current Result	Status
A real-time demo on a speed of sound phantom in preparation for the validation of ultrasound tomography reconstruction methods.	None	Not Started
A real-time demo on a realistic pelvis phantom to show the automaticity and safety of the framework	None	Not Started
Integration of virtual fixture for the TRUS probe	None	Not Started (Needs Discussion about feasibility)

- [1]Gilboy, Kevin Michael. ROBOTIC ULTRASOUND TOMOGRAPHY AND COLLABORATIVE CONTROL. 2020, [https://drive.google.com/file/d/19cGn\\_ZnCLbUESI9dta3l0s91Qdg-DwQl/view?usp=sharing](https://drive.google.com/file/d/19cGn_ZnCLbUESI9dta3l0s91Qdg-DwQl/view?usp=sharing).
- [2]Ting-Yun Fang, Weiqi Wang. Co-Robotic Ultrasound Imaging System. 2017, <https://drive.google.com/file/d/16PvOISm7f2qzwKBoGVO7q6Qlb2Tdrwy/view?usp=sharing>.
- [3]Zerdine, Z.-Skin. Multi-Modality Pelvic Phantom. <https://www.cirsinc.com/wp-content/uploads/2019/04/048A-DS-120418.pdf>.
- [4]Gilboy, Kevin M., et al. Dual-Robotic Ultrasound System for In Vivo Prostate Tomography. 2020, [https://link.springer.com/chapter/10.1007/978-3-030-60334-2\\_16](https://link.springer.com/chapter/10.1007/978-3-030-60334-2_16).
- [5]Zhang, Haichong K., et al. 'Phantom with Multiple Active Points for Ultrasound Calibration'. J. Med. Imag. 5(4), 045001 (2018), Doi: 10.1117/1.JMI.5.4.045001., 2022b, <https://pubmed.ncbi.nlm.nih.gov/30525061/>.
- [6]Bray, F., et al. Global Cancer Statistics 2018: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. Vol. 68(6), 2018, pp. 394–424.
- [7]Horn, Berthold K. P., et al. 'Closed-Form Solution of Absolute Orientation Using Orthonormal Matrices'. Journal of The Optical Society of America A-Optics Image Science and Vision, vol. 5, 1988, pp. 1127–1135.
- [8]Seifabadi, R. 'Correlation of Ultrasound Tomography to MRI and Pathology for the Detection of Prostate Cancer'. Medical Imaging 2019: Ultrasonic Imaging and Tomography International Society for Optics and Photonics, vol. 10955, 2019, p. 109550C.
- [9]Aalamifar, F. 'Co-Robotic Ultrasound Tomography: A New Paradigm for Quantitative Ultrasound Imaging'. Ph. D. Thesis, Johns Hopkins University, Oct. 2016.

**Thank you**



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