Seminar Presentation:

A Cooperatively Controlled Robot for Ultrasound Monitoring of Radiation Therapy

Cooperative Control with Ultrasound Guidance for Radiation Therapy

Presented by group7: Co-robotic Ultrasound imaging system
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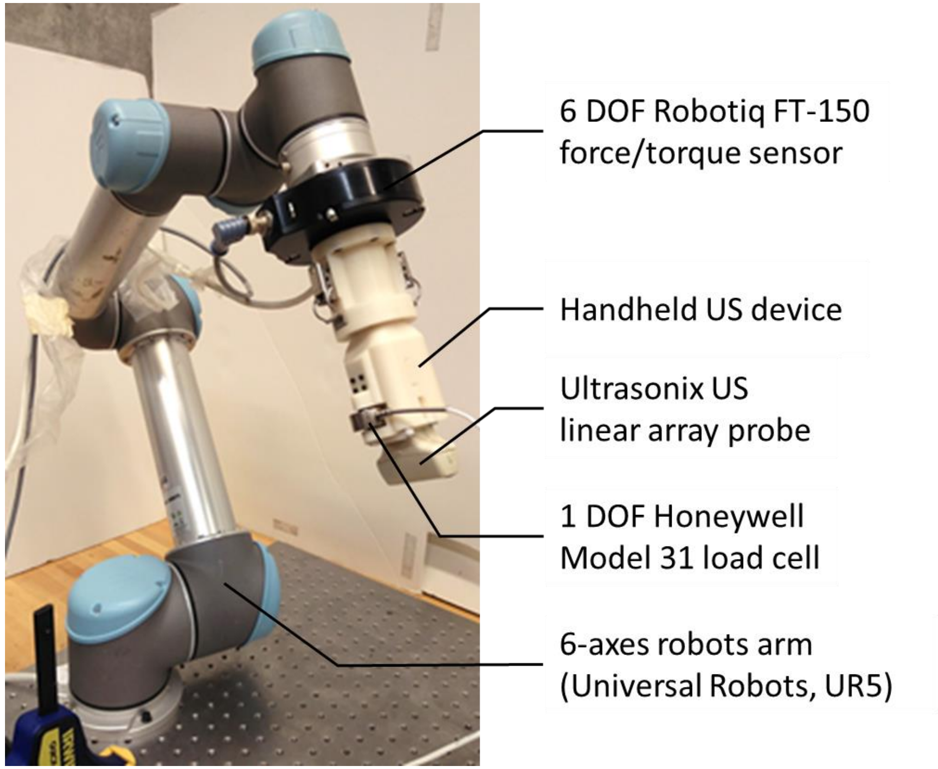
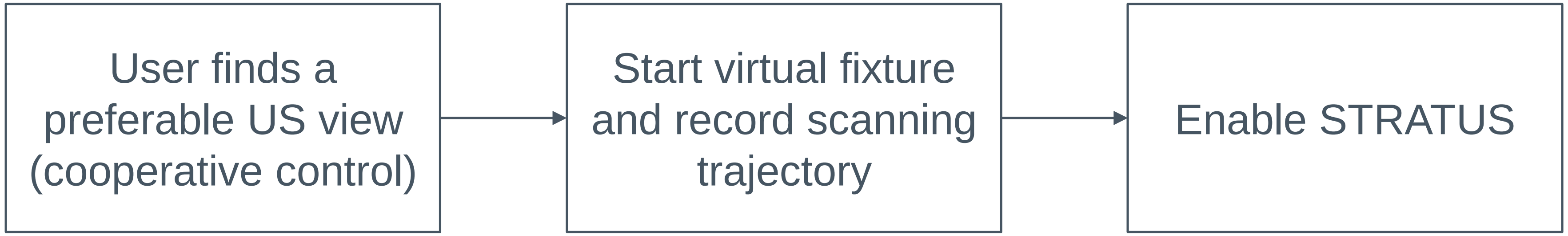
Project Summary

- Integrate the power steering UR5 system with synthetic tracked aperture ultrasound (STRATUS) imaging algorithm
- Validate STRATUS in multiple direction through phantom study and in vivo study
- Extend the existing system to a higher dexterity



Project Summary



- Virtual fixtures:
  - – stay on line (both lateral and elevation)
  - – stay on plane + rotation
  - – follow a trajectory
- Virtual fixtures enable STRATUS and can make the procedure repeatable

Paper Abstract

- Paper 1: A Cooperatively Controlled Robot for Ultrasound Monitoring of Radiation Therapy
- Paper 2: Cooperative Control with Ultrasound Guidance for Radiation Therapy

- Goal: reproduce the ultrasound guidance that is consistence with the treatment plan

- Method: using a co-manipulation strategy that uses static VFs (paper 1) or incorporates real-time US imaging in the control loop to update the VFs (paper 2)

Background

› Radiation therapy: CT scan for treatment planning → delivery of treatment according to the plan

› Ultrasound (US) can be used to both assist with patient setup and to provide real-time monitoring of soft-tissue targets.

› Challenges:

1) the ultrasound probe contact pressure can introduce inconsistence deformation to the target area
2) radiation therapists typically do not have ultrasound experience

Material and Method

(1) Unconstrained
(2) Static VFs
(3) Dynamic VFs

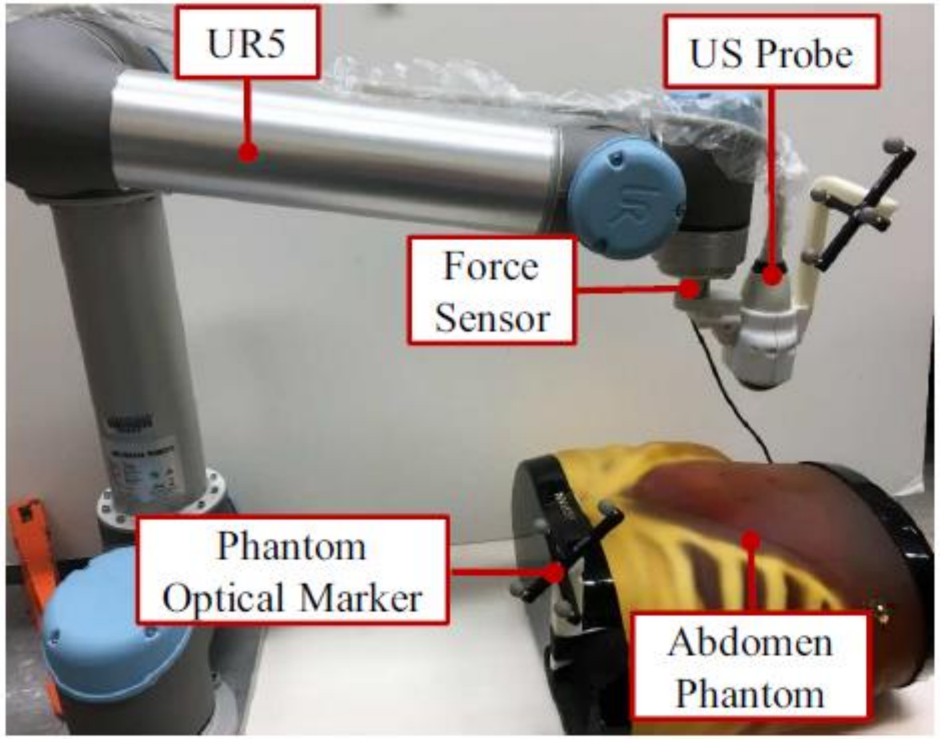


FIGURE 1 | Robot system and experimental setup.

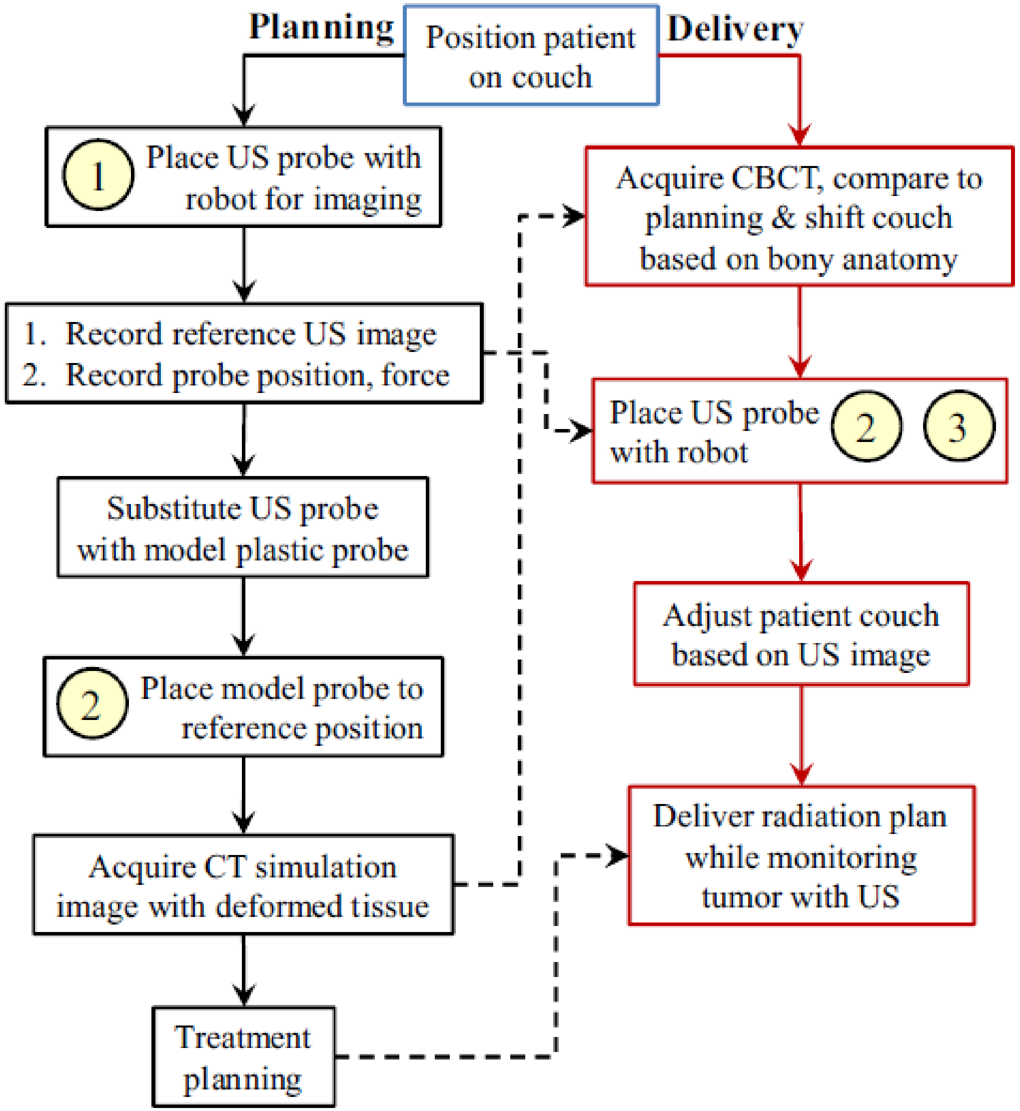


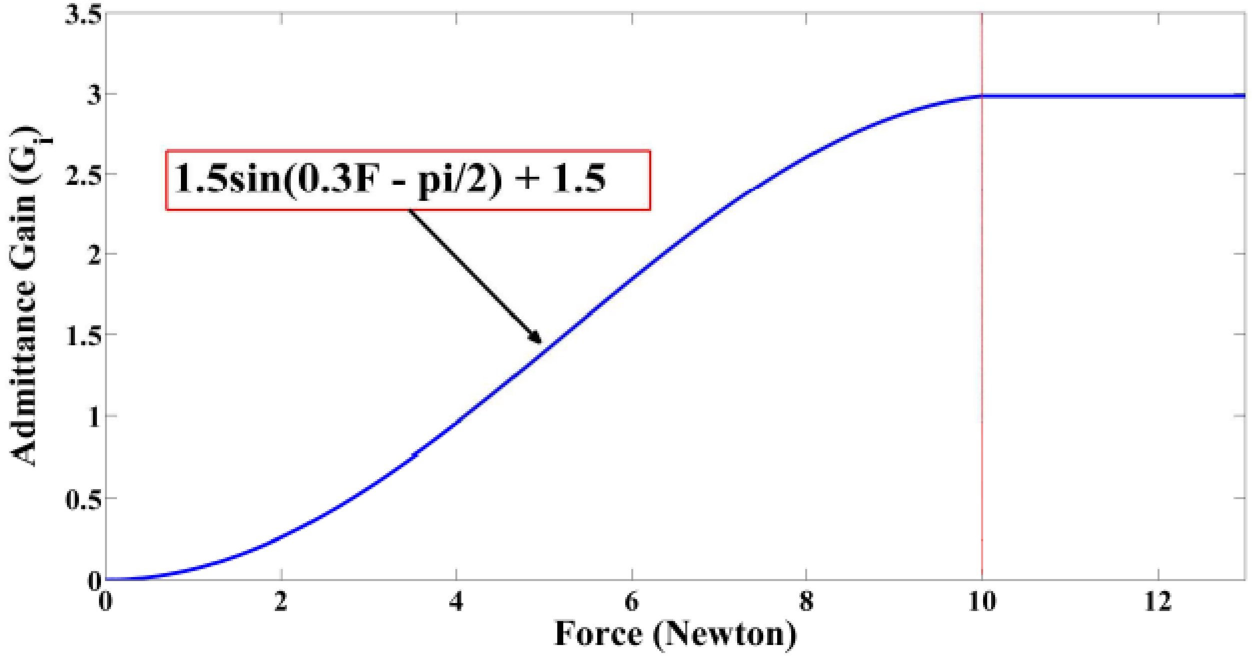
FIGURE 2 | Proposed robotic-assisted ultrasound-guided IGRT workflow, showing use of (1) unconstrained cooperative control, (2) static virtual fixtures, and (3) dynamic virtual fixtures. Box (1) is performed by expert sonographers, and boxes (2) and (3) are performed by therapists. The dashed arrows represent data transferred from the planning day to the delivery day.

Admittance Control

$$\begin{bmatrix} \vec{v}_F \\ \vec{w}_F \end{bmatrix} = \begin{bmatrix} G_1 & 0 & \cdots & 0 \\ 0 & G_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & G_6 \end{bmatrix} \cdot \begin{bmatrix} \vec{f}_F \\ \vec{\tau}_F \end{bmatrix}$$

$$\begin{bmatrix} \vec{v}_R \\ \vec{w}_R \end{bmatrix} = \begin{bmatrix} R_R^{Pr} \cdot R_{Pr}^{F} & 0_{3\times 3} \\ 0_{3\times 3} & R_R^{Pr} \cdot R_{Pr}^{F} \end{bmatrix} \cdot \begin{bmatrix} \vec{v}_F \\ \vec{w}_F \end{bmatrix}$$

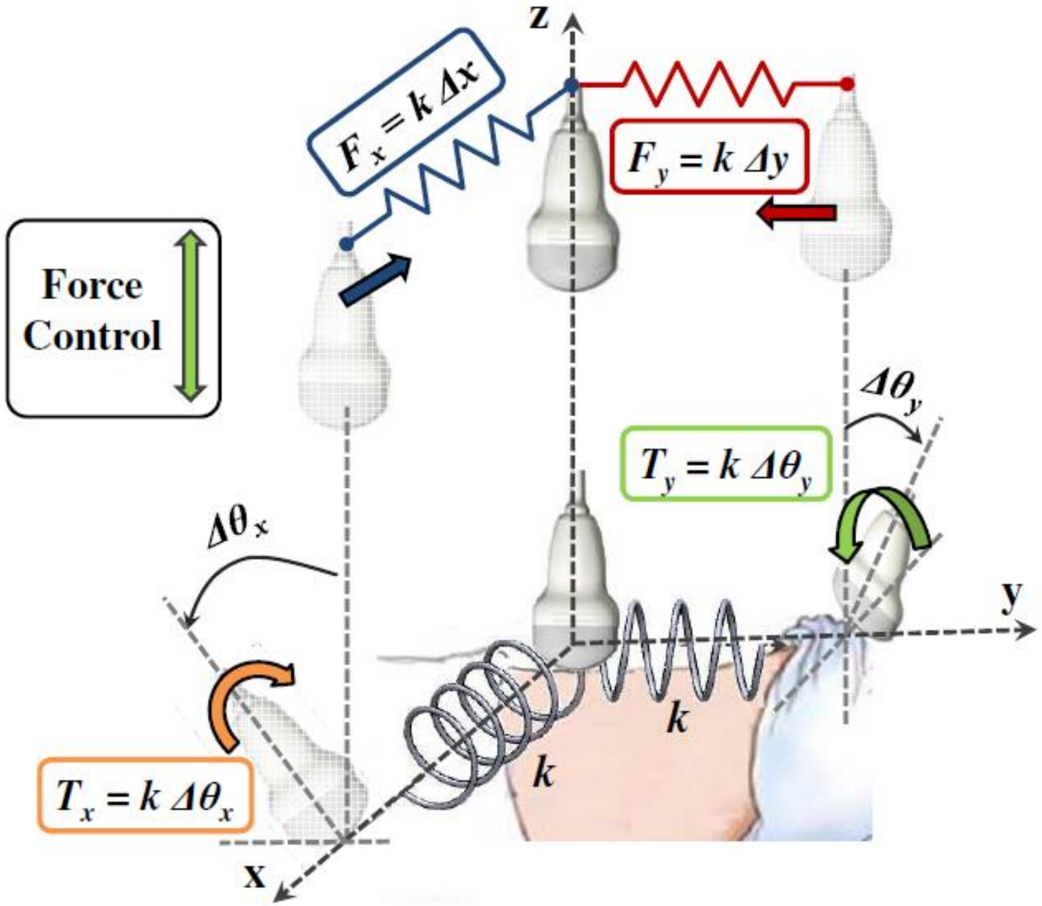
$$\dot{\vec{\theta}} = J^{-1}(\vec{\theta}) \cdot \begin{bmatrix} \vec{v}_R \\ \vec{w}_R \end{bmatrix}$$



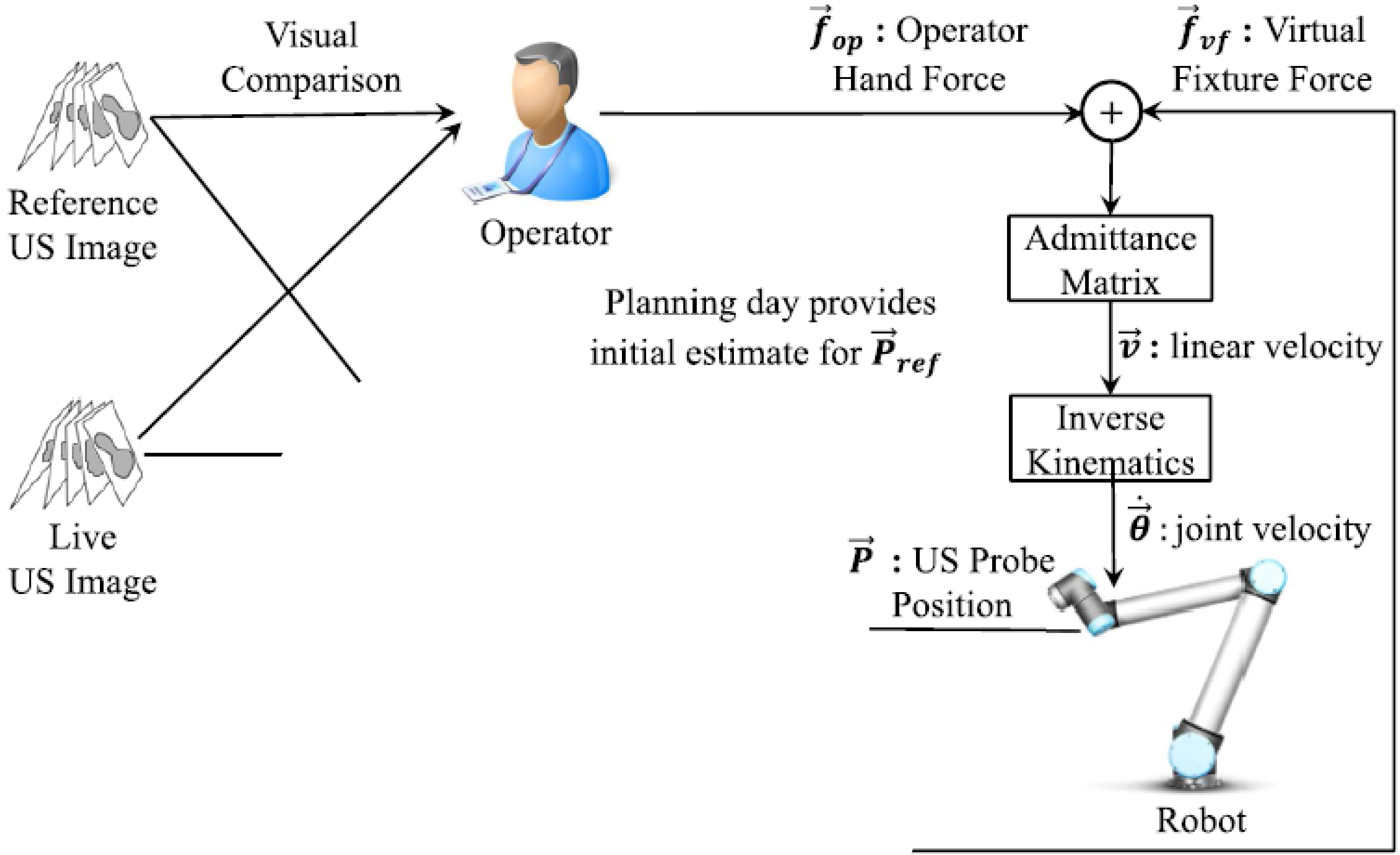
Virtual Fixture

$$\begin{bmatrix} \overrightarrow{f_{vf}} \\ \overrightarrow{\tau_{vf}} \end{bmatrix} = \begin{bmatrix} k_x & 0 & \cdots & 0 \\ 0 & k_y & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k_{\theta_z} \end{bmatrix} \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ 0 \\ \Delta\theta_x \\ \Delta\theta_y \\ \Delta\theta_z \end{bmatrix}$$

$$\begin{bmatrix} \overrightarrow{f_F} \\ \overrightarrow{\tau_F} \end{bmatrix} = \begin{bmatrix} \overrightarrow{f_{op}} \\ \overrightarrow{\tau_{op}} \end{bmatrix} + \begin{bmatrix} \overrightarrow{f_{vf}} \\ \overrightarrow{\tau_{vf}} \end{bmatrix}$$

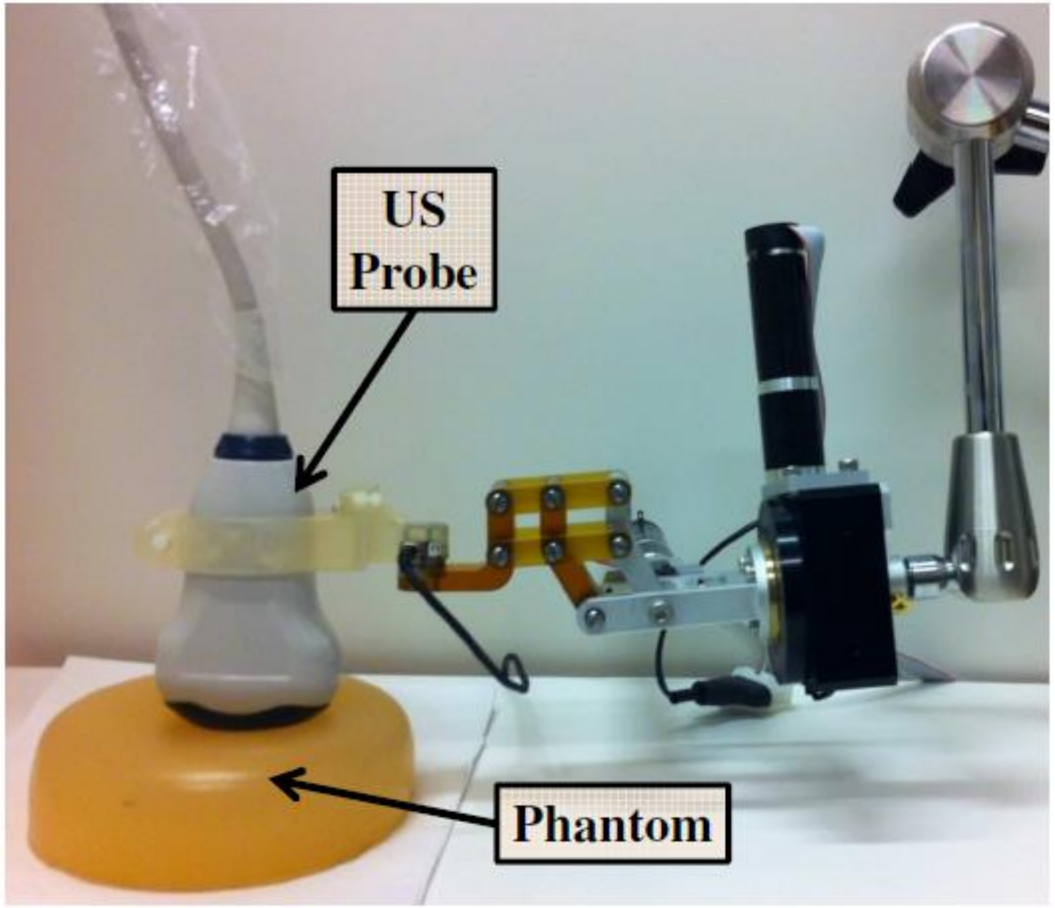


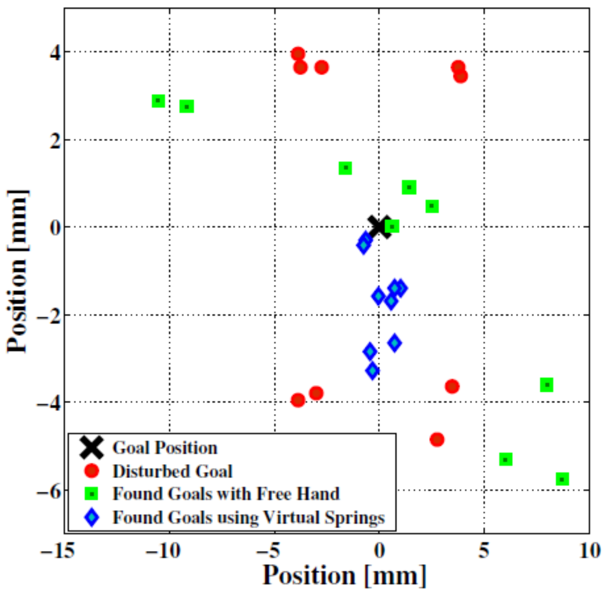
Static VFs

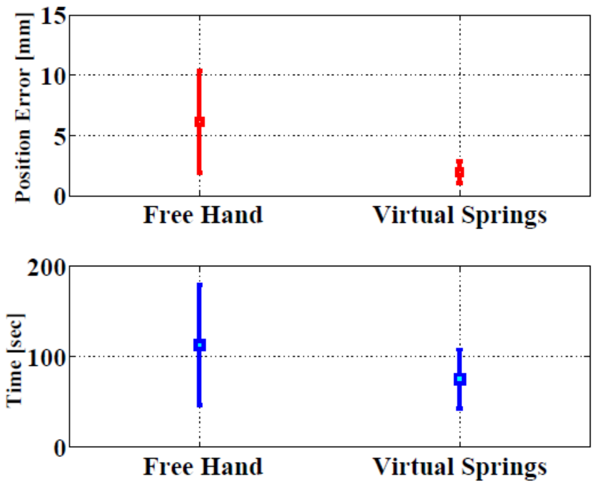


Visual Comparison
Reference US Image
Live US Image
Operator
$\vec{f}_{op}$: Operator Hand Force
$\vec{f}_{vf}$: Virtual Fixture Force
+
Admittance Matrix
$\vec{v}$: linear velocity
Inverse Kinematics
$\dot{\vec{\theta}}$: joint velocity
$\vec{P}$: US Probe Position
Planning day provides initial estimate for $\vec{P}_{ref}$
Robot

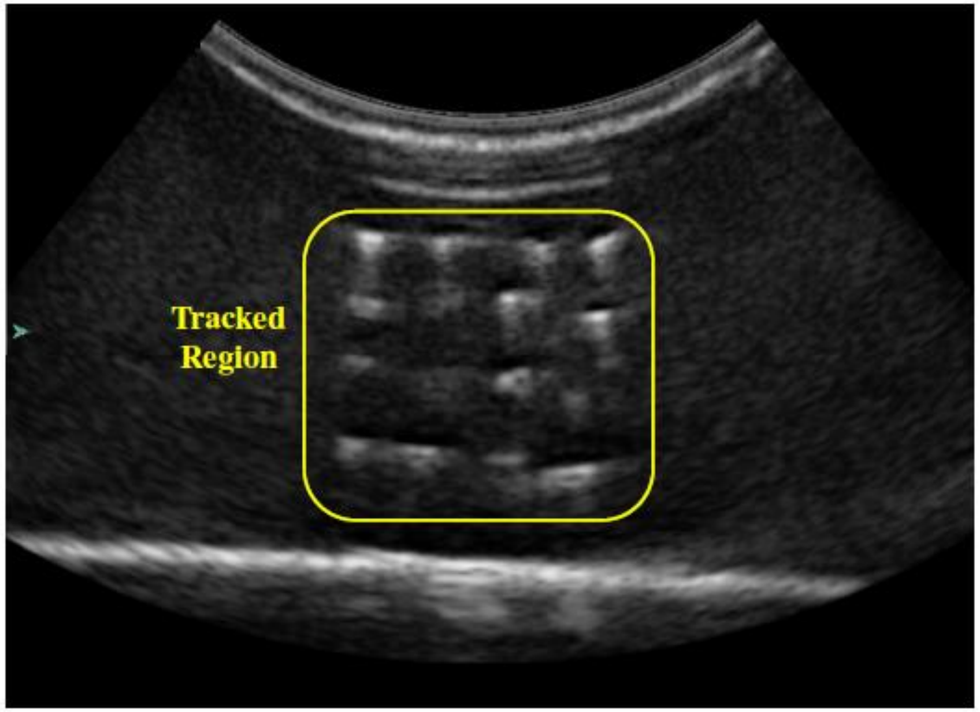
Experiment 1

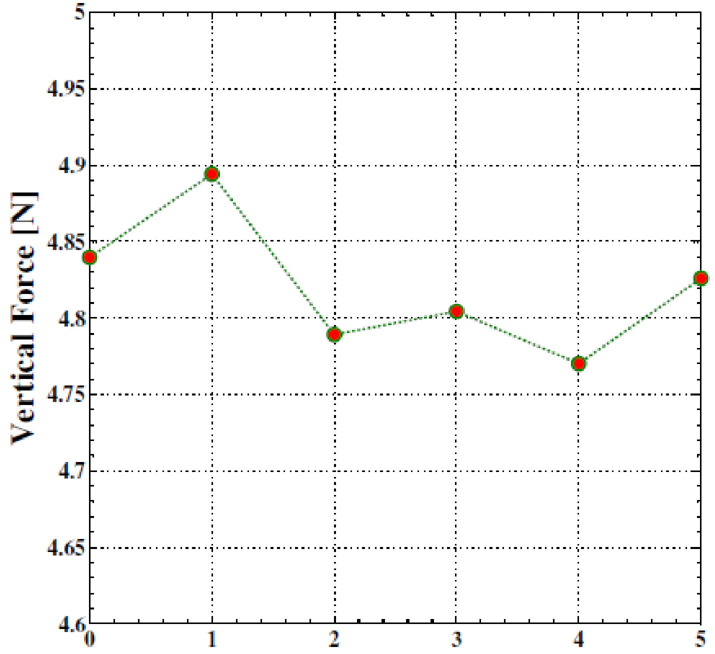


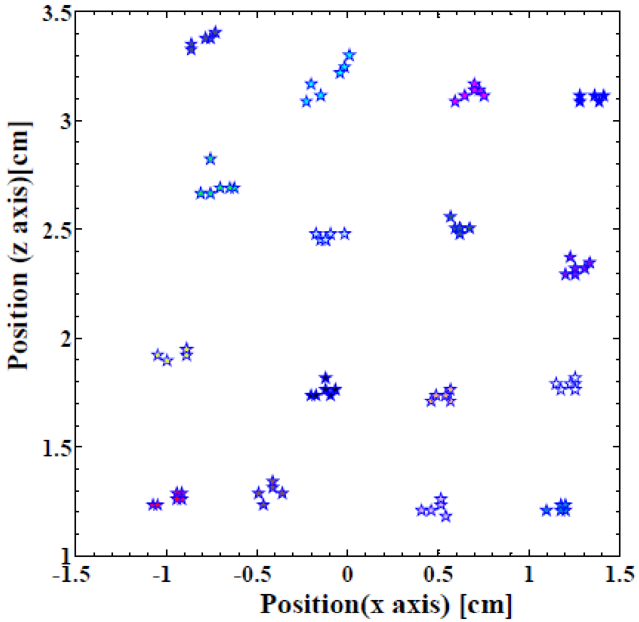




Experiment 2



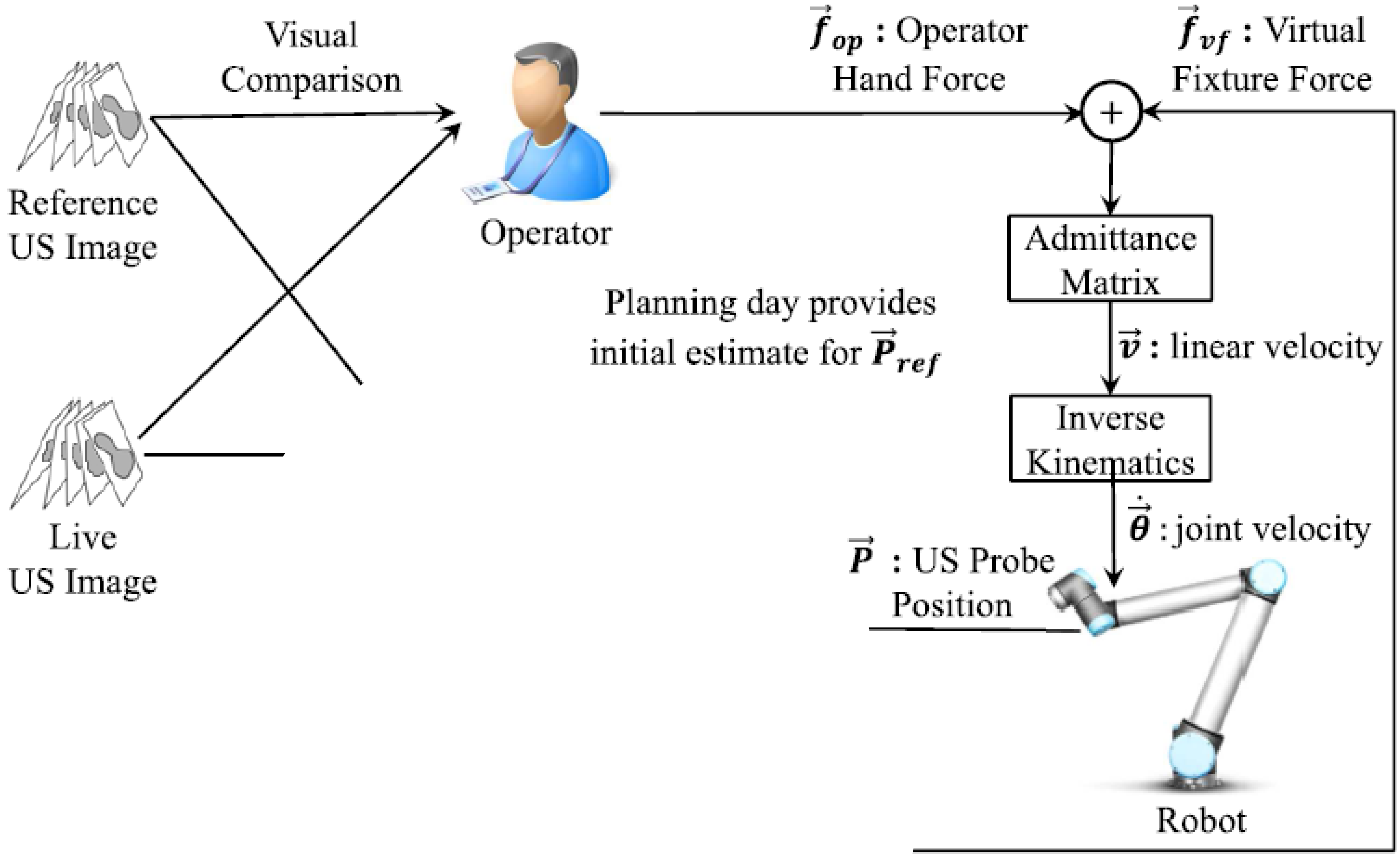




The results showed a mean absolute error in x direction as 0.9 ± 0.5 mm and 0.3 ± 0.3 mm in z direction

When a mean normalized cross-correlation is used for experiment images and reference images, it yields a coefficient of 0.91 ± 0.01

Static+Dynamic VFs



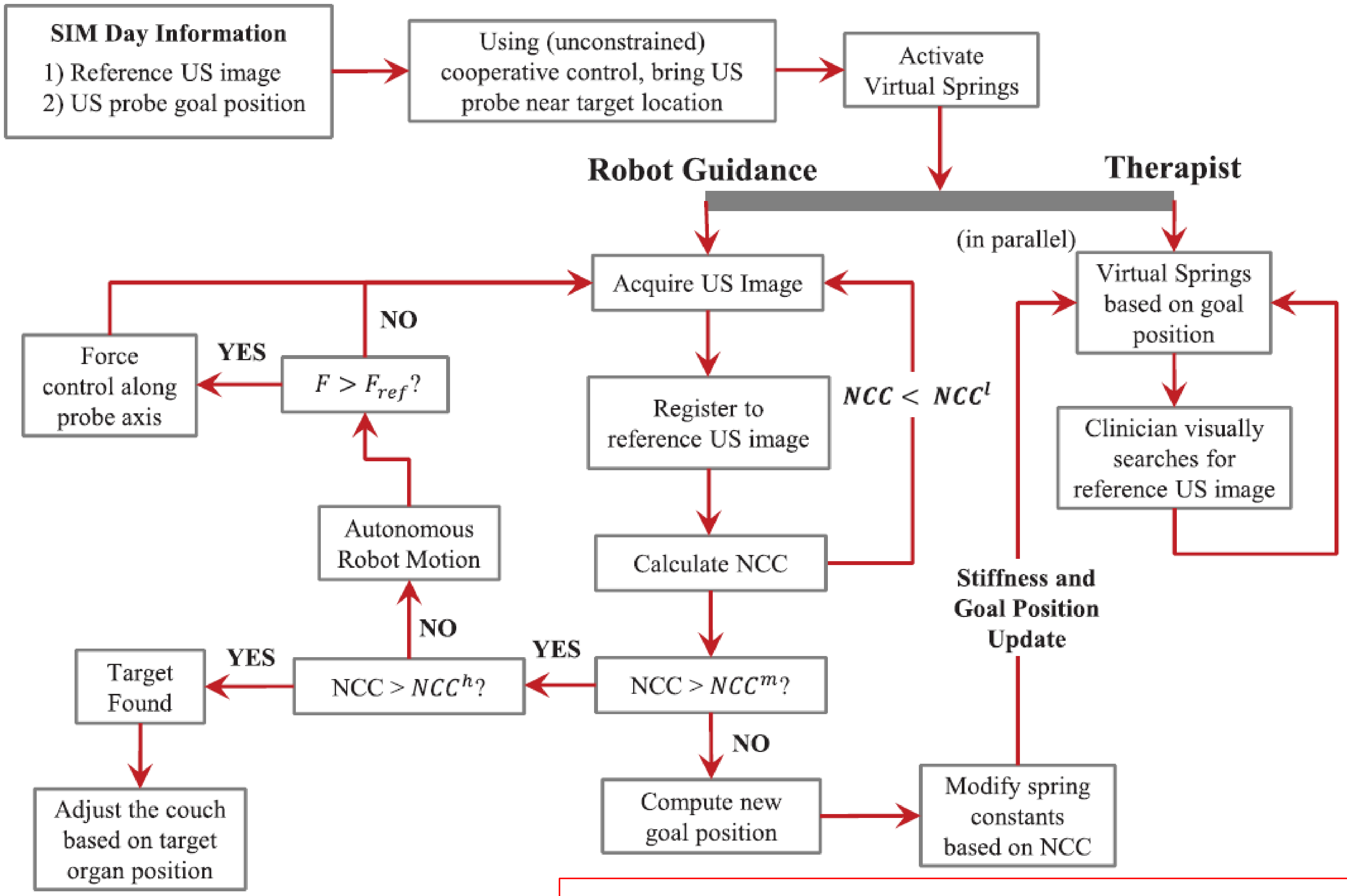


FIGURE 6 | Treatment day US probe placement process.

$$
{}^{u}k_i = \left\{ \begin{array}{lcr} k_i^{nom} & \textbf{for} & NCC \leq NCC_l \\ 2 \times k_i^{nom} \times NCC & \textbf{for} & NCC_l < NCC \leq NCC_m \end{array} \right\} \quad (8)
$$

Data Analysis

$$\overrightarrow{d}_{true} = {}^{ref}\overrightarrow{P}^{Opt}_{Ph} - \overrightarrow{P}^{Opt}_{Ph}$$

$$\overrightarrow{d} = T^{Pr_o}_{Opt} \cdot T^{Pr}_{Pr_o} \cdot T^{us}_{Pr} \cdot \left({}^{ref}\overrightarrow{P}^{us}_{tumor} - \overrightarrow{P}^{us}_{tumor} \right)$$

$$error = \left\| \overrightarrow{d}_{true} - \overrightarrow{d} \right\|$$

$$T_{diff} = T^{Pr}_{Ph} \cdot \left(T^{Pr}_{Ph} \right)^{-1}_{true}$$

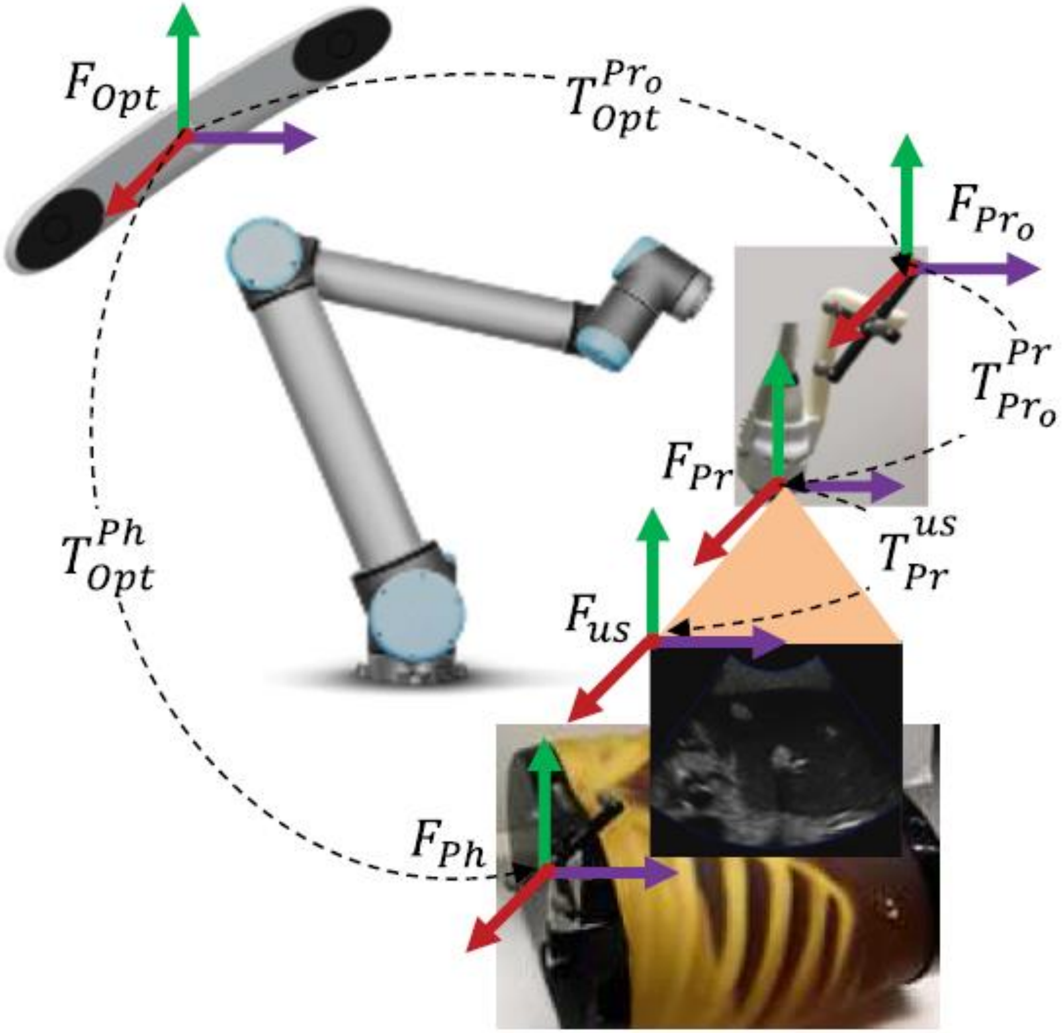


FIGURE 8 | Experimental setup transformation map. During the experiments, the camera frame, F_{Opt}, and the transformations $T^{Pr}_{Pr_o}$ and T^{us}_{Pr} remained fixed, and the transformations $T^{Pr_o}_{Opt}$ and T^{Ph}_{Opt} were moving.

Result

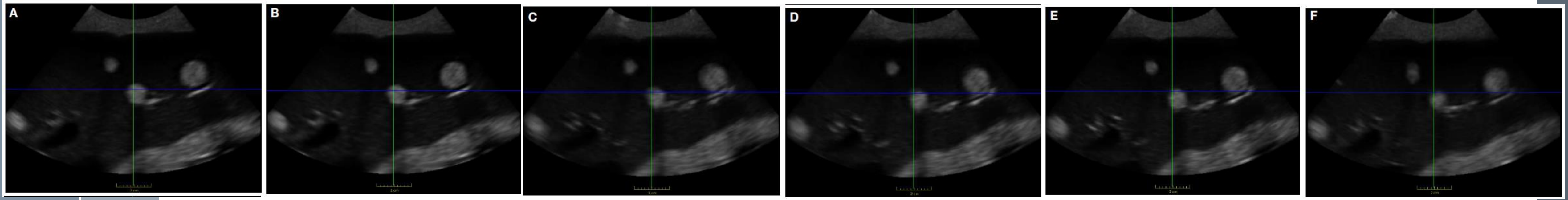
TABLE 1 | US image-based 3D positional patient setup errors for experiments 1 through 6.

Experiment number	Error (mm)
1	1.60
2	1.47
3	1.65
4	2.16
5	2.03
6	1.88
Overall (mean ± SD)	1.79 ± 0.27

TABLE 2 | US probe placement position and orientation difference.

Experiment	Position (mm)	Orientation (deg)
1	5.1	0.8
2	4.3	1.6
3	14.7	0.8
4	14.9	1.0
5	6.4	2.1
6	6.4	4.5
Overall (mean ± SD)	8.64 ± 4.86	1.79 ± 1.45

The last row shows the mean, μ, and the SD, σ.



Paper Assessment

- The paper provides a method to reproduce US image
- Clear workflow for the application, algorithm and experiment
- Virtual forces/torques enable both VFs and haptic guidance for cooperative control
- Limitations:
- Only one sample size
- Not-yet clinically applicable
- Only one sensor
- Larger error in clinical setup due to tissue motion

Conclusion/Application

- Virtual fixture can provide haptic guidance to reproduce consistence US image and probe placement
- It a co-manipulation strategy where the human is always in control of the robot
- We attempt to implement the virtual force/torque method to our "follows trajectory" VF case
- It can also possibly be incorporated with our second 1 DOF force sensor (e.g. maintaining a certain pressure during a scan)

- Question/Comment?