Critical Review

Group7: Co-robotic Ultrasound Imaging System

Ting-Yun Fang, Weiqi Wang

Paper1: Cooperative Control with Ultrasound Guidance for Radiation Therapy

H. Tutkun Sen, Alexis Cheng, Kai Ding, Emad Boctor , John Wong, Iulian Iordachita and Peter Kazanzides

Paper2: A Cooperatively Controlled Robot for Ultrasound Monitoring of Radiation Therapy

H. Tutkun Sen, Muyinatu A. Lediju Bell, Iulian Iordachita, John Wong, and Peter Kazanzides

Project Overview and Relevance:

In our project, we are integrating a power steering imaging UR5 system, developed in previous research, with synthetic tracked aperture ultrasound (STRATUS) imaging algorithm, developed by our phd student mentor. With dual force sensors mounted on the robot, UR5 follows user's motion and magnifies the US probe contact pressure through cooperative control and admittance robot control.

STRATUS is a technique for improving the US image resolution by tracking the US imaging coordinate with a robot arm. In order to enable STRATUS in cooperative control, essential feature, virtual fixtures (VFs), has to be considered. VFs limits the robot motion to a certain path or position. Necessary VFs in our system includes: 1) stay on a straight line with fixed tool direction; 2) stay on a plane; 3) follow a trajectory.

The papers we choice is relevant and a lot similar to our project. It introduces a novel co-manipulation strategy to reproduce US image throughout the whole radiation treatments. They are using a robot arm, with static/dynamic VFs to provide the user an intuitive haptic guidance. Quantitative evaluation is included in the paper.

Mathematical Background:

The two key mathematical formulations in the paper are admittance robot control and virtual fixture. To generate virtual fixture, virtual springs are added to the system using Hooke's Law. It can generate both virtual force and torque and would drive the user moving to the target position. The standard spring model is given by equation:

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

The virtual force/torque is then summed up with the operator's motion (measured by a 6-dof force sensor mounted on the robot's tip):

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

The summed forces, linear and torsional force in the force sensor frame, are then used to calculate the desired tool tip velocity in the force sensor frame through admittance control:

$$\begin{bmatrix} \overrightarrow{v_F} \\ \overrightarrow{w_F} \end{bmatrix} = \begin{bmatrix} G_1 & 0 & \cdots & 0 \\ 0 & G_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & G_6 \end{bmatrix} \cdot \begin{bmatrix} \overrightarrow{f_F} \\ \overrightarrow{\tau_F} \end{bmatrix}$$

Finally, using robot kinematics, tool tip velocity in the robot frame, robot joint speed can be found.

$$\begin{bmatrix} \overrightarrow{v_R} \\ \overrightarrow{w_R} \end{bmatrix} = \begin{bmatrix} R_R^{Pr} \cdot R_{Pr}^F & 0_{3\times 3} \\ 0_{3\times 3} & R_R^{Pr} \cdot R_{Pr}^F \end{bmatrix} \cdot \begin{bmatrix} \overrightarrow{v_F} \\ \overrightarrow{w_F} \end{bmatrix}$$

$$\dot{\overrightarrow{\theta}} = J^{-1}(\overrightarrow{\theta}) \cdot \begin{bmatrix} \overrightarrow{v_R} \\ \overrightarrow{w_R} \end{bmatrix}$$

Summary of Experimentation and Results:

The only difference between the two papers is that the first paper uses static virtual fixture to guide the user; the second paper takes US image as closed loop control feedback and modifying the stiffness matrix of the virtual spring model (dynamic virtual fixture).

There are a total of three experiments in both papers, each asserting a different merit of utilizing virtual fixture in ultrasound imaging.

Paper 1:

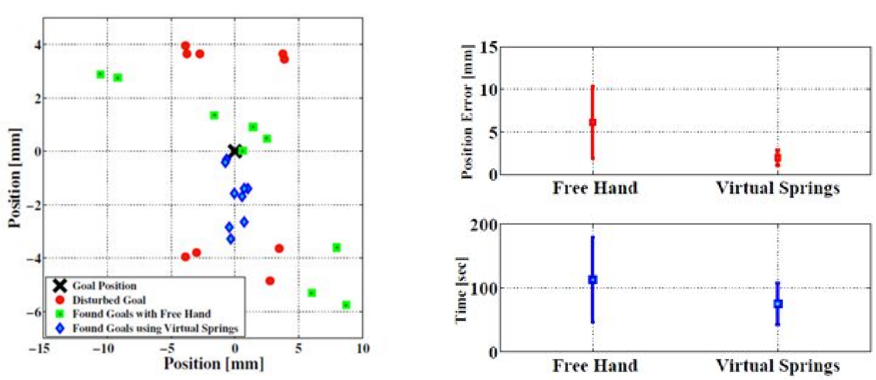
The experiments use a phantom inserted with pencil lead to form a grid, this allows the user to easily identify the the difference between the experimental images and the reference image.

Experiment 1:

This experiment aims to determine the accuracy of ultrasound imaging with virtual fixture, in other words, how well can this concept aid the surgeon in finding the desired location. The procedure of the experiment is as followed,

1. Retrieve a ultrasound image from phantom as reference and record the tool position and orientation.
2. The subject takes control of the robot
3. The subject attempts to recreate the reference image using free hand
4. The subject attempts to recreate the reference image using virtual fixture
5. Repeat steps 3 and 4

Errors can and will occur when setting up the patients for surgery: the operation table may have an offset, the patients may be laying on a slightly different position, the tumor itself may change sizes between the treatment planning and the actual treatment. To mirror these errors, an errorous goal position is generated during each trial. The disturbed goal will be what the virtual fixture will consider to be the goal position, and the surgeons must displace the probe to the correct position.



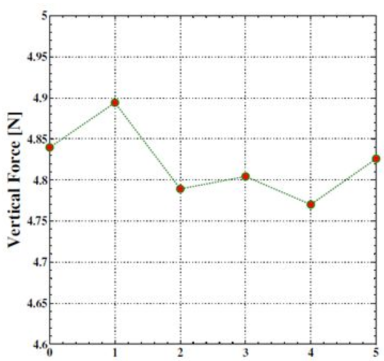
The virtual spring control shows an improvement in both time and accuracy when compared to free hand control

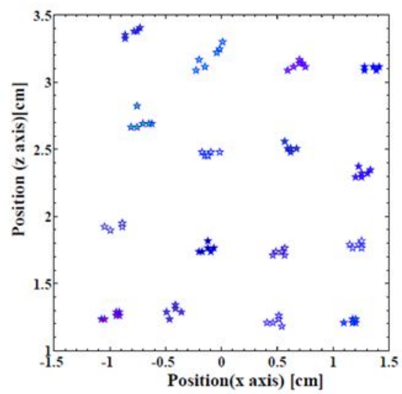
Experiment 2:

When the probe is pressed against skins, the deformation in tissues varies each trial, a large tissue movement in US image can make finding the reference image rather difficult. To validate its repeatability, the virtual spring should be able to provide similar pressure force and tissue deformation.

The experiment procedure is as followed:

1. Create a day 0 ultrasound image, record the image and force applied on phantom
2. The robot probe is moved up
3. Activate virtual spring and allow the probe to contact the phantom to reach similar force, and record the US image.
4. Repeat steps 2 and 3.





It was confirmed that the virtual spring can mimic similar force on phantom as it did on day 0. The error in reproducing the deformation is defined as the distance between the center of each grid marker on the experimental images and those of the reference image. 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.

Paper 2:

The experiment workflow is shown in the following figure:

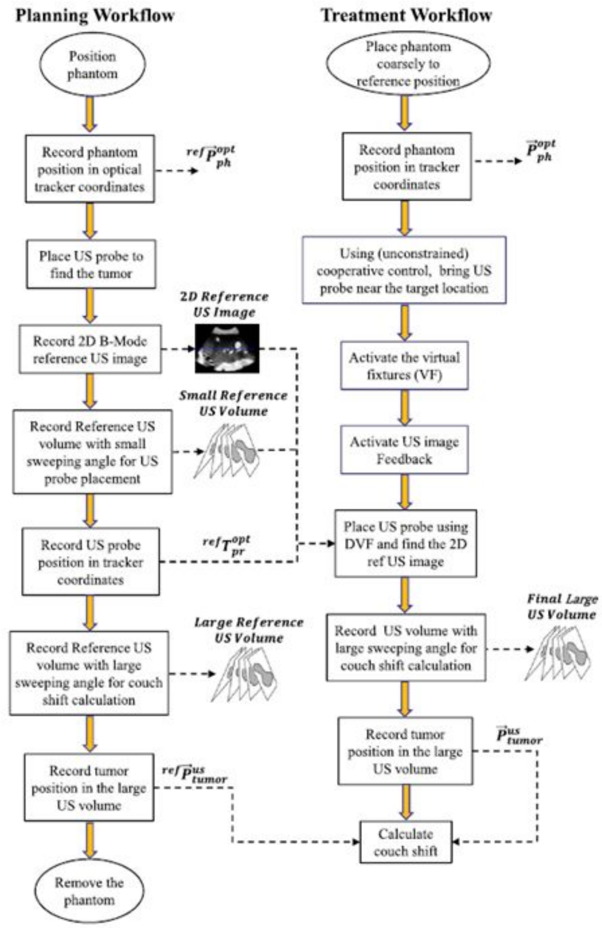


FIGURE 7 | Experiment workflow for testing US image-based patient setup.

Since the goal of the proposed method is to reproduce US image and make it consistent with the reference US image acquired during the treatment planning stage. The position of the US probe relative to the scanning phantom should be consistent. They used optical trackers to record the positions of the probe, phantom and tumor. Those records in the treatment planning serves as ground true and are then compared with the records during the treatment delivery. Two quantitative errors, image-based error and probe placement error, are evaluated.

Firstly, the ground truth translation of the tumor position between planning and delivery w.r.t the optical tracker frame can be calculated using the two recorded phantom positions in the optical tracker frame:

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

The difference in tumor centroid position (between planning and delivery) in the probe frame can be transformed into optical tracker frame to find the error:

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

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

The second quantitative error, probe placement, can be obtained by computing the transformation between the US probe tip and the phantom optical marker, and comparing it to the true (reference) US probe tip transformation:

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

They performed six experiments with a single user and the result is shown in the following tables and figure.

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.

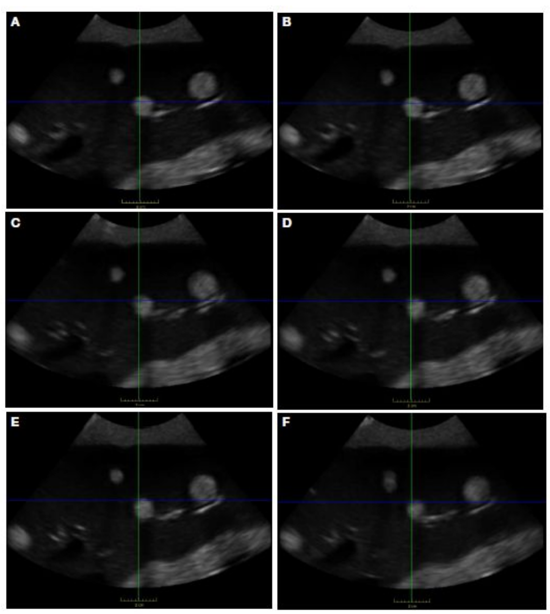


FIGURE 10 | Final US images found after treatment workflow. US images **(A–F)** correspond to experiments 1–6, which are all similar to the reference US image shown in **Figure 9**.

Paper Evaluation:

The papers provide a co-manipulation method to reproduce US image. It has clear strategy and workflow for proposed application, algorithm and experiment. We attempt to include the virtual spring method into our project especially for our “follow a trajectory” VF case. It can also potentially incorporate with the second load cell in our system, such as using DVFs to maintain a certain probe contact pressure.

Some limitation of the papers includes:

1) The experiment in paper 2 only tested with one subject. A larger sample size would be more convincing.
2) This strategy is not yet practical for the clinical environment. First of all, they’ll need to find a way to attach the plastic probe model with the patient after US reference acquisition to generate consistent deformation for the CT scan. Secondly, also mentioned in the paper, the accuracy of the method would be lower when implementing the system to in vivo subjects as there would be tissue motion and much larger variation in couch shift.