Co-Robotic Ultrasound Imaging

600.446. Advanced Computer Integrated Surgery

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1 Abstract

Sonographers commonly suffer from musculoskeletal pain and repetitive strain injuries because the clinical necessity of applying a large force against patients during an ultrasound scanning. Especially when facing obese patients, pregnant women or imaging of deep organs, large contact force is inevitable to find a clear, diagnosable ultrasound image. To overcome this challenge, this project aims to use a cooperatively controlled robotic arm, UR5, to help the operator apply forces and improve the images stability at the same time (Figure 1). Moreover, the robotic system enables the implantation of synthetic tracked aperture ultrasound (STRATUS) imaging, which improves the resolution of ultrasound images (Figure 2).

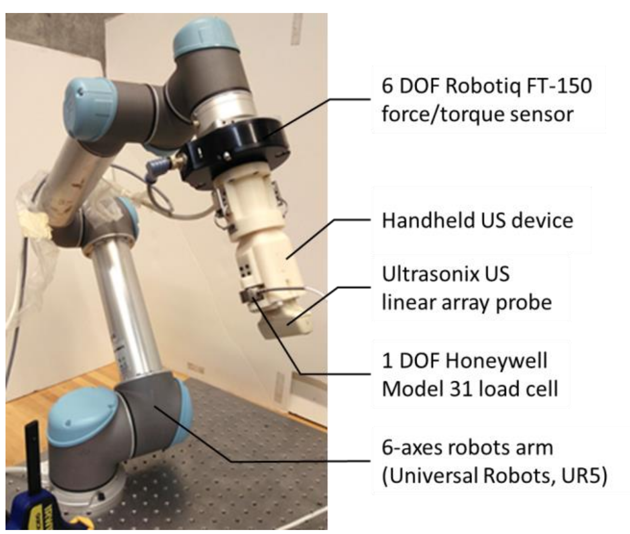


Figure 1. The co-robotic ultrasound imaging system. (TY. Fang et al. IPCAI 2017)

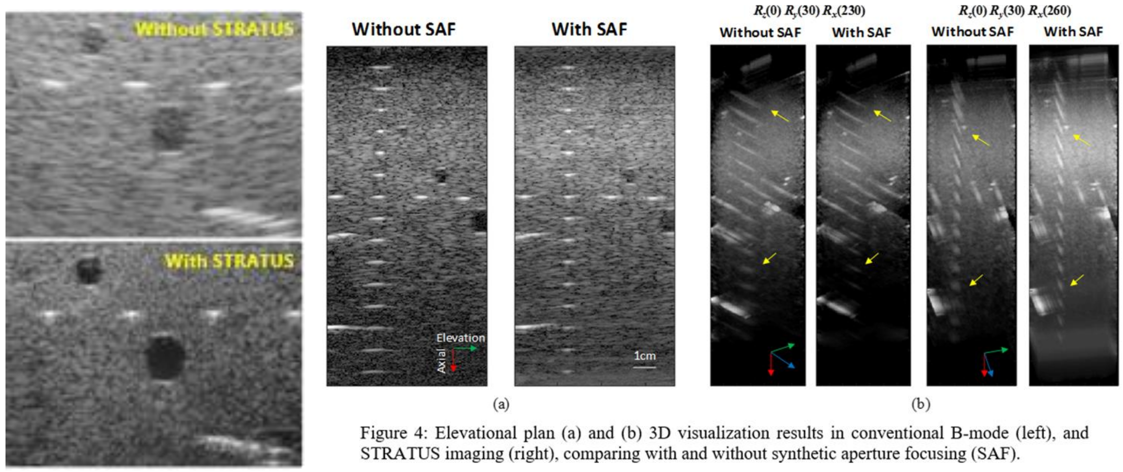


Figure 2. The result of STRATUS algorithm in lateral plane (left) and in elevational plane (right).

2 Background

In many clinical situations, sonographers have to apply large force against patients to acquire a clear, diagnosable ultrasound (US) image; especially when facing obese patients, pregnant women, or making deep organs diagnosis. Because of these common demands, sonographers often suffer from musculoskeletal pain and repetitive strain injuries. To overcome this challenge, we are using a robotic arm, to assist the sonographer during the US scanning procedure. This project started in 2015 by Rodolfo Finocchi, Dr. Russ Taylor and Dr. Emad Boctor; I, Ting-Yun Fang, joined the project in 2016 and started with improving the previous control algorithm and mechanical design for an US device (Figure 3). The co-robotic US imaging system is constructed with a robotic arm, UR5, an US machine and probe, a 6 degree-of-freedom (DOF) force sensor and a 1-DOF load cell. The dual force sensors allow the robot to differentiate the force applied by the sonographer and the actual contact force between the US prove and the tissue. Our experiment shows that the co-robotics system can reduce the force applied by the user while improving the US image stability.

The co-robotic US system is also used in synthetic tracked aperture ultrasound (STRATUS) Imaging algorithm. STRATUS uses the robotic arm to track and actuate the US probe then transform the US images into a uniform coordinate. By summing up the US signal in the uniform coordinate, the resulting US image has a better resolution and would be beneficial for making diagnosis. This algorithm can be applied to both lateral and elevational direction and has a potential to perform 3D object scanning.

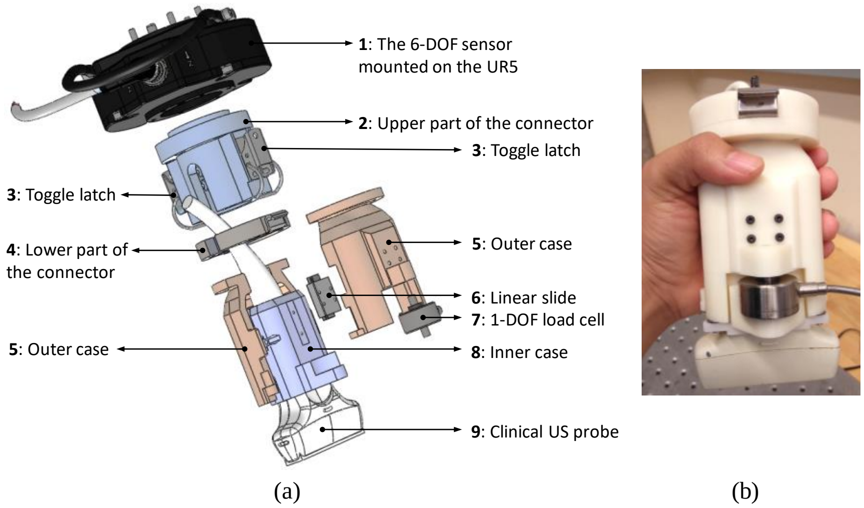


Figure 3. The improved US device, probe holder, with axial sensing feature. (a) The CAD model of the device (b) 3D printed probe holder applied to an US probe.

3 Project Plan and Goal

Combining the two valuable features of the co-robotic US imaging system: 1) reduces the force applied by the user and improves the stability of the US images; 2) enables the STARTUS algorithm and increases the image resolution; this project aims to integrate the two applications and makes the system fits better into practical clinical applications. Using cooperative control corresponds with virtual fixtures enables the operator to move the robot and applies STRATUS algorithm on specific region of interests. The virtual fixtures restrain the motion of the robot/user and makes sure the fixed direction of probe motion. The optimum goal would be implementing real time STRATUS that generates US images with better resolution during a scan. Moreover, in order to cover general clinical practices, measuring contact forces between probe and tissue along three directions is inevitable. For example, in the case of echocardiography, the US probe is first pushed against the middle of the chest then orientated to find a preferable view. By replacing the current 1-DOF load cell with a multi axis force sensor, force measurement can be extended to other axes and the robot dexterity can be increased.

4 Deliverables

<u>Minimum</u>

a. Design an animal (pig) experiment protocol and submit to ACUC for approval
b. Design an IRB protocol for human factor study and human imaging study

c. Implement virtual fixture features to the system
d. Design a new probe attachment that is compatible with the convex probe used for the STRATUS algorithm
e. Integrate STRATUS algorithm with the system (2D in-plane scanning)

Expected

a. Ultrasound calibration for the new attachment
b. System validation using a phantom (a general US phantom or a female uterus phantom)
c. Extended synthetic tracked aperture (SA) from 2D to 3D and perform out-of-plane scanning
d. Experiment with the extended SA using a phantom

Maximum

a. Design a GUI for real-time interface to visualize collected US data
b. Apply one or more of imaging protocol on in vivo subjects
c. Replace the 1-DOF load cell with a multi-axis force sensor for higher dexterity
d. Upgrade the current mechanical design of the US probe holder

5 Technical Approach

Figure 3 shows the control diagram of the system.

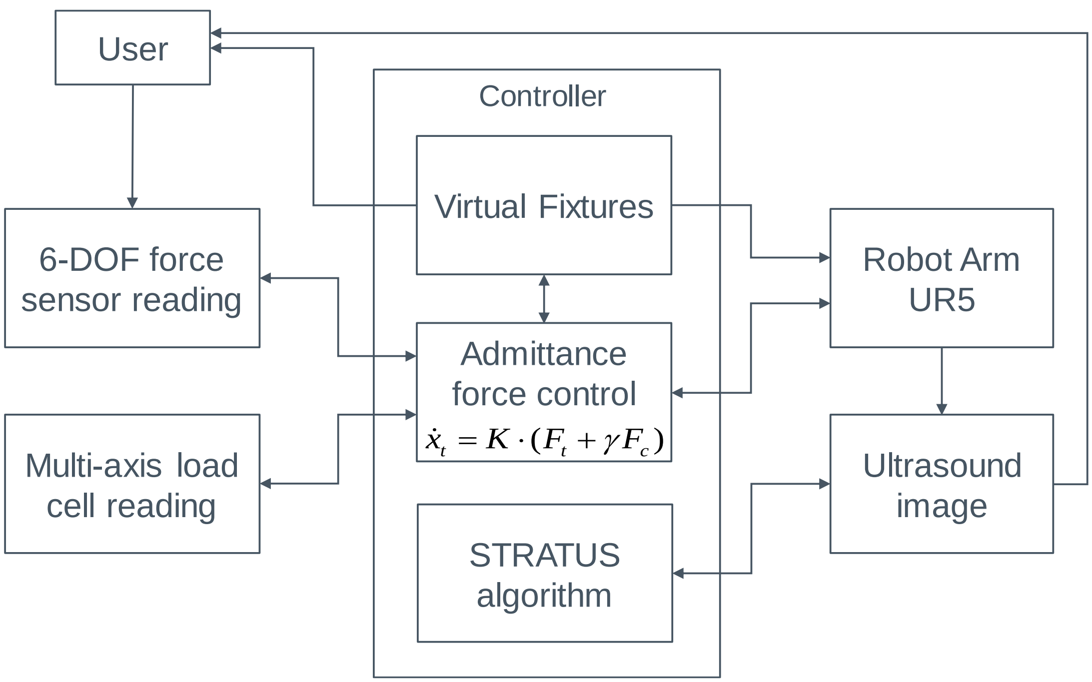


Figure 3. The Control diagram of the system

Integration of STRATUS algorithm

To enable a STRATUS algorithm in cooperative controlled robot, virtual fixtures is essential. In planar cases (lateral direction), it limits the out-of-plane motion and ensures the US images are aligned; where in 3-dimensional cases, virtual fixtures make sure the elevational motion of the probe. It can be extended to scanning objects with irregular shape such as human body and permits the tissues do not have drastic change in deformation. Thus, we will be developing different virtual fixtures to the robot including stay-on-line, stay-on-plane…etc.

Besides, to verify the system in clinical practice, we would like to extend the previous system to perform animal or IRB protocol. Therefore, we would be designing the experiment and conducted it if approved.

Increasing of dexterity of the system

We propose to replace the current 1-DOF load cell with a tri-axis load cell can enable the contact force measurements in axial, lateral, and elevational axis. With admittance robot control, we are able to magnify the user's force in any direction based on applications. Because of the change, we will be designing a new mechanical structure for the probe holder.

System Validation

In previous experiments, we were using phantom for validation. We would like to design an animal / IRB protocol and bring the system a step further to clinical practice. When waiting for the approval, we will develop the STRATUS and improve the load sensing as described previously; then evaluate the system with a general phantom.

6 Dependencies

Dependency	People	Status
Robot arm, UR5	Mentor	V
Ultrasound machine and probe, Ultrasonix	Mentor	V
Code for STRATUS	Mentor	V
Animal/human experiment	ACUC/IRB approval needed	on going
A multi-axis load cell	Mentor	purchasing
Access to the lab	Mentor	V
Training and access to machine shop	WSE Manufacturing	V

7 Project Milestones

<u>Timeline</u>

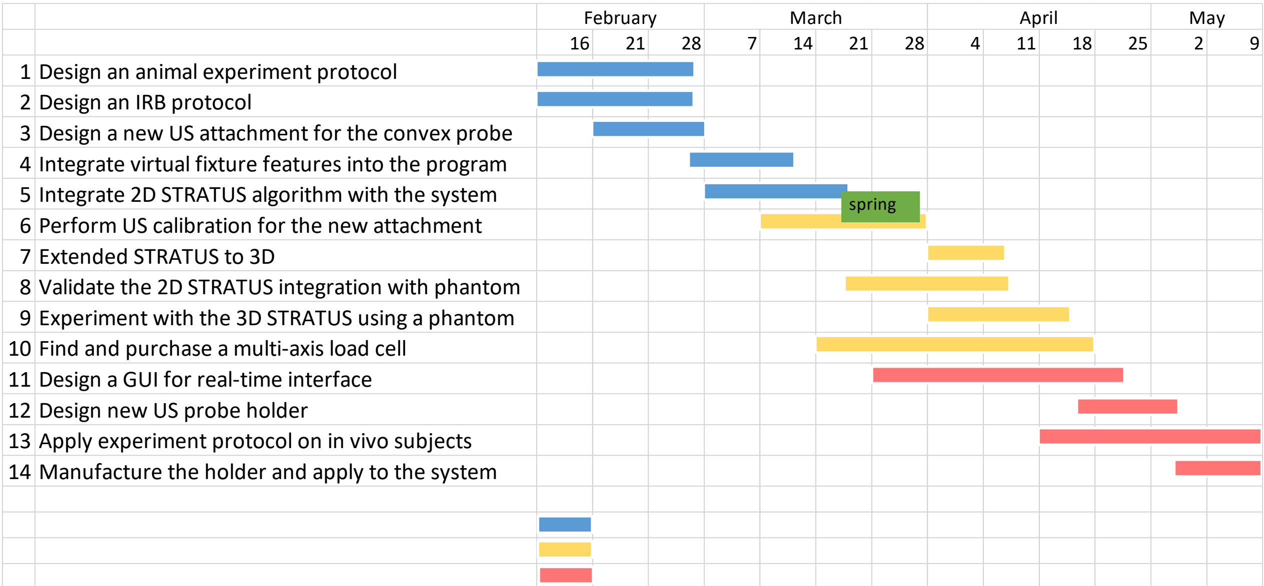
Minimum: 1-5, expected finish by March 16

Expected: 6-10, expected finish by April 18

Maximum: 11-14, expected finish by May 9

		Expected finish	Status
Minimum			
1	Design an animal experiment protocol	Feb 26	ongoing
2	Design an IRB protocol	Feb 26	ongoing
3	Design a new US attachment for the convex probe	Feb 28	ongoing
4	Integrate virtual fixture features into the program	March 9	ongoing
5	Integrate 2D STRATUS algorithm with the system	March 16	not started
Expected			
6	Perform US calibration for the new attachment	March 26	not started
7	Extended STRATUS to 3D	April 6	not started
8	Validate the 2D STRATUS integration with phantom	April 6	not started
9	Experiment with the 3D STRATUS using a phantom	April 13	not started
10	Find and purchase a multi-axis load cell	April 18	not started
Maximum			
11	Design a GUI for real-time interface to visualize collected US data	April 20	not started
12	Design new US probe holder that is compatible with the load cell	April 27	not started
13	Apply one or more of imaging protocol on in vivo subjects	May 9	not started
14	Manufacture the holder and apply to the system	May 9	not started

Chart



8 Management Plan

Meetings

- Weekly meeting on Tuesday 11:00 a.m. with phd mentor Kai.
- Meeting once every two weeks with mentor Dr. Emad Boctor.

Work distribution

Ting-Yun Fang: Hardware design and manufacture, protocol design, US calibration, system validation experiments

Weiqi Wang: Virtual fixtures implementation, real-time GUI for STATUS algorithm, US calibration, system validation experiments

9 Reading list

[1] Zhang HK, et al. (2016) Synthetic tracked aperture ultrasound imaging: design, simulation, and experimental evaluation. Journal of Medical Imaging 3:027001. doi: 10.1117/1.jmi.3.2.027001

[2] Zhang HK, et al. (2016) Co-robotic synthetic tracked aperture ultrasound imaging with cross-correlation based dynamic error compensation and virtual fixture control. 2016 IEEE International Ultrasonics Symposium (IUS). doi: 10.1109/ultsym.2016.7728522

[3] Li M, et al. (2005) A constrained optimization approach to virtual fixtures. 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems. doi: 10.1109/iros.2005.1545420

[4] Gilbertson MW, Anthony BW (2013) An ergonomic, instrumented ultrasound probe for 6-axis force/torque measurement. 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). doi: 10.1109/embc.2013.6609457

[5] Fang TY, et al. (2017) Force Assisted Ultrasound Imaging System through Dual Force Sensing and Admittance Robot Control. International Conference on Information Processing in Computer-Assisted Interventions. Submitted for publication