Paper Critique

Robotic Ultrasound Assistance via Hand-Over-Hand Control

EN 601.656 Computer Integrated Surgery II

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1. My Project Summary

My work is addressing the problem that sonographers typically develop work-related musculoskeletal disorders [1] as a result of holding an US probe in high force, static, contorted positions for long periods of time and for multiple patients per day [2]. The overall goal of my work, as well as previous work and future work in the field, is to provide sonographers with a robotic US "power-steering" system composed of a hand-guidable, US probe-wielding robot that does all the strenuous probe holding currently expected of a sonographer. By alleviating this aspect of a sonographer's job, we hope to make them less susceptible to developing musculoskeletal disorders, while also improving their quality-of-life and extending their career duration. My personal niche within this goal is to improve the perceived "transparency" of robot motion, based on the previous prototypes developed by Finocchi [4, 3] and Fang [5].

2. Paper Selection

The paper selected for this review and critique is:

R. Finocchi, F. Aalamifar, T. Fang, R. Taylor and E. Boctor, "Co-robotic ultrasound imaging: a cooperative force control approach", *Medical Imaging 2017: Image-Guided Procedures, Robotic Interventions, and Modeling*, 2017. Available: 10.1117/12.2255271.

Note: Throughout this report, I will refer to aspects of this paper as "Finocchi's" (i.e. Finocchi's experiment, Finocchi's algorithms, Finocchi's results...) for brevity although there are multiple authors for it. Additionally, I will be explicit if referencing a separate work of Finocchi's, such as his thesis paper written in 2016.

This paper is very relevant to me since the very premise of my work is to expand upon, and improve, Finocchi's algorithms and implementation described in this paper. In doing so, I will be using the same robot and 6-DoF force/torque (F/T) sensor as Finocchi, as well as starting with his F/T$\rightarrow$Velocity admittance control gains. Since Finocchi and I both seek to address the same problem of alleviating ultrasonographer exertion to mitigate musculoskeletal issues, our results can be directly compared to determine the success of my project.

3. Summary and Key Result

In summary, the research conducted for this paper sought to design and develop a robotic US assist prototype, followed by a user study to help in quantitative validation of the methods. This study consisted of measuring participant exerted grip force while scanning and resultant image stability, as well as a task load survey assessing device difficulty, intuitiveness, and strenuousness.

His experimental setup is shown below in Fig. 1.

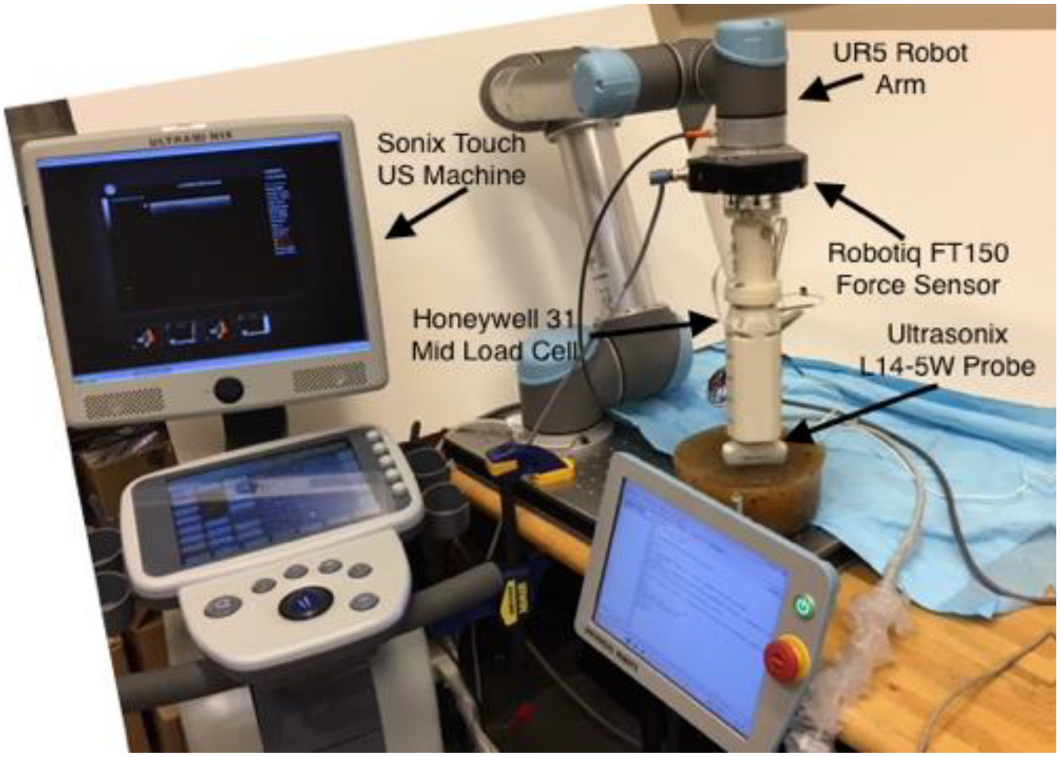

Figure 1: Figure from Finocchi's paper [3] showing his experimental setup and components.

The results of the experiment, put generally, showed that the developed robotic assist system was less strenuous on the user, allowed more stable contact force of the probe against the patient, and produced better (more stable) image quality. These last two items are related as stability of the probe directly correlates to quality of image. The author believed that the robotic probe stabilization compensated for sonographer hand tremor and relieved them from making frequent hand readjustments due to lower muscle fatigue, therefore resulting in a better captured sequence of US frames.

4. Significance

Finocchi's result was significant on two fronts described below.

4.A Human Factors

The results of this paper showed lowered strenuousness (via grip strength and questionnaire metrics), which has positive human factors implications for sonographers. Lowered strain during scanning would undoubtedly alleviate some of the musculoskeletal disorders that sonographers too frequently develop, therefore extending their careers and delaying work-related pain onset.

4.B Ultrasound Capabilities

The results of this paper showed better image stability through more consistent probe force in static positions, which has many implications on future robot-dependant US techniques. This includes synthetically tracked US (STRATUS) imaging which relies on stable images to get obtain a better resolution, and US tomographic reconstruction which highly depends on stable images to perform limited angle reconstruction to obtain an adequate result.

5. Background

This research is built on the foundation of admittance control which is the translation of forces at a robot's end effector (EE) into Cartesian linear and rotational EE velocities. In this experiment, as with most admittance control applications, forces and torques applied to the robot's EE were induced by a human hand with the intention of moving the robot towards where the user is pushing. A typical admittance control algorithm is described below, as described in Finocchi's paper.

First, F/T values $\begin{bmatrix}\boldsymbol{F} & \boldsymbol{\tau}\end{bmatrix}^T$ at the EE are multiplied by a gain scaling matrix K to get a desired EE Cartesian velocity $\dot{x}_e$ as shown in equation 1.

$$\dot{\boldsymbol{x}}_e = K\left(\begin{bmatrix}\boldsymbol{F} \\ \boldsymbol{\tau}\end{bmatrix}\right) \tag{1}$$

Second, since these resolved velocities are in the EE frame, they must be transformed into the world frame by multiplying the Cartesian velocities by $Ad_{g_{we}}$, a 6x6 adjoint matrix describing this frame transformation. This produces Cartesian velocities $\dot{x}_w$ in the world frame.

$$\dot{\boldsymbol{x}}_w = Ad_{g_{we}}\dot{\boldsymbol{x}}_e \tag{2}$$

This adjoint matrix can be determined through the known current rotation angle of the robot and its forward kinematics g_{we} which is shown in equation 3.

$$g_{we} = \begin{bmatrix}R_{we} & p_{we} \\ 0 & 1\end{bmatrix},\ where\ R_{we} \in SO(3)\ and\ p_{we} \in R^{3x1} \tag{3}$$

$$Ad_{g_{we}} = \begin{bmatrix}R_{we} & skew(p_{we})R_{we} \\ 0 & R_{we}\end{bmatrix} \tag{4}$$

Third, the Cartesian velocities in the world frame are converted into individual angular joint velocities which can be commanded to the robot. This is done by solving the constrained optimization problem shown in equation 5 assuming known Jacobian matrix J, performed in a least squares sense for this paper.

$$J\dot{\boldsymbol{q}}_w = \dot{\boldsymbol{x}}_w,\ where\ J \in R^{6xDoF} \tag{5}$$

This optimization problem can be optionally constrained by developer-specified upper and lower allowed angular joint velocities $\dot{\boldsymbol{q}}_{up}$ and $\dot{\boldsymbol{q}}_{low}$ respectively as shown in equation 7.

$$H\dot{\boldsymbol{q}}_w \leq h \tag{6}$$

$$\begin{bmatrix}-I_{6x6} \\ I_{6x6}\end{bmatrix}\dot{\boldsymbol{q}}_w \leq \begin{bmatrix}\dot{\boldsymbol{q}}_{low} \\ \dot{\boldsymbol{q}}_{up}\end{bmatrix} \tag{7}$$

At the end of the admittance control procedure, F/T values applied at the EE have been successfully converted into angular joint velocities that can be commanded to the robot to give the user a feeling of transparent hand-guidance.

6. Contributions

The work performed by Finocchi had two main contributions: his mechanical housing design for attaching all components to the robot end-effector and his admittance control workflow for US robotic assistance.

6.A Housing

Performing admittance control in the use case of sonography requires the robot's end-effector to contain an US probe as well as dual-force sensors. Two force sensors must be used to decouple and then compensate for the force of the probe against the patient from the forces applied by the user's hand-guidance. This was accomplished by use of a 6-DoF Robotiq-FT150 sensor located at the top of the housing to resolve hand forces, and a separate 1-DoF Honeywell load cell placed in the middle of the housing's clamshell design to resolve probe-patient forces. The design from Finocchi is shown in Fig. 2 below. As can be seen, when the user presses the probe against a surface, the clamshell design squeezes the load-cell embedded within, allowing this applied force to be resolved separately from the other force sensor and therefore permitting compensation of this force.

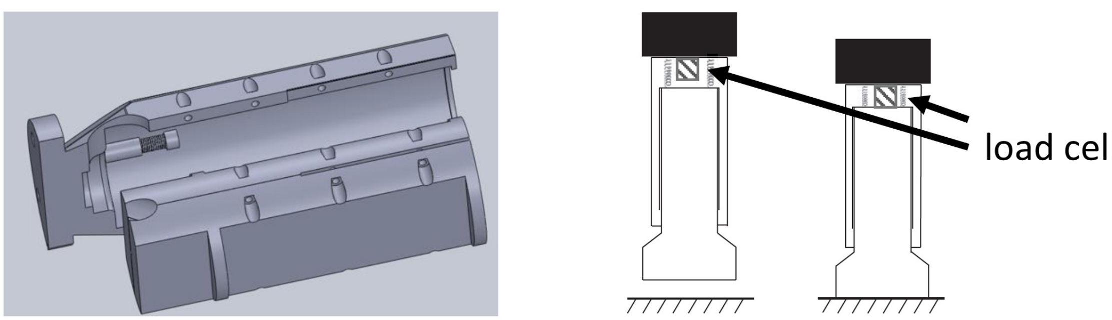

Figure 2: Two figures from Finocchi's paper [3] with text overlain on the right figure to explicitly show the load cell. *Left:* A cross-section of the clamshell design in computer-aided design software. *Right:* A diagram of how the load-cell resolves compression forces inside of the clamshell design.

6.B Admittance Control Workflow

This paper presents a novel application of admittance control to US robotic assistance through the workflow shown below in Fig. 3.

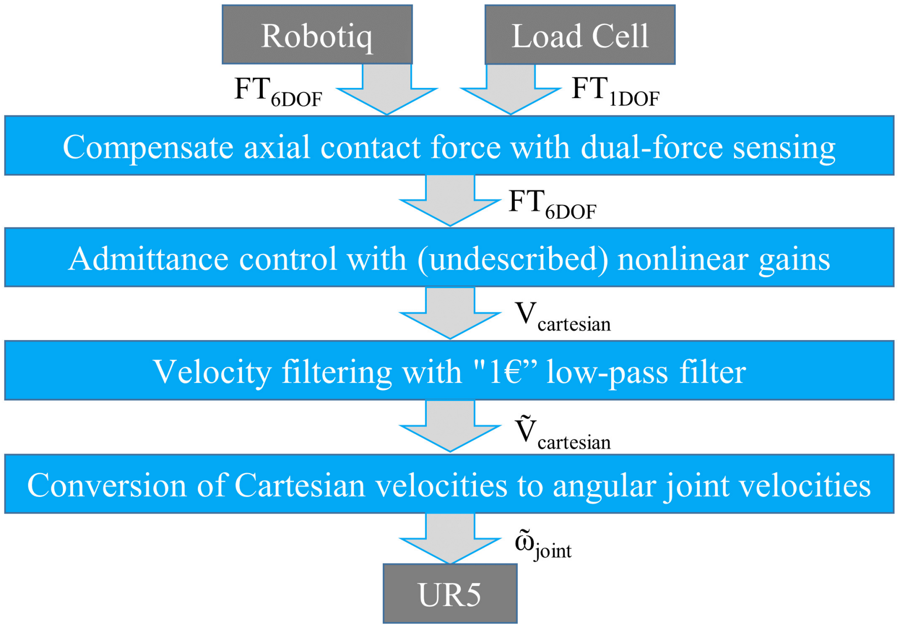

Figure 3: A flow diagram created to depict the flow and conversion of sensor data into commandable angular joint velocities.

While most of this diagram follows the typical admittance control procedure outlined in Section 5, it does additionally include the use of non-linear admittance control gains and a 1€ low-pass filter to smooth out Cartesian velocities in the world frame before converting them to angular joint velocities. With the aim to smooth out human hand motion, this was the most significant part of the author's workflow.

7. Experiment

This research involved two user study experiments, testing many quantitative factors surrounding user exertion, difficulty, and image quality.

7.A User Study [1/2]: Grip Strain and Probe Stability

The first user experiment sought to measure strenuousness of the robotic assist system via applied grip force and a questionnaire. For this experiment, users were asked to apply a steady 5N, 15N, 25N, 35N, and 45N force against a phantom for 10 seconds both freehand (FH) and with robotic assist (RA). In both instances, visual feedback was given on a GUI (right of Fig. 4) to "close the loop" and let the user know how much force they were applying. The grip force measurement occurred during scanning trials and was measured via FlexiForce film placed in seven strategic locations on the housing handle (left and center of Fig. 4) based on prior literature on grip strength measurement. The questionnaire was distributed after the experiment to assess the operator's task load by asking questions regarding perceived strenuousness, difficulty, and intuitiveness.

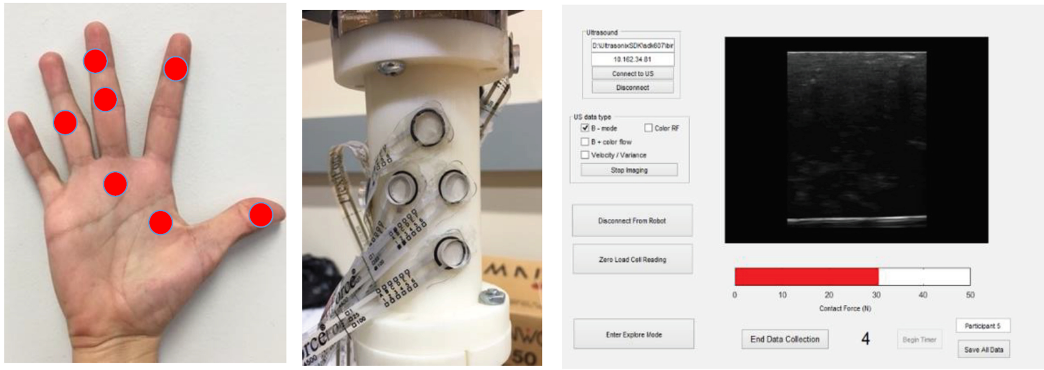

Figure 4: Three figures from Finocchi's paper [3] showing different aspects of his user study procedure. *Left:* The location of where force sensors would measure grip force. *Center:* Grip force sensors placed on the handle of the housing. *Right:* The GUI used to relay current probe-phantom force readings to the study participant in real time.

7.B User Study [2/2]: Image Quality

The second user experiment sought to measure acquired US image stability via a sum of square differences (SSD):

$$SSD = \sum_{m} \sum_{n} (I_{ref} - A_i)^2 \tag{8}$$

In this equation, m and n are the rows and columns of pixels in the image, I_{ref} is the first acquired US frame, and A_i is acquired US frame i. Essentially, this equation is taking the sum of squared differences of every frame compared to the first frame to deduce stability. For this experiment, users were asked to apply a steady 20N of force against a phantom for 20 seconds while US frames were acquired. This task was performed three ways: 1) FH; 2) with RA and no force limits; and 3) with RA and a maximum allowed force of 20N.

8. Results and Discussion

8.A User Study [1/2]: Grip Strain and Probe Stability

The result of the first user study experiment (n=6), summarizing applied grip force and stability of contact force, is shown in Fig. 5 below.

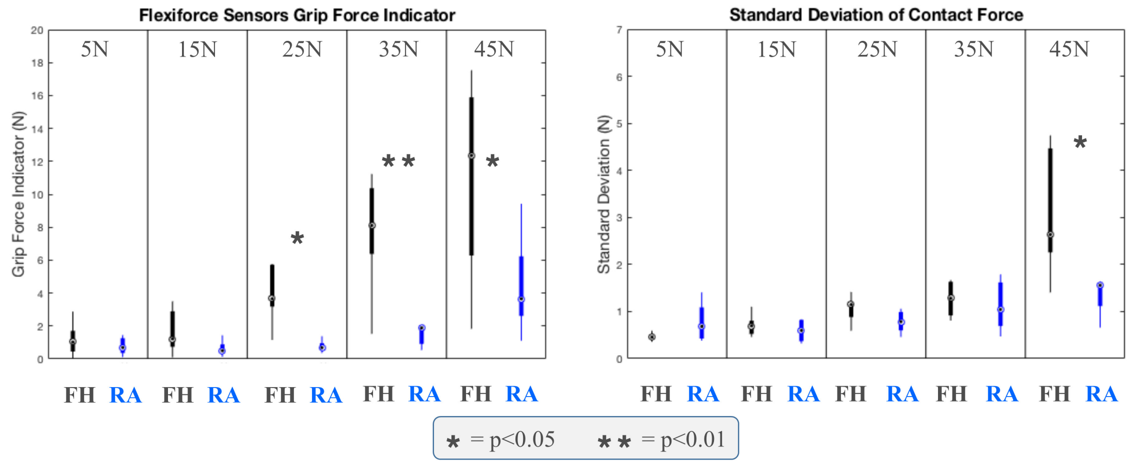

Figure 5: Augmented figure from Finocchi's paper [3] showing the results of average grip force and standard deviation of contact force (n=6). I have overlain some text to make it more clear.

As seen, the robot assistance significantly lowered the mean grip force required for holding the probe when the applied force was greater than or equal to 25N, however this was accompanied by a large range of values amongst test subjects. In addition, the robot assistance helped lower standard deviation of contact force (e.g. more stable) for higher forces when compared to the FH method. It should be noted that the robot made stability worse in low force cases, but as per Finocchi this is likely because of the limited ability of the load-cell to resolve small forces, as well as an admittance control transition condition at low forces that may have caused abrupt changes in robot behavior.

8.B User Study [1/2]: Difficulty and Strenuousness

The result of the first user study experiment (n=6), summarizing user-reported difficulty and strenuousness of scanning, is shown in Fig. 6 below.

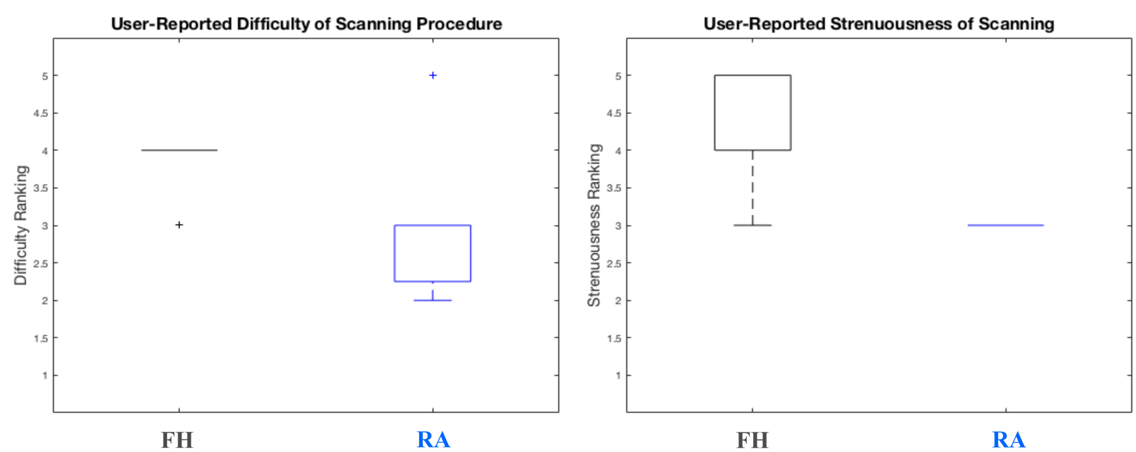

Figure 6: Augmented figure from Finocchi's paper [3] showing the results of the survey outlining user perceived scanning difficulty and strenuousness (n=6). I have overlain some text to make it more clear.

As seen, the robot assistance was more commonly reported to be less difficult and less strenuous to use versus the FH method. This is a great result for this work, since even if grip strength is lowered and image stability improved, the users must be happy with it to adopt it into their clinical workflow.

8.C User Study [2/2]: Image Quality

The result of the second user study experiment (n=7), summarizing the SSD for all three performed tasks, is shown in Fig. 7 below.

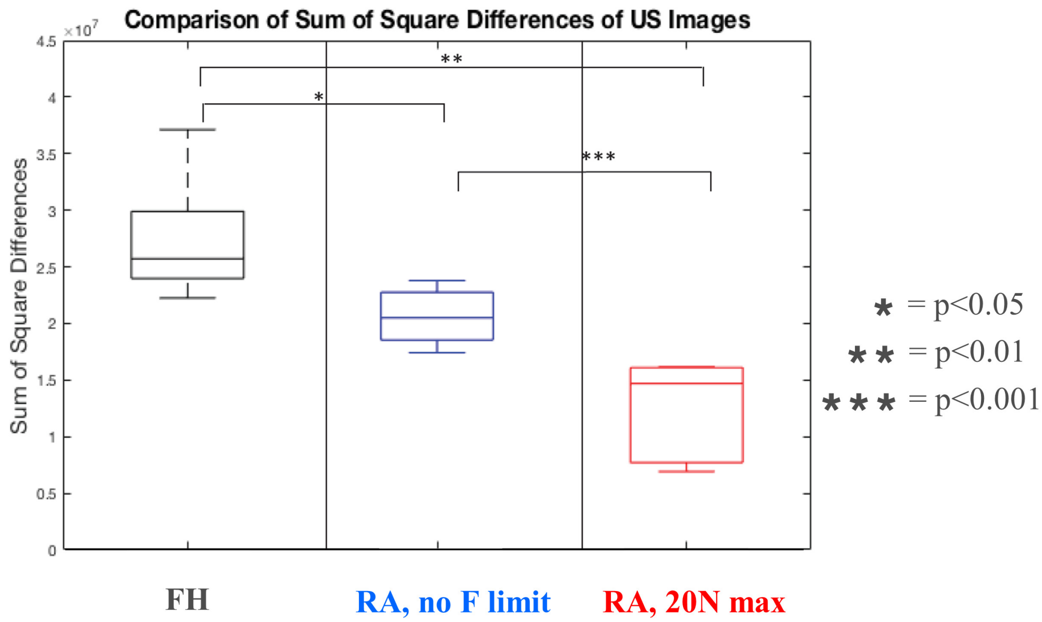

Figure 7: Augmented figure from Finocchi's paper [3] showing the results of the SSD image stability metric (n=7). I have overlain some text to make it more clear.

As seen, the robot assistance increased image stability over the FH method, with the most significant result being for the robot assistance with 20N maximum applied force limit. This makes sense, as the user could simply push as hard as they could against the phantom focusing solely on stability while the robot takes care of all force limiting.

8.D Summary

In summary, the robotic assistance showed promising results especially for high force sonographic tasks. In particular, it lowered mean grip force, standard deviation of contact force, perceived strenuousness and difficulty of scanning, while also increasing image stability. Finocchi makes the point that just because the improvements were best for high force applications, this does not mean it would not be successful in low force applications. He points out that the effects of muscle fatigue still arise in prolonged, low-force procedures and therefore users could still benefit from the robotic assist's reduction of tremor and readjustment necessity.

9. Assessment

In this section, the "good" and "could be improved" parts of the paper and the underlying research will be discussed, as well as where future work could be directed.

9.A The Paper

This paper was generally well written, but certainly contained some aspects that could be improved upon.

The "Good":

- This paper demonstrated a strong knowledge of robot kinematics, especially in terms of admittance control. It does a good job of clearly describing the equations and terms, including their dimensionality and set belonging.

- The results of this paper were presented in a clean and easily understandable manner. Box-and-whisker plots represented this data well and all instances of significance were clearly marked between plots.

The "Could be Improved":

- The pictures included in this paper were rather unclear and could have been improved to aid in understanding the experimental setup. For instance, the experimental image (shown in Fig. 1) was cluttered and used black text on a rather dark image. Additionally, the probe holder (shown in Fig. 2) cross-section did not show or label the locations of inner components such as the F/T sensors or US probe.

- The experiment could not be reproduced from the information provided. Most notably, Finocchi does not describe his nonlinear gains used to convert F/T values at the EE to desired Cartesian EE velocities. Reading into his thesis, a separate paper, he describes an elaborate sigmoidal gain function with a deadband zone when the F/T was less than 0.1N [4]. However, none of this information is described here. Additionally, he does not describe his gravity compensation methodology, which was performed as it exists in his codebase located on a JHU lab computer. While gravity compensation may not be extremely important when applying a restricted 20N of force against a patient, the probe does contribute approximately 5N of force which can be significant if the user is applying low forces or moves the robot off the patient and expects the robot to stay in place. In the latter case, without gravity compensation, a robot moved off of a patient would start to dangerously fall back towards them due to the gravity contribution of the probe.

- The paper does not discuss the programmatic implementation of the robot control software, containing only one mention of MATLAB when describing how a least squares optimization problem was solved. With a task as tricky as controlling a robot (which usually includes latencies, dropped packets, multitasking, concurrent data access, and more) the absence of implementation details was noticeable and should have been discussed to a certain extent.

9.B The Research

The research performed for this paper was generally sound and produced a successful admittance control approach for robotic US assistance. However, there are certainly aspects of this research that could be improved upon.

The "Good":

- This research accomplished a full implementation of an admittance controlled system, built using novel housing and advanced filtering methods. In itself, this is a difficult, and great accomplishment.
- The mechanical clamshell design allowing probe-patient force compensation through an additional embedded load-cell sensor was clever and successful.

The "Could be Improved":

- While the load-cell could help compensate $+z$ probe forces applied against a patient, there are likely forces and torques in the other directions that need to be compensated for in a clinical setting. Cardiac imaging is a good example, where the probe is held under the sternum, looking up and under the ribs at the heart. In instances such as this, there are many non-axial forces and torques introduced. Therefore, an additional 6-DoF F/T sensor, instead of a load-cell, should be used to resolve these forces.
- Only $n = 6$ and $n = 7$ participants were used for each experiment respectively. These numbers are rather low to draw conclusions from, especially in analyzing survey-based results which are usually subject to user bias and skew.
- Since this experiment only used grip force sensing, it can only conclude that the robotic US assist lowers exerted grip force which arguably may or may not have any affect on sonographer musculoskeletal disorder development. An improved study should look at better ways to quantify "exerted effort" as it pertains to increasing risk for mulsculoskeletal issues.
- The grip force measurement system completely ignores typical sonographer probe grips. In the experiment, the seven force sensors were placed on the handle of the housing, requiring the user to hold it with a barbell hammer grip to make contact with all sensors. In a clinical setting, users typically hold a probe like a pencil or teapot in which case their palm does not make contact with the probe. Since this work seems to be suggesting a new paradigm for "how to hold an US probe during robotic assist," there should be sonographer feedback on if the new hammer grip is acceptable and realistic for a clinical setting.

9.C Future Work

9.C.1 Improvements

This work could be improved in the future by addressing the comments made earlier in this section. Most importantly, 1) the user study should be expanded to more than n=6 and n=7 users; 2) more than 1-DoF should be used to resolve probe-patient forces; and 3) better methods for characterizing sonographer "exertion" should be explored.

9.C.2 Applications

An operational, hand-over-hand controlled US robot opens up a realm of new US technique possibilities... aside from the fact that this work benefits almost any robotic US procedure that requires a probe be maneuvered by hand from bedside to patient. Some key applications of robotic US include STRATUS imaging, robotic US tomography (especially in prostate imaging and diagnosis), autonomous catheter tracking, dual-US mirroring for venous US procedures, and performing repeatable biopsies with respiratory gating.

10. Conclusion and Personal Relevance

In conclusion, this work produced a successful prototype of an US robotic assistance system. Since the aim of my project is to improve upon the motion transparency of this one, I will be adopting, modifying, and changing some aspects of Finocchi's work to arrive at a more stable result.

Adopting:

- The physical setup. I will be using the same robot and 6-DoF F/T sensor, as well as similar housing which was modified by Fang [5].
- The nonlinear admittance control gains. These will likely be modified later on, but are a great starting point.
- The questionnaire. The survey did a good job of assessing operator task load, and by using the same survey my results can be directly compared with his as a measure of personal success.

Modifying:

- The load-cell to be a 6-DoF F/T sensor to compensate non-axial applied probe forces.
- The user study to include surface EMG (sEMG) sensing for quantifying exertion regardless of sonographer grip. This should allow sonographers to use the robotic assist in a way similar to their current workflow, while measuring muscle activity which is a better and more whole quantifier of physical exertion than just grip force.

Changing:

- The implementation to be written in C++ as opposed to MATLAB. This should speed-up the admittance control calculation and filtering allowing me to command the robot at a faster rate.
- The filtering to be done by an adaptive Kalman filter. This will help infer inter-packet F/T values allowing me to command the robot at a faster rate with more accuracy.

Overall, this paper is a great starting point for my work and I have learned a lot about how to improve upon Finocchi's research by carefully combing through the details described here. With this knowledge, I aim to produce a smoother admittance control experience for users while also maintaining (and hopefully improving) Finocchi's decreased strenuousness of scanning and increased US image stability.

References

[1] T. Rousseau, N. Mottet, G. Mace, C. Franceschini and P. Sagot, "Practice Guidelines for Prevention of Musculoskeletal Disorders in Obstetric Sonography", *Journal of Ultrasound in Medicine*, vol. 32, no. 1, pp. 157-164, 2013. Available: 10.7863/jum.2013.32.1.157.

[2] A. Schoenfeld, J. Goverman, D. Weiss and I. Meizner, "Transducer user syndrome: an occupational hazard of the ultrasonographer", *European Journal of Ultrasound*, vol. 10, no. 1, pp. 41-45, 1999. Available: 10.1016/s0929-8266(99)00031-2.

[3] R. Finocchi, F. Aalamifar, T. Fang, R. Taylor and E. Boctor, "Co-robotic ultrasound imaging: a cooperative force control approach", *Medical Imaging 2017: Image-Guided Procedures, Robotic Interventions, and Modeling*, 2017. Available: 10.1117/12.2255271.

[4] R. Finocchi, "Co-robotic ultrasound imaging: a cooperative force control approach", The Johns Hopkins University, 2016.

[5] T. Fang, H. Zhang, R. Finocchi, R. Taylor and E. Boctor, "Force-assisted ultrasound imaging system through dual force sensing and admittance robot control", *International Journal of Computer Assisted Radiology and Surgery*, vol. 12, no. 6, pp. 983-991, 2017. Available: 10.1007/s11548-017-1566-9.