Project Proposal

Robotic Ultrasound Assistance via Hand-Over-Hand Control

EN 601.656 Computer Integrated Surgery II

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1. Clinical Motivation

This project is motivated by the fact that ultrasound (US) guided procedures typically require a sonographer to hold an US probe against a patient in static, contorted positions for long periods of time while also applying large forces [1]. As a result, 63%-91% of sonographers develop occupation-related musculoskeletal disorders compared to only about 13%-22% of the general population [2].

The vision of this work, as well as the previous works discussed in the next section, is to provide sonographers with "power-steering" via a hand-guidable robot that they can maneuver to a point-of-interest and then release, having the robot do all the strenuous holding on their behalf.

2. Prior Work

Prior work in robotic ultrasound assistance has been performed by numerous individuals at JHU, with the most notable contributions coming from Rodolfo Finocchi and Ting-Yun (Angel) Fang whose work serves as a starting point for this project. Finocchi was an original developer of the first robotic ultrasound assistance prototype, in which he used MATLAB code to add admittance control to a UR5 robot using dual-force sensors (to decouple forces applied to a patient) in a custom housing. His main contributions included the custom ultrasound probe and dual-force sensor housing, algorithms for admittance control and contact force control, use of a 1€ filter to smooth force/torque (F/T) inputs, use of a sigmoidal force-to-velocity conversion function, and user-study verification through grip force measured via FlexiForce film [3, 4]. Finocchi's setup is shown in Fig. 1 below.

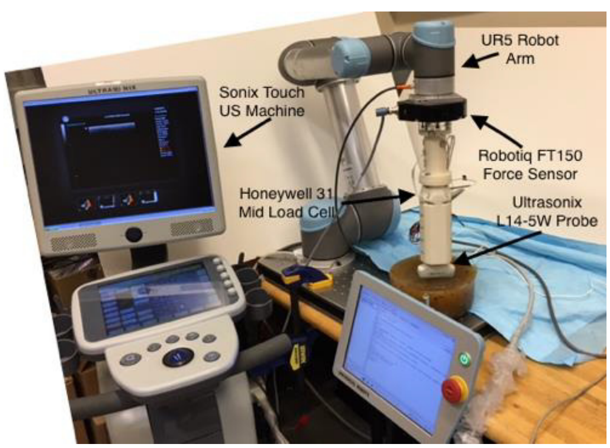

Figure 1: The experimental setup developed by Finocchi [3, 4]. The custom probe and dual-force sensing housing can be seen attached to the UR5 robot.

As an application of Finocchi's work, Zhang used the developed cooperatively controled robotic system in combination with virtual fixtures to implement synthetic tracked aperature ultrasound (STRATUS) imaging [5]. Additionally, Finocchi's robotics work was extended by Fang who iterated upon the custom housing design to make it more compact and validated the result through applied force reduction, stability of contact force, and stability of ultrasound images [6]. Fang's improved setup is shown in Fig. 2 below.

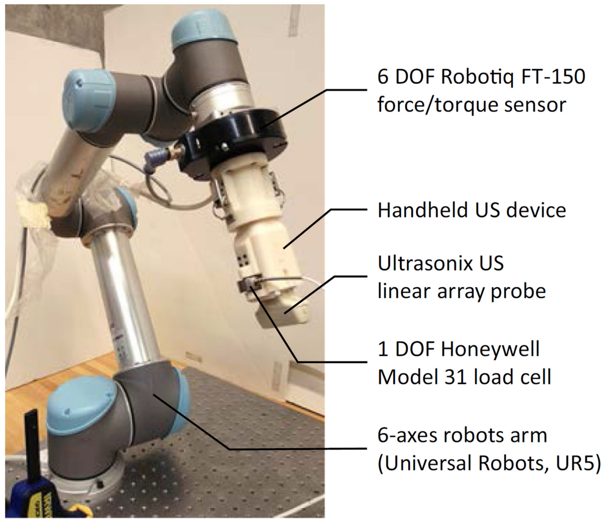

Figure 2: The experimental setup developed by Fang [6]. The improved end-effector housing can be seen attached to the UR5 robot.

While all of these works were successful in relieving grip strain while maintaining force profiles and capturing quality ultrasound images, multiple users (namely Dr. Russell Taylor and Dr. Emad Boctor) have reported that their prototypes lacked the "transparency" of power-steering necessary for clinical usage.

3. Goals

In the previous section, it was shown that previous attempts at cooperatively-controlled robotic ultrasound with dual-force sensing were successful in many applications such as maintaining force profiles, enforcing virtual fixtures, and relieving grip strain, but lacked the overall motion transparency to be practical in a clinical setting. The goal of this work is to improve upon the previous robotic ultrasound assist prototypes and create a more transparent power-steering, cooperative-control experience for sonographers. While the same sensors, housing, and robot will be used, it is believed that additional algorithms can be developed to help smooth the commanded robot motion.

If successful and validated, this work will be an important progression toward mitigating sonographers' susceptibility to work-related musculoskeletal disorders. It also has consequences for all procedures under the umbrella of robotic ultrasound, as the control algorithms developed for this work will underlay and improve all applications built on top of it. Some examples include enforcing virtual fixtures for synthetic aperture procedure, imaging with respiratory gating, replicating a position/force profile for repeatable biopsy procedures, and conducting co-robotic ultrasound tomography scans.

4. General Experimental Setup

The experimental setup will be as shown in Fig. 3 below. A desktop computer will be used to communicate with a 6-DoF UR5 robot using TCP/IP on a private LAN. Through this connection, the computer will receive position, velocity, and force information while transmitting commanded velocities. The dual-force sensing, ultrasound probe wielding end effector developed by Fang [6] will be attached to the robot. The system uses “dual-force” since in addition to the 6-DoF Robotiq FT-150 F/T sensor, a 1-DoF Honeywell Model 31 load cell will be used to discern forces applied by the probe against a patient or phantom. In the scope of this work, a phantom will be used with at least one subsurface, tubular feature that can be scanned as part of the testing procedure outlined in Section 6.

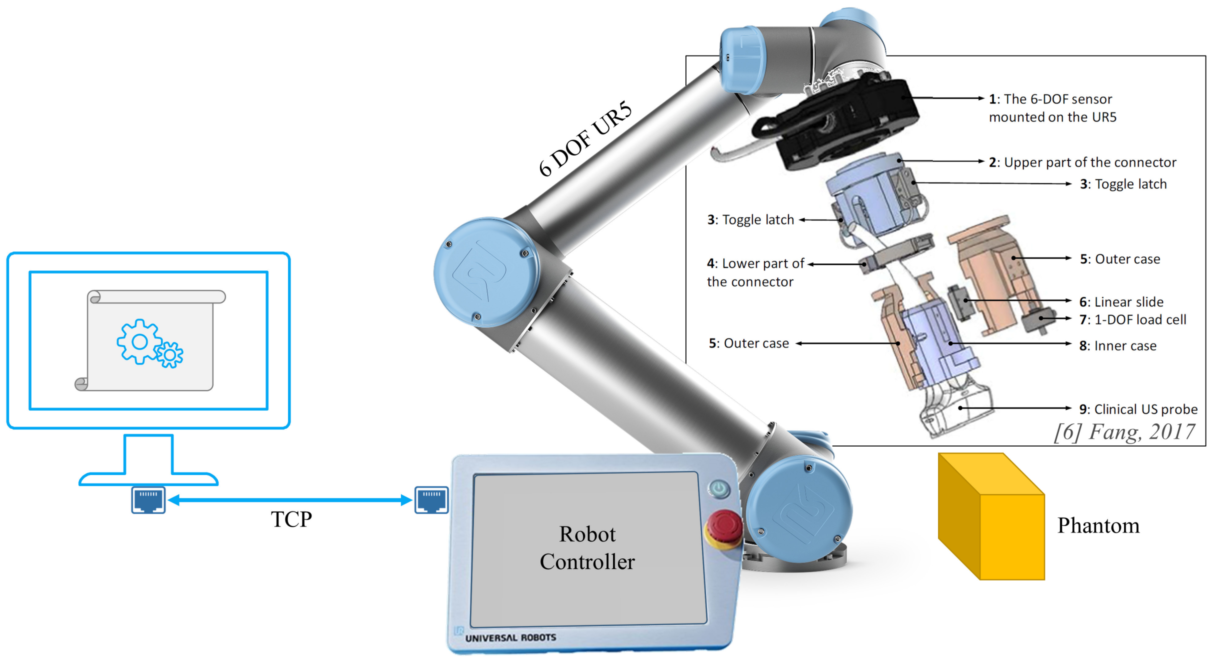

Figure 3: The experimental setup for this work, including a computer commanding a UR5 robot over TCP/IP as well as probe-holding end-effector developed by Fang [6] (figure inside the black border is from Fang, 2017).

5. Technical Approach

5.A Control System Approach - Kalman Filtering

As mentioned in Section 2, the algorithms used by Fang [6] and Finocchi [3, 4] primarily focused on filtering the F/T signals received to produce more stable velocities, namely through their use of nonlinear F/T-velocity gains and the 1€ filter used for smoothing hand-guided motion. While they still achieved an adequate result, their work does not consider data sparsity and latency which greatly contributes to the user experience in real-time robotics.

The issue with data sparsity and latency arises primarily from the 6-DoF F/T sensor which sends 100 Hz of data in TCP packets that arrive at 20 Hz (e.g. a packet arrives every

50ms containing the previous 5 samples of F/T data). A naive approach at robotic control could be developed which commands new robot velocities immediately upon receiving an incoming F/T packet, but this would mean the UR5 is commanded at 20 Hz, much lower than its maximum supported rate of 125Hz (Fig. 4).

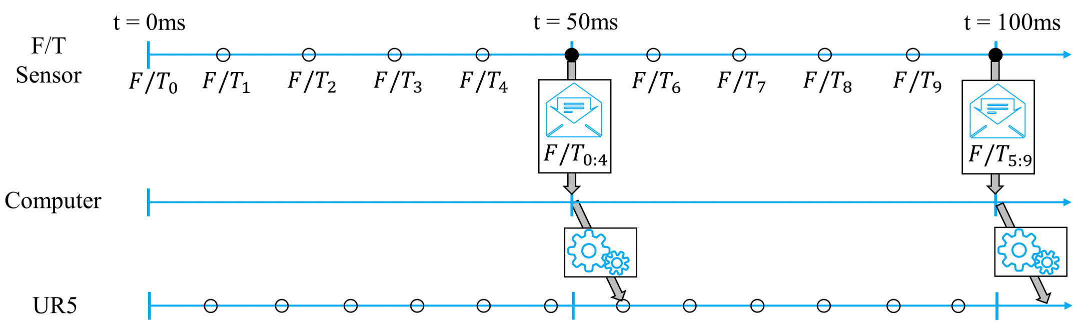

Figure 4: A naive robot control scheme that only commands the robot when a F/T packet arrives. Since packets arrive at 20 Hz and the robot can be commanded at 125 Hz, this approach does not utilize the robot to its fastest capability.

In this work, an adaptive Kalman Filter will be used to generate inter-packet F/T inferences therefore allowing the robot to be commanded at its full 125 Hz potential (Fig. 5). It is also suspected that the Kalman Filter can be tuned to help alleviate the effects of TCP latency between when the F/T packet is sent and when the robot is commanded in response. It is worth noting that the filter will be made "adaptive" to improve future predictions by automatically updating its covariance matrices when a new F/T packet arrives based on how well its predictions matched the real measured F/T values.

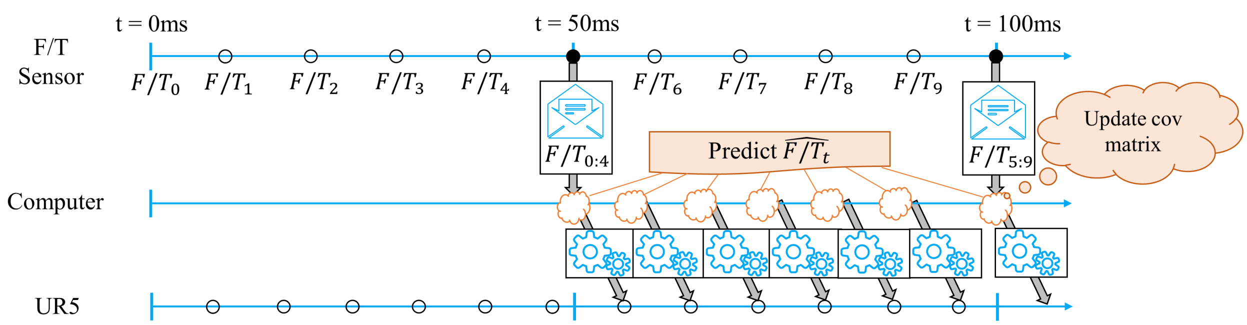

Figure 5: A more advanced robot control scheme that uses adaptive Kalman filtering to predict inter-packet F/T readings so that it can command the robot as fast as possible.

5.B Programmatic Approach - C++ Implementation

As mentioned in Section 2, Fang [6] and Finocchi [3, 4] implemented all of their code in MATLAB and used client software running on the UR5 to relay F/T values to the computer. While they still achieved an adequate result, using an interpreted language such as MATLAB and running unnecessary client-side code introduces latency and overhead which is detrimental to the user experience of any real-time system. In this work, C++ will be used in combination with the open-source CISST/SAW libraries to get data from, and command the UR5 without any client-side code. A simplified diagram is shown in Fig. 6.

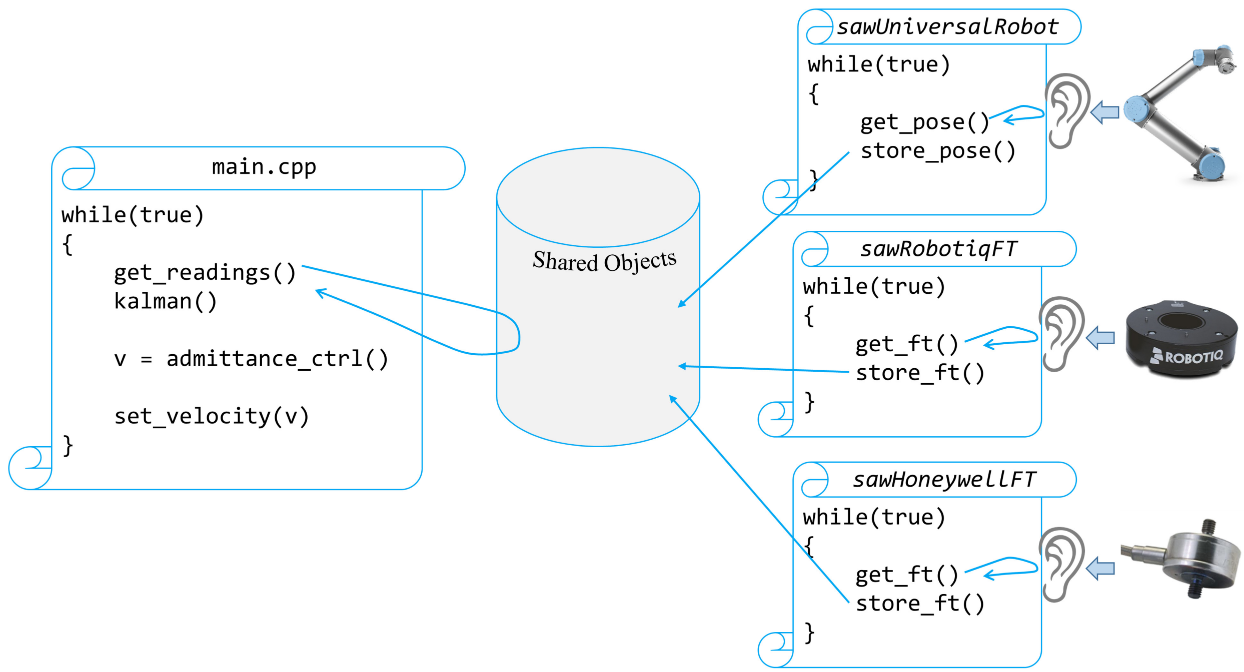

Figure 6: A simplified code flow diagram showing the asynchronous component listeners and `main.cpp` which will perform the admittance control, filtering, and robot commanding.

As shown, there will be three SAW components listening for data from the robot and F/T sensors respectively and storing them in objects accessible by `main.cpp`. The main script, in addition to performing component initialization, will essentially be an infinite loop of fetching readings, filtering, and commanding a velocity to the UR5 SAW component. It is worth noting that the CISST/SAW libraries have native support for accessing shared data in a way that prevents race conditions, which is very useful since this program relies on asynchronous, multitask execution and is therefore prone to data corruption.

6. Testing Plan

Testing will follow a generic, industrial-inspired verification and validation (V&V) approach.

6.A Verification

Verification will test if our system is acting as it is expected to, e.g. if the admittance control seems transparent to the user and helps relive wrist strain. This will be measured via qualitative and quantitative methods described in the subsections below.

6.A.1 Surface Electromyography Measurement

Previous work by Murphey and Milkowski [7] used surface electromyography (sEMG) to quantitatively measure sonographer musculoskeletal strain while performing scans in different postures. For their work, they placed a sensor on the left upper trapezius (trapezius region is strained when using ultrasound control panel) and the right suprascapular fossa (rotator-cuff region is strained while scanning the patient). While control panel strain is not in the scope of this project, using sEMG to measure rotator cuff strain (and possibly another to measure scanning forearm strain) would help in quantifying sonographer physical effort/exertion during scanning tasks when performed freehand versus when using the robotic assist. The tasks proposed in the HIRB appliction include 1) holding the probe against a phantom with a constant 20N for a period of time to measure (testing stability of contact force); and 2) tracing a subsurface, tubular feature within the phantom with the probe while applying a force of 20N (testing probe maneuverability). It should be pointed out that the 20N amount is adopted from Finocchi [3, 4].

6.A.2 Questionnaire

A questionnaire is an adequate way to learn more about a study participant's potential confounding variables as well as gauge their experience trialing the system. In Finocchi [3], a survey was used for this purpose and will be replicated for this experiment. The survey is provided in Appendix A and asks the subject about their perceived easy/difficulty performing ultrasound scanning tasks (described above) freehand versus when using the robotic assist. Since this project aims to improve the transparency of Finocchi's previous work, using the same survey conveniently provides a metric for comparison of the two projects. Additionally, this work will also present test subjects with NASA's Task Load Index (TLX) which is a broadly used survey to assess operator exertion and workload [8]. The survey is provided in Appendix B, which is copied from NASA's website.

6.B Validation

Validation will test if our system is filling the role it should be, e.g. if the system in its current state could be useful in a clinical setting. While there are no concrete plans to test with real sonographers within the HIRB study, the team expects to communicate with approximately five sonographers (or physicians who routinely perform sonography) toward the end of the project and have them trial the device (without sEMG) to get their qualitative, professional opinions on the system and its clinical usability. While these results will be casual and unpublished, they will let the team know if they are on the right track and may help guide future JHU ultrasound robotics research and proposals long after CIS2.

7. Key Activities and Deliverables

The key activities and their respective deliverables for this project are listed in the table below, categorized as either a minimum, expected, or maximum activity/deliverable. A graphical timeline of these activities and deliverables can be found in Section 9.A.

	Activity	Deliverable
Min.	C++ interface with robot and dual force sensors to collect data	Datasets for multiple static poses
	Implement rudimentary in-air admittance control, gravity compensation	Video of functionality, graphs showing compensation, code and documentation
Expected	Implement improved admittance control through adaptive Kalman filtering incorporating probe-pt. force feedback	Video of functionality, code and documentation
	Qualitatively & quantitatively evaluate the system with test subjects	Report with graphs and statistical validation
Max.	Virtual fixtures	Video of functionality, code and documentation

Figure 7: The minimum, expected, and maximum key activities with their corresponding deliverables

Essentially, the minimum activity is to interface with the robot and implement very simple, unfiltered admittance control as a proof of functionality; the expected activity is to implement the main contribution of this work, the adaptive Kalman Filter, to improve admittance control as well as test the system with subjects in an HIRB-approved study; and the maximum activity is to implement virtual fixtures as would be necessary for synthetic aperture imaging. Throughout all these activities, deliverables in the form of datasets, graphs, figures, videos, code, and documentation will be produced.

8. Dependencies

There are multiple dependencies embedded in this project, including both physical objects and approvals that the team members do not have direct and personal control over. These dependencies are described in the table below in terms of how the team plans to resolve each dependency, when each has to be resolved by (soft and hard deadlines), and the contingency plan if a particular dependency is not met. A graphical timeline of dependency resolution is provided in Section 9.B.

Dependency	Need	Status	Followup	Contingency Plan	Planned Deadline	Hard Deadline
Robot	Actuated to provide "power-steering"	Have a working UR5	N/A	If breaks, could seek continued permission to use UR3 in B08	2/1	2/1
6DOF F/T Sensor	Admittance control input	Have a working Robotiq FT-150	N/A	If breaks, look to order another through the MUSiiC Lab	2/1	2/1
Load Cell	Decouples force from probe on pt.	Have a Honeywell Model 31	Must test the load cell asap	If broken, look to order another through the MUSiiC Lab. Otherwise do the best possible with just the 6-DoF F/T sensor.	2/12	2/28
Ultrasound Probe	Key component for realistic testing	Have a curved probe, several others available in our lab pod	N/A	If disappears, seek permission to use another probe available in lab pod	2/1	4/1
sEMG sensor	Used to measure physical exertion while scanning	Will look to acquire through the MUSiiC Lab	Speak with Dr. Boctor	If unable to acquire, the team can approach Dr. Taylor to order the item if it could be useful to other LCSR labs. Otherwise, testing can still proceed without sEMG data	3/8	3/15
Phantom (non-anatomical)	Something to test the probe on	Un-acquired, several available in our lab pod	Seek permission from Dr. Boctor to use phantoms in lab pod	If unable to acquire, test on easily available surfaces like polyethylene foam	2/1	4/1
HIRB Approval	Testing with sonographers	Unsubmitted, untrained for human subjects testing, HIPPA	Undergo training, revise and submit plan from Nov '16	If not approved in time, we can still perform qualitative validation with sonographers to see if exertion is improved in their expert opinion.	2/22	3/1

Figure 8: The status, resolution plan, and contingency plans for important project dependencies.

9. Timeline

The timeline for this project can be broken into three parallel tasks: hand-over-hand control implementation, dependency resolution, and reports and documentation. The respective timelines for each of these are shown below, with the JHU spring break week highlighted in yellow.

9.A Hand-Over-Hand Control

Hand-over-hand control will be implemented sequentially according to the activity expectations set forth in Section 7. The aim is to achieve the minimum activities of gravity compensation and rudimentary admittance control using only the 6-DoF F/T sensor by the end of February, then move onto the expected activities of Kalman filtering and incorporating the 1-DoF load cell for improved admittance control through early April. It is planned to perform HIRB-approved user testing, an expected activity, during April in parallel with the maximum activity of virtual fixture implementation as testing should ideally not occupy much of the team's time. Implied throughout this timeline and all of its subtasks is the continuous documentation of code.

Hand-over-hand Control

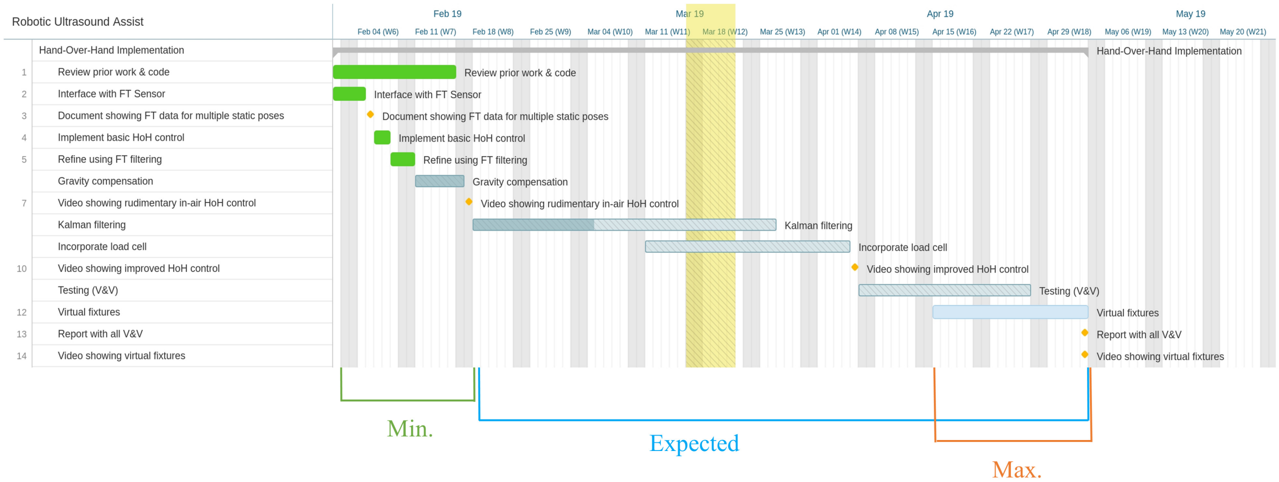

Figure 9: The collapsed timeline for hand-over-hand control implementation. An expanded version of the timeline showing subtasks can be found in Appendix C.

9.B Dependency Resolution

All dependencies are expected to be resolved by the end of February, at which time all required hardware will be either acquired or ordered and an HIRB application will have been submitted.

Dependency Resolution

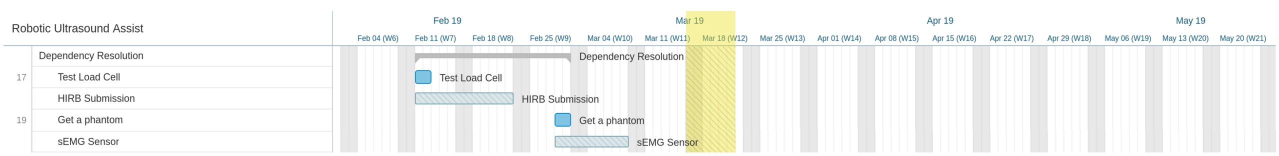

Figure 10: The timeline for dependency resolution.

9.C Reports and Documentation

In addition to constant code documentation performed throughout the project, specific documents and presentations are required for the class and therefore impact the team's workload. The times where the team plans to work on these items, as well as their due dates, are shown in the timeline below.

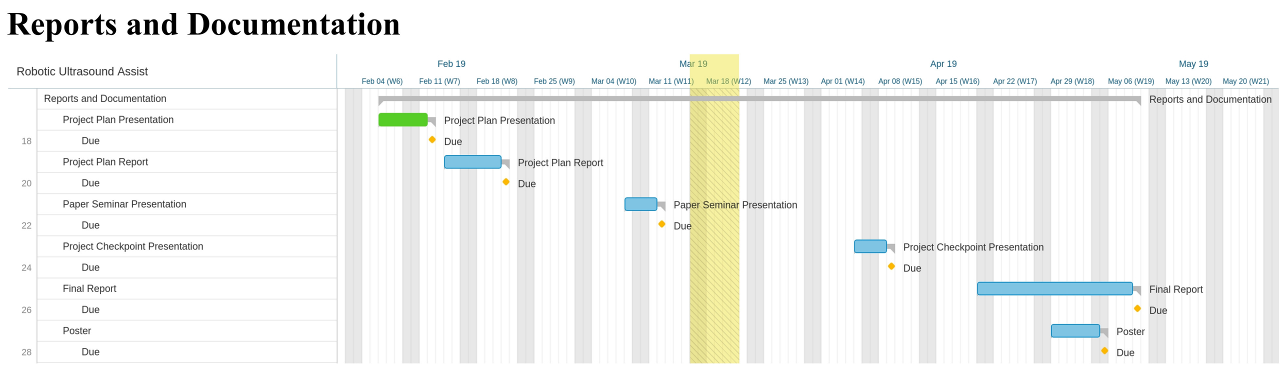

Figure 11: The timeline for reports and documentation, including times when these items will be worked on as well as their due dates.

10. Team Members/Mentors and Roles

10.A Team Members

The team consists of:

- **Kevin Gilboy** (kevingilboy@jhu.edu)
  MSE student, Department of Electrical and Computer Engineering, first-year
  Sole responsibility for all tasks required in this project.

10.B Team Mentors

The mentors consist of:

- **Dr. Emad Boctor** (eboctor1@jhmi.edu)
  Assistant Professor, Department of Radiology and Computer Science
  Expertise in ultrasound, computer-integrated surgery, and the future of ultrasound technology. Can help provide JHMI connections as needed for system evaluation.

- **Dr. Mahya Shahbazi** (mahya.sh@jhu.edu)
  Postdoctoral Fellow, LCSR
  Expertise in control systems design, computer-integrated surgery, robot kinematics.

11. Management Plan

11.A Meetings

Currently, there are two scheduled weekly meetings where team mentor(s) will be present for project updates and questions. The first is a weekly Ultrasound robotics status update meeting at 1PM on Friday afternoons where Dr. Boctor and Dr. Shahbazi will attend, and the second is a weekly MUSiiC Lab meeting at 3PM on alternating Wednesday and Friday afternoons where Dr. Boctor will attend. There will likely also be additional ad hoc meetings between team members and mentors as needed.

11.B Platforms

Several platforms will be used to support the development of this project and its accompanying reports.

- **Communication**: All communication will be performed by email or phone/text, as all team members and mentors have exchanged emails and cellphone numbers.
- **Code**: All code will be stored initially in a private GitHub repository, likely to be made public by the end of the research after all disclosure considerations have been made.
- **Report Writing**: All reports will be written using Overleaf, an online, collaborative LaTeX editing environment.
- **Document Storage**: All final documents, presentations, deliverables, and links to external resources will be curated on the CIIS Wiki page made for this project.

12. Reading List

Listed below are several invaluable sources related to this work and implementation. Above each source, in **bold**, is a brief description of each work.

- **Virtual fixture mathematics** Ming Li, A. Kapoor and R. H. Taylor, "A constrained optimization approach to virtual fixtures," *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Edmonton, Alta., 2005, pp. 1408-1413. doi: 10.1109/IROS.2005.1545420
- **Virtual fixtures and cooperative control for robotic STRATUS procedure:** H. K. Zhang, R. Finocchi, K. Apkarian and E. M. Boctor, "Co-robotic synthetic tracked aperture ultrasound imaging with cross-correlation based dynamic error compensation and virtual fixture control," *2016 IEEE International Ultrasonics Symposium (IUS)*, Tours, 2016, pp. 1-4. Available: 10.1109/ULTSYM.2016.7728522
- **Thesis, development of initial robotic ultrasound assist prototype using the UR5:**
R. Finocchi, "Co-robotic ultrasound imaging: a cooperative force control approach", The Johns Hopkins University, 2016.
- **Initial robotic ultrasound assist prototype using the UR5:**
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.
- **Improved probe holder for Finocchi's work using the UR5**
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.

- **Kalman filtering for improved admittance control in an industrial application:**
  S. Farsoni, C. Landi, F. Ferraguti, C. Secchi and M. Bonfe, "Compensation of Load Dynamics for Admittance Controlled Interactive Industrial Robots Using a Quaternion-Based Kalman Filter", *IEEE Robotics and Automation Letters*, vol. 2, no. 2, pp. 672-679, 2017. Available: 10.1109/lra.2017.2651393.

References

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[2] 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.

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

[4] 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.

[5] H. K. Zhang, R. Finocchi, K. Apkarian and E. M. Boctor, “Co-robotic synthetic tracked aperture ultrasound imaging with cross-correlation based dynamic error compensation and virtual fixture control,” *2016 IEEE International Ultrasonics Symposium (IUS)*, Tours, 2016, pp. 1-4. Available: 10.1109/ULTSYM.2016.7728522

[6] 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.

[7] S. Murphey and A. Milkowski, “Surface EMG Evaluation of Sonographer Scanning Postures”, *Journal of Diagnostic Medical Sonography*, vol. 22, no. 5, pp. 298-305, 2006. Available: 10.1177/8756479306292683.

[8] S. Hart and L. Staveland, “Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research”, *Advances in Psychology*, pp. 139-183, 1988. Available: 10.1016/s0166-4115(08)62386-9.

Appendix A Ease of Use Survey

ID: _____

Ease of Use Survey: UR5 Robotic Assisted Ultrasound

1. How much experience do you have with handling ultrasound-imaging systems (select all that apply)?
    - ❑ Clinical Experience
    - ❑ Research Experience
    - ❑ Other Experience: ________________________
    - ❑ No Experience

2. How easy/difficult was it to perform the imaging tasks using freehand ultrasound (without robotic assistance)?
    - ❑ Extremely easy (1)
    - ❑ Somewhat easy (2)
    - ❑ Neither easy nor difficult (3)
    - ❑ Somewhat difficult (4)
    - ❑ Extremely difficult (5)

3. How easy/difficult was it to perform the imaging tasks with UR5 robotic assistance?
    - ❑ Extremely easy (1)
    - ❑ Somewhat easy (2)
    - ❑ Neither easy nor difficult (3)
    - ❑ Somewhat difficult (4)
    - ❑ Extremely difficult (5)

4. How physically strenuous was the imaging task using freehand?
    - ❑ Not at all strenuous (1)
    - ❑ Minimally strenuous (2)
    - ❑ Moderately strenuous (3)
    - ❑ Very strenuous (4)
    - ❑ Extremely strenuous (5)

5. How physically strenuous was the imaging task using robotic assistance?
- ❑ Not at all strenuous (1)
- ❑ Minimally strenuous (2)
- ❑ Moderately strenuous (3)
- ❑ Very strenuous (4)
- ❑ Extremely strenuous (5)

6. How intuitive was the manipulability of the UR5 robotic system compared to freehand (only using ultrasound probe)?
- ❑ Much less intuitive (1)
- ❑ Somewhat less intuitive (2)
- ❑ Neither more nor less intuitive (3)
- ❑ Somewhat more intuitive (4)
- ❑ Much more intuitive (5)

Appendix B NASA TLX (Task Load Index) Survey

Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Appendix C Expanded Development Schedule