Augmentation of Haptic Guidance into Virtual-Reality Surgical Simulators

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Introduction

The number of robotic-assisted minimally invasive surgeries (RMIS) performed annually is rapidly increasing, and new surgeons must be trained to meet this demand. In the current standard of training, novices often spend many hours completing practice tasks which are graded with observational feedback. Getting this feedback requires trained surgeons to spend time going through the videos or watching in real-time, leading to high operational costs and low efficiency. Furthermore, if not corrected early trainees can develop poor habits that will take longer to break after being ingrained over several days of training.

There is a need for new technologies that can lower these mentorship barriers to and speed up training. Current work being done in the space involves building Virtual Reality simulators on daVinci Research Kits (dVRK) for basic tasks such as suturing (see figure 1). While these tasks are able to provide real-time feedback visually (in the example, the green colored ring indicates a proficient needle entry), they do not provide any corrective guidance for wrong motions. The goal of this project is to incorporate real-time corrective guidance to these virtual simulators with reference to the optimal path for the task. Coupled with the visual feedback, we will be able to work to determine the efficacy of haptic feedback in teaching RMIS principles.

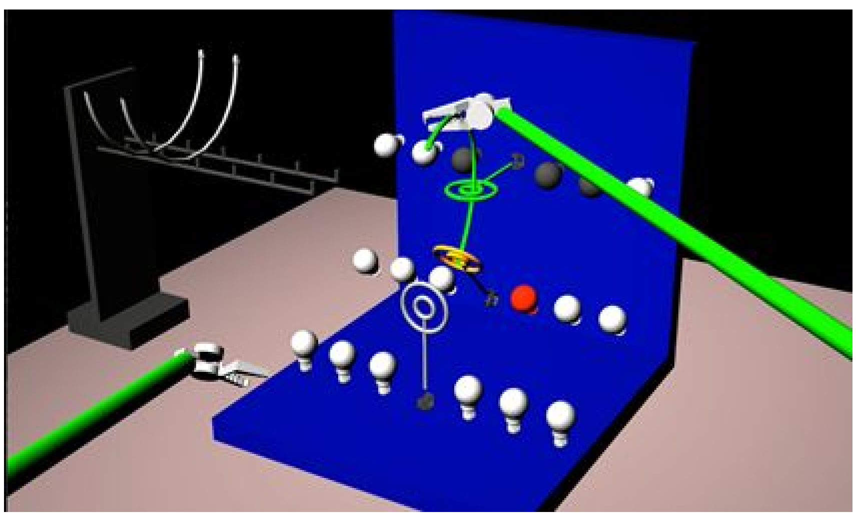


Figure 1: State of surgical simulator at start of semester.

Project Goal

There are three (3) main project goals. The first is to augment a virtual reality surgical simulator with real-time feedback. The second is to evaluate the effects of this real-time feedback in a user study. The third is to conduct another user study to evaluate the effects of brain stimulation while using the surgical simulator.

These project goals are specified as deliverables, divided into three categories, and described here:

- **Minimum:** (Expected by 4/19)
    1. Code for computing and applying haptic feedback to dVRK manipulators stored in GitLab
    2. Code for computing and displaying visual feedback on dVRK stereoscopic viewer stored in GitLab
    3. Documentation of environment including operation, maintenance, and future

- **Expected:** (Expected by 4/26)
    1. Documentation of study protocol for evaluating implemented feedback stored on Google Drive.
    2. Scripts for data collection and data analysis stored in GitLab
    3. Report on user study evaluating the effects of real-time feedback and our chosen approach(es) (Goal n = 15)

- **Maximum:** (Expected by 5/09)
    1. Documentation of study protocol for using brain stimulation stored on Google Drive.
    2. Scripts for data collection and data analysis for brain stimulation stored in GitLab
    3. Report on user study evaluating the effects of brain stimulation

Technical Approach

There are two phases for this project: implementation and evaluation. The implementation section is written in as a standard technical approach. The evaluation section is written as if it were the 'Methods' section of a journal paper, and it therefore repeats some of the information from the implementation section.

Implementation

A. Haptic Feedback

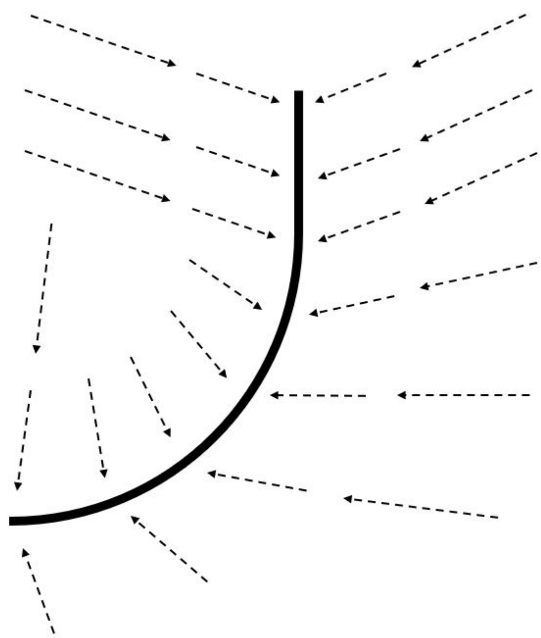


Figure 2: 2D representation of haptic guidance forces applied in 6-D to the master gripper. Forces are applied pointing toward the desired path and with some forward forces. Both forces and torques are applied.

The majority of implementation work is in creating the haptic force algorithm.

The desired path of the 6-DoF suture tip poses if encoded as 100 poses, each of which contain a position and rotation matrix. The positions form a curved path followed by a perfect quarter-circle, and the orientations are always tangent to the path.

The simulation runs at 200 Hz. At each time step, we read the pose of the suture tip and the pose of the end effector. Because we are using a simulation, we know these positions exactly. We use this data to calculate the transformation between the suture tip and end effector ($T_{suture, EE}$).

We search through the vector of poses to find the desired pose. The desired pose is defined as the pose 3 indices ahead of the pose with the lowest translational error to the current translational position of the suture tip. This allows for a predictive guidance, and the 3 indices was chosen from feedback received during some initial pilot testing. In order to prevent the desired pose from rapidly jumping to different sections of the desired path, each newly calculated desired pose is limited to be within a small distance from the previous desired pose.

We then apply the previously calculated tip to end effector transformation ($T_{suture, EE}$) to the desired pose. This results in the desired end effector pose. We use the translational and rotational error between the current and desired end effector poses to calculate the haptic feedback to be applied to the end effector.

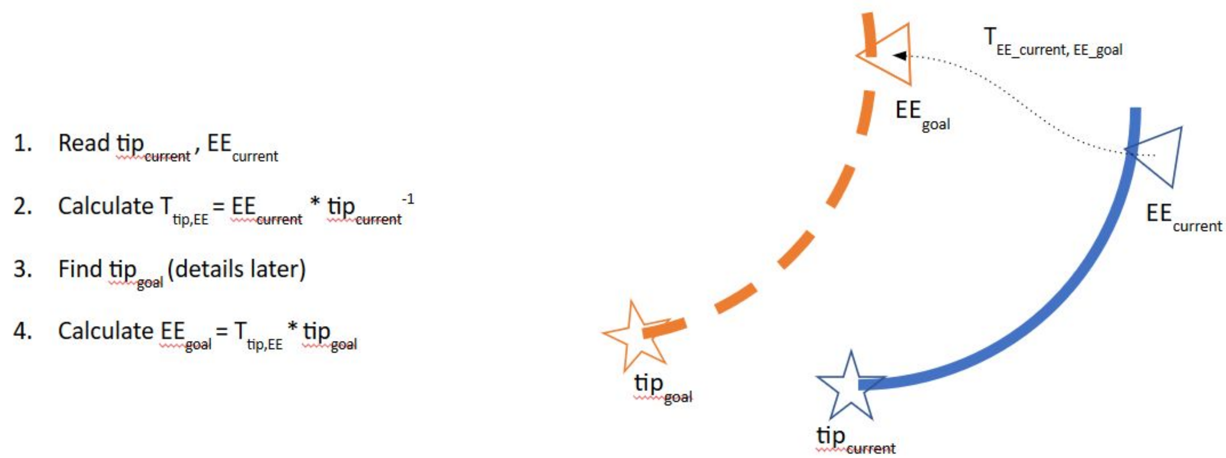


Figure 3: Calculating the desired end effector pose

The force vector is then calculated as:

$$\mathbf{F} = -k_{translational} * (\mathbf{x}_{current} - \mathbf{x}_{desired}) - d_{translational} * \mathbf{v}_{current}$$

Equation 1: Translational force vector calculation. $k_{translational}$ is the translational spring constant, $\mathbf{x}_{current}$ is the 3-DoF current position vector, $\mathbf{x}_{desired}$ is the 3-DoF desired position vector, $d_{translational}$ is the translational damping constant, and $\mathbf{v}_{current}$ is the current 3-DoF velocity vector.

Analogously, the torque vector is calculated as:

$$\mathbf{R} = -k_{rotational} * (\mathbf{R}_{RPY,\ current} - \mathbf{R}_{RPY,\ desired}) - d_{rotational} * \boldsymbol{\omega}_{current}$$

Equation 2: Rotational torque vector calculation. $k_{rotational}$ is the rotational spring constant, $\mathbf{R}_{RPY,\ current}$ is the RPY representation of the current rotation matrix, $\mathbf{R}_{RPY,\ desired}$ is the RPY representation of the desired rotation matrix, $d_{rotational}$ is the rotational damping constant, and $\boldsymbol{\omega}_{current}$ is the current angular velocity vector.

The values for the spring damper constants were fine-tuned with pilot testing, and with these values calculated, the forces and torques can be applied directly at the end effector to help guide the user.

B. Visual Feedback

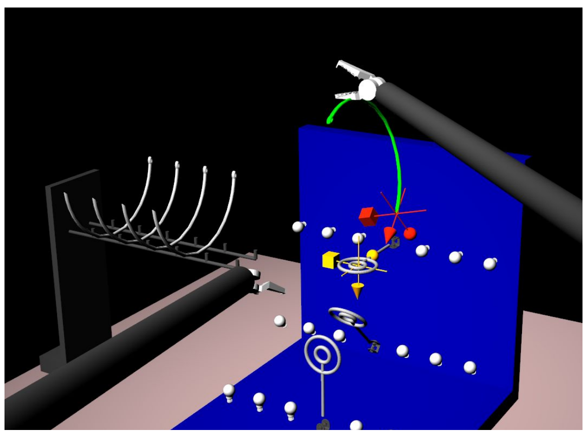


Figure 4: Visual feedback. Subjects are told that the yellow frame is the closest pose on the desired path and that the red frame is the current suture tip pose. When the suture is directly on the desired path, the poses are exactly on top of each other.

The implementation of visual feedback takes advantage of much of the work already done in the haptic feedback implementation.

The visual frame used for visual feedback is a 3D marker with arrows pointing perpendicularly to each other in all 6 directions. At the end of each arrow is a different shape, which allows each arrow to be differentiated from the others. The shapes used are a cone, a cube, and a sphere. In order to differentiate the visual frames, each is a different color from the others.

During the trials, the two visual frames are the current suture tip and the desired suture tip. The visual frames are overlaid onto the current suture tip pose and the desired suture tip pose. These poses are already calculated to compute the haptic feedback. When the current suture tip pose is exactly the desired suture tip pose, the visual frames are directly on top of each other.

Before each trial, another two visual frames are displayed as an aid for initially grasping the suture. These two visual frames are the current end effector pose and the ideal end effector pose for grasping the suture. The current end effector pose is read directly from the simulation. The ideal end effector pose is calculated by applying a standard $T_{suture, EE}$. When the current end effector pose is exactly the desired end effector pose, the visual frames are directly on top of each other.

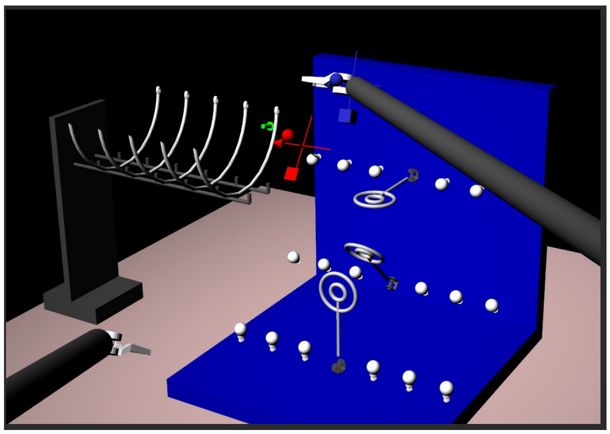


Figure 5: Visual feedback. Current end effector pose and desired end effector pose for initially grasping the suture.

Additionally, it is possible to display visual frames for the current end effector pose and the desired end effector pose during the trials. These frames are also already calculated for the haptic feedback. These two visual frames were ultimately disabled, as the screen became too crowded with too many visuals.

C. Performance Metrics

To evaluate subject performance, we calculate 5 metrics: trial time, translational path error, rotational path error, starting angle error, and ending angle error.

Trial time is calculated as the time from when the suture enters the first ring to when the suture exits the final ring. This metric quantifies speed.

$$\text{Trial time} = t_{ring3} - t_{ring1}$$

Equation 3: Trial time calculation

Translational path error is calculated as the area of a surface between the actual path and the desired path, as shown in Figure 4. At each time step, we read the current end effector position ($\mathbf{x}_{t,\ actual}$) and we calculate the distance to the closest point on the desired path ($\mathbf{x}_{t,\ desired}$). We also calculate the distance between the current closest point on the desired path and the previous closest point on the desired path ($\mathbf{x}_{t-1,desired}$). We multiply these two distances to get an area for each data point on the actual path, and then we sum the areas for all of the data points on the actual path to get the final metric. This metric quantifies accuracy.

$$\text{Translational path error} = \sum_{t=t_{ring1}}^{t_{ring3}} (\mathbf{x}_{\text{t, actual}} - \mathbf{x}_{\text{t, desired}}) * (\mathbf{x}_{\text{t, desired}} - \mathbf{x}_{\text{t-1, desired}})$$

Equation 4: Translational path error calculation

Rotational path error is calculate analogously to translational path error, except that an angle difference is used rather than the distance between the actual and desired positions. These two path error metrics and their descriptions are taken directly from M. M. Coad et al., “Training in divergent and convergent force fields during 6-dof teleoperation with a robot-assisted surgical system,” IEEE World Haptics Conf., 2017, pp. 195–200.

$$\text{Rotational path error}= \sum_{t=t_{ring1}}^{t_{ring3}} (\mathbf{R}_{\text{RPY, t, actual}} - \mathbf{R}_{\text{RPY, t, desired}})*(\mathbf{R}_{\text{RPY, t, desired}} - \mathbf{R}_{\text{RPY, t-1, desired}})$$

Equation 5: Rotational path error calculation

Starting angle error is the angle difference between the current pose and the desired pose when the suture enters the first ring. Analogously, ending angle error is the angle difference when the suture exits the final ring.

$$\text{Angle error} = ||\mathbf{R}_{\text{RPY, current}} - \mathbf{R}_{\text{RPY, desired}}||_2$$

Equation 6: Angle error calculation

Much of the data collection code was already created in the simulation before we began our work. Our work included modifying the data collection scripts to also collect the desired poses and implementing the above functions to extract features from the time-series data.

Evaluation

D. Surgical Robotic Platform

The experiment uses a da Vinci Research Kit (dVRK). Participants look into the stereoscopic viewer to see a simulated 3D environment of an experimental task. All experiments were carried out with the teleoperation scale factor set to 0.2. Participants were not allowed to use the clutch to reposition the master manipulators, move the camera, or change the zoom level.

E. Procedure

Participants are asked to complete a virtual suturing task. The virtual environment is shown in Figure 1. They are instructed to pick up a suture from the left side of the simulation, and then follow a path defined by 3 rings. This desired path is defined as a vector of 6-DoF poses. The positions form a straight line followed by a perfect quarter-circle, and the orientations are always tangent to the path.

Before the participants begin the experiment, they are introduced to the dVRK. This occurs in a separate virtual environment, where only the virtual end effectors are loaded. This allows the participant to learn to the details of controlling the robot (coag as head sensor, pinch to start moving, etc). Participants are then shown an animation of perfect trial.

Each participant completes 50 trials of the suturing task. Participants are given a short break and asked to complete a survey after each session of 5 trials. This survey consists of the NASA-TLX survey, as well a question about the strategy the participant took and a question about how the haptic/visual feedback if applicable.

There are four (4) experimental groups. The control group (Group 1) completes all 50 trials with no haptic or visual feedback. The three (3) test groups receive haptic and/or visual feedback during trials 6-30. All groups receive no feedback in the first 5 trials (trials 1-5) and the last 20 trials (trials 31-50).

The haptic group (Group 2) receives haptic feedback, which guides the user towards and along the desired path. This force/torque field is applied in both position and orientation, with a 3-DoF force vector applied based on how far their position was from the position of the desired pose, and with a 3-DoF torque vector applied based on how far their orientation was from the orientation of the desired pose. The desired pose is the pose slightly in front of the closest pose on the desired path, i.e., if the 1st pose in the ordered list of ideal poses is the closest pose, the desired pose is the 4th pose.

The visual group (Group 3) receives visual feedback. This overlays a 6-DoF frame on top of the suture tip, as well as a 6-DoF frame on top of the closest pose on the desired path. If the user is exactly on the desired path, these 2 frames are directly on top of each other. Additionally, while the subject is picking up the suture, 6-DoF frames are overlaid on to the end effector and the ideal suture pick-up position.

The visuo-haptic group (Group 4) receives both visual and haptic feedback. The feedback is exactly the same as the feedback received by the haptic and visual groups.

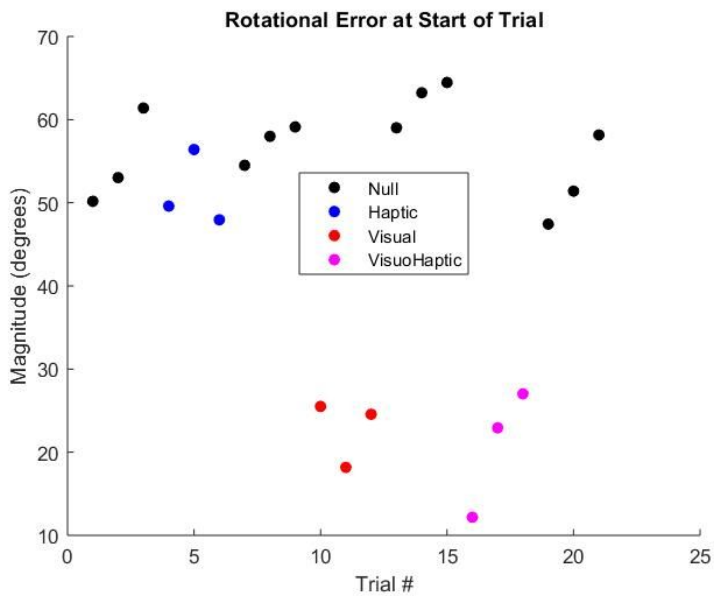
We have the option of changing the task position and orientation between sets of trials. By changing the camera angle, we can change the motion required to complete the task. This may be useful in order to avoid teaching a specific path instead of general surgical robotics skill as desired. However, with the advice of our mentors, we decide to keep the path constant between sets of trials. This is because the suturing motion follows a specific path, and it may be useful to teach this specific path.

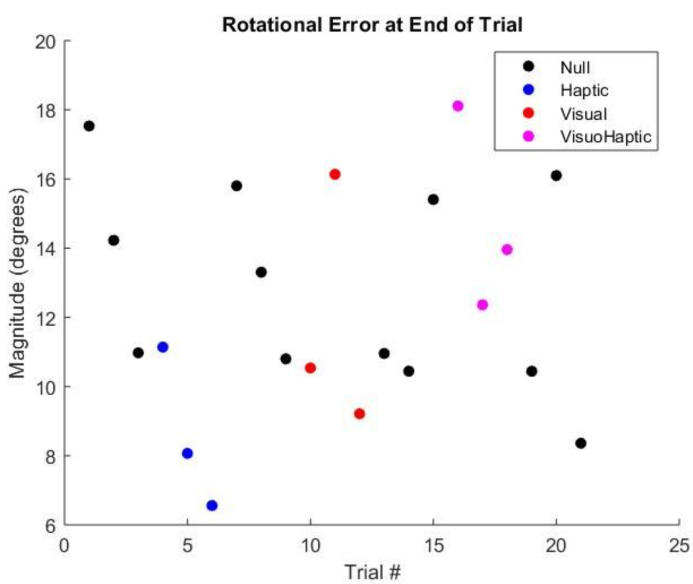
F. Participants

Participants will be recruited according to HIRB00005942. Participants will be novices with little to no experience with the da Vinci Surgical System or the da Vinci Research Kit.

Results

We were unable to complete a full user study. Presented here are results from pilot studies. During these pilots, 2 subjects were given all three forms of feedback. In sets of 3, trials alternate between null feedback and one of the feedback conditions. A total of 42 trials were collected. The blue background represents trials with haptic feedback. The red background represents visual feedback. The purple background represents visuo-haptic feedback.





Discussion

These results serve as a proof of concept that the system is working and that real-time feedback could potentially be useful in training for robotic minimally invasive surgery. Our results show that real-time feedback has an effect on performance.

In trials with visual or visuo-haptic feedback, subjects reduced the magnitude of their rotational error at the start of each trial. In trials with haptic feedback, subjects reduced the magnitude of their rotational error at the end of each trial. However, these decreases do not hold when feedback is removed. We still believe, though, that real-time feedback can lead to better training even after feedback is removed. We believe that aspects of the simulation can be changed to bring out this effect.

Currently, in the simulation, the rings light up as green or yellow depending on how accurately the suture enters the ring. Users took the rings turning green as a measure of success. This led them to not focus on the other aspects of accuracy. For example, the rings currently light up only depending on translational error. Therefore, users are more focused on translational error and less focused on rotational error. We believe that, if focus is shifted to rotational error, the improvements from feedback may hold after feedback is removed. In the future, we plan to stop lighting up the rings.

Qualitative feedback from pilot subjects also led to many changes to the system. For example, we reduced the size of the visual frames provided during visual feedback because they were too large. We also reduced the number of visual frames shown for visual feedback, and we learned which frames were most important to keep from the pilot studies.

We also used the pilot studies to decide the strengths of the spring and damper constants. We learned that subjects liked having the spring constant be three times higher than we originally estimated.

Conclusion

We were able to augment a surgical simulator with both visual and haptic feedback. We conducted pilot user studies. After implementing minor changes according to the feedback we received during the pilot studies, we will be ready to conduct a full user study.

Management Plan

We had a weekly mentor meeting with the full mentor team. We had an additional weekly mentor meeting with just Guido Caccianiga. We met without mentors three times per week.

All members participated in all aspects of the project, but each student took the lead on different components. Eric lead discussions on the code structure and data flow chart. Vipul wrote a majority of the code. Eric and Vipul oversaw pilot data collection. Eric handled communications between the team and mentors. Brett took the lead on presentations and the final poster.

Final Deliverable Status

- **Minimum:** (Expected by 4/19)
    1. Code for computing and applying haptic feedback to dVRK manipulators stored in GitLab
    2. Code for computing and displaying visual feedback on dVRK stereoscopic viewer stored in GitLab
    3. Documentation of environment including operation, maintenance, and future work stored on Google Drive

- **Expected:** (Expected by 4/26)
    1. Documentation of study protocol for evaluating implemented feedback stored on Google Drive
    2. Scripts and documentation for data collection and data analysis stored in GitLab and Google Drive (partially complete)
    3. ~~Report on user study evaluating the effects of real-time feedback and our chosen approach(es) (Goal n = 15)~~

- **Maximum:** (Expected by 5/09)
    1. ~~Documentation of study protocol for using brain stimulation stored on Google Drive.~~
    2. ~~Scripts for data collection and data analysis for brain stimulation stored in GitLab~~
    3. ~~Report on user study evaluating the effects of brain stimulation~~

Our original minimum deliverable was the implementation of two forms of haptic feedback: guidance and forbidden region. We were successful in doing this. We were also successful in implementing visual feedback.

Our expected deliverable was evaluating the forms of feedback in a user study. While we were unable to conduct this study, we were able to create the protocols and conduct pilot studies. After changing the simulation according to feedback received during the pilots, the system will be ready for the full user study.

Our maximum deliverable was conducting a user study involving brain stimulation. Due to both unavailability of equipment and a lack of time, we were unable to conduct this study.

Lessons Learned

Many valuable lessons were learned through this course and project. Firstly, and possibly most importantly, ensure that the team is working with its full potential. In a team of 3, it's possible to work on many different aspects of the project simultaneously. Be sure to identify which parts of the project can be done in parallel. Using the full team to solve single issues, when time could be better spent working on multiple issues slowed progress on this project.

We also learned to plan for setbacks. Allow yourself time to tackle unforeseen problems. Solutions hardly work as intended the first time. Once you create a timeline, stick to it. Update the timeline if needed. Referring back to the timeline can help keep the project on schedule.

Another lesson learned is to create prototypes. We spent a large portion of the semester making plans for the implementation. While this was very useful when we eventually started creating the program, we likely could have accomplished the same thing more quickly if we had just jumped in to it. By spending so much time creating plans, we didn't leave ourselves enough time to finish many of the changes we wanted to make to the finished product.

Another lesson learned is the create general debugging tools. Halfway through the semester, our haptic feedback calculation was not working properly. We attempted to quickly solve the bugs without fully knowing the root cause. We ended up spending more than a week failing to find this bug. Finally, after we implemented a visual tool to describe the haptic feedback, we were able to locate the issue and quickly correct it. We may have been able to accomplish more for the project if we didn't spend the time before the debugging tool.

Future Work

Preparations have been made to pass on this work to future student researchers, potentially for Summer 2019. The current student researchers may continue this work in Fall 2019. The next steps are to make minor modifications to the system according to pilot subject feedback and to complete a full user study. Beyond that, there are a number of larger future directions for the system.

Currently, the system uses data from ROS publishers in order to calculate the haptic and visual feedback. This limits the feedback refresh rate to around 200 Hz. If the system is overhauled and adapted to use the dVRK plane optimizer, the refresh rate can be boosted to 1.8 kHz.

Furthermore, one interesting technique currently being researched in the field of haptics is feedback-as-needed. As subjects become more skilled with the task, the strength of beneficial haptic feedback can be reduced. This change can occur between sets of trials or even dynamically during trials. Implementing feedback-as-needed into this system will require a substantial amount of work and could potentially be another CIS project.

Our mentors may be able to submit this project for a grant from Intuitive. We may also use this project to apply for funding as undergraduate researchers.

Acknowledgments

This project was made possible by our mentors. The entire system is built on top of a simulation developed by one of our mentors, Guido Cacciagina. Additionally, we'd like to thank Anton Deguet for his help setting up the programming environment and for providing his expertise with the dVRK. Another thanks goes to the creators of the jhu-ciist and jhu-saw libraries, without which we would not have been able to undertake this project.

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Appendices

Google Drive:
https://drive.google.com/drive/folders/14SCRv1vqzIYPqj8pMy0QRrX2cFIgayOF?usp=sharing

Documentation (also in Google Drive):
https://drive.google.com/drive/folders/1EVcFGfJDSnpfe2z_TSQZeiI6QWZ7xP48?usp=sharing

CIS2 Wiki Page:
https://ciis.lcsr.jhu.edu/dokuwiki/doku.php?id=courses:456:2019:projects:456-2019-14:project-14

GitLab Repo: https://git.lcsr.jhu.edu/atar_cis2