Towards Asymmetric Oscillatory Haptic Feedback through the dVRK Platform

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***Abstract*—This project designed a novel directional haptic feedback system to augment existing haptic feedback methods for the da Vinci® surgical system. The new device generates haptic feedback by commanding two linear resonant actuators to oscillate asymmetrically; therefore a planar pseudo-force vector can be resolved for haptic feedback. The hardware transduces collisions of a simulated slave manipulator with an obstacle in Rviz into asymmetric oscillations perceived by the user as a directional resistance.**

CONTENTS

I. INTRODUCTION

Haptic feedback can greatly enhance the process of robot-assisted minimally invasive surgery (RMIS). For traditional RMIS, surgeons interact with a patient via a master manipulator. A computer interprets the motion of the master manipulator and moves the patient manipulator. This system unfortunately eliminates tactile cues and masks force cues. The lack of the significant haptic feedback may lead to increased intra-operative injury[1].

Natural haptic feedback generally includes two parts, kinesthetic and cutaneous,which provides myriad information like force, pressure distribution, temperature, vibration, and texture. Thus, understanding the mechanism behind haptic feedback and finding an effective way to transfer haptic information from slave actuator to master control console will improve the performance of teleoperation.

The intention of this work is to compare active impedance control with oscillatory haptic feedback. Traditional haptic feedback actuates the master manipulator's joints so that the master exhibits impedance in a direction when the slave manipulator's end-effector collides with a simulated obstacle. This project generates comparable haptic feedback by asymmetrically oscillating linear resonant actuators housed in a stand-alone module.

In section II, foundational haptic-feedback research projects will be introduced. In Section III, we will show the systems level design, mechanical design, simulation operation, and signal generation required to operate the haptic module. Results are demonstrated in Section IV and future work is described in Section V-B.

II. PRIOR ARTS

A. Asymmetric Vibrations - CMU

The foundation of asymmetric vibration for haptic feedback began with researchers at Carnegie Mellon University (CMU) [2]. Their design allowed a user to sense a directional cue in a plane when a gripper was vibrated asymmetrically.

The haptic module that our group designed was motivated by the principles derived in [2]; specifically, the asymmetric waveform from this paper is expanded upon in Section V-C.

B. Asymmetric Vibrations - GRASP

Dr. Culbertson, from GRASP Lab, documented that an asymmetric shearing oscillation applied to a test subject's skin results in the sensation of a force [3]. In the experiment, the users pinched a rod that had two voice-coils mounted on it. Due to the asymmetric shearing motion of the user's skin, they identified a pushing or pulling sensation as shown in Figure 2. The coils were driven using an asymmetric current waveform of a step followed by a ramp function, as seen in Figure 3. Using the TL-002-14R Haptuator, her results determined that the optimal input frequency is 40 Hz, with a step-input period of 7 ms, and a ramp period of 18ms.

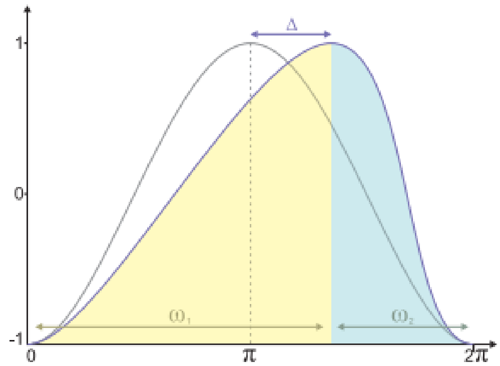

Fig. 1: Asymmetric sinusoid vibration input described in Reference [2].

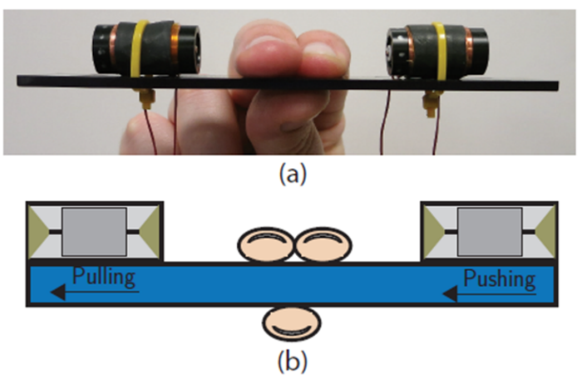

Fig. 2: Experiment setup described in Section II-B.

C. dVRK Gazebo Simulation - WPI

The AIM Laboratory at WPI [4] is seeking to improve the accuracy, confidence, and speed of RMIS. The AIM lab has shown that when the Patient Side Manipulator (PSM) contacts a simulated obstacle in a Gazebo simulation, the Master Tool Manipulator (MTM) can provide haptic feedback to the surgeon [5]. The simulation used is the da Vinci® Research Kit (dVRK) [6], an open source simulation initially developed by John Hopkins University.

In [5], Fischer and Munawar transduce haptic feedback force from a collision between a virtual object in the workspace environment and virtual elastic spherical probe (SPR) attached to the end-effector of the PSM.

Using the dVRK, this project built on the work from the AIM lab to make haptic feedback more realistic and fabricated a modular device to provide Asymmetric Oscillatory Haptic (AOH) Feedback for master manipulators without access to proprietary control systems. This device would also allow for haptic feedback when the original servo modules do not have the necessary bandwidth to provide AOH Feedback.

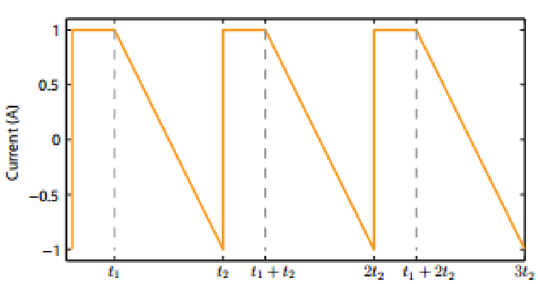

Fig. 3: Driving current waveform.

III. Methodology

A. Systems Level Design

In this section, we describe the scope of the project using a systems engineering approach that includes concepts of operation, functional systems requirements, and a high level system diagram to understand the scope of the project. Figure 4 illustrates the high level systems diagram showing how force readings were acquired from the simulation and either exerted as haptic feedback to a simulated MTM or on real physical haptic actuators referred to as Haptuators.

When the SPR of the PSM collides with an object in the environment, the force readings are measured and then decomposed into forces along the x, y, and z axis in the tool frame. On the hardware implementation side, this decomposed force is passed through a personal computer with a sound card. An algorithm transforms this force into three current signals that similar to Figure 3. These signals are passed through an audio amplifier and results in each Haptuator vibrating independently.

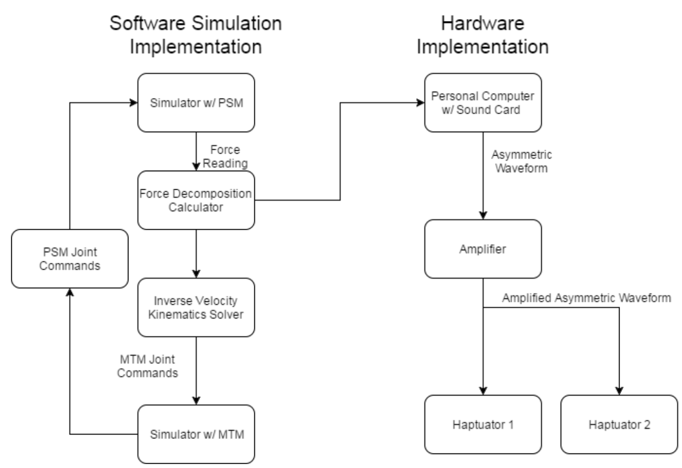

Fig. 4: System Interface Diagram.

B. Simulation

The simulation implementation can be divided into two major parts as seen in Figure 6. The first part is enclosed in the blue dashed box. The input to this setup is managed using a PSM joint command *Graphical User Interface*. When the insertion needle of the PSM touches an object in the simulation environment, a three-dimensional force vector is generated in both the insertion frame and the world frame by subscribing to to a haptics feedback force topic. This can be seen in Figure 5, where the green arrow is in the world frame, and the red in the insertion frame. The force vector is normalized for ease of implementation in the following stages.

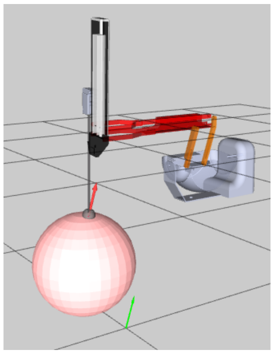

Fig. 5: Visualization of reaction force on the PSM.

There are two ways to generate haptic feedback from a force vector. The first way is shown in Figure 7. When external vibration actuators are utilized, the vibration is generated from the vibration actuators, as detailed in subsection III-D. When external actuators are absent, the MTM motors can be utilized to generate haptic feedback. An Inverse-Velocity-Kinematics solver is run in Matlab to make MTM joints generate required torques. This torque information is sent back to MTM simulator and makes the MTM vibrate.

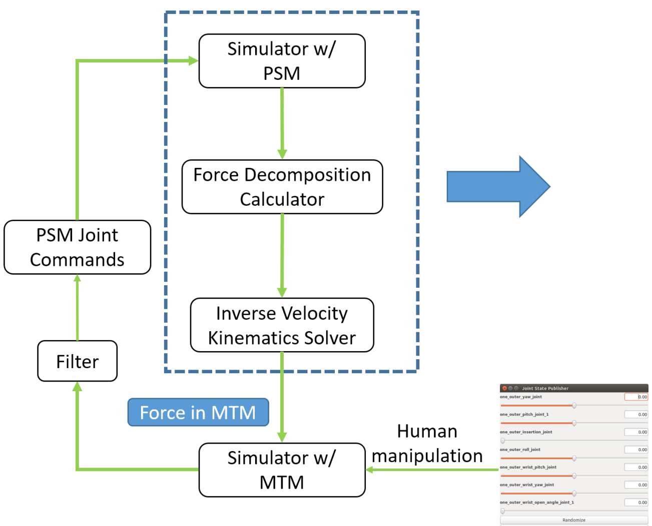

Fig. 6: Simulation in ROS.

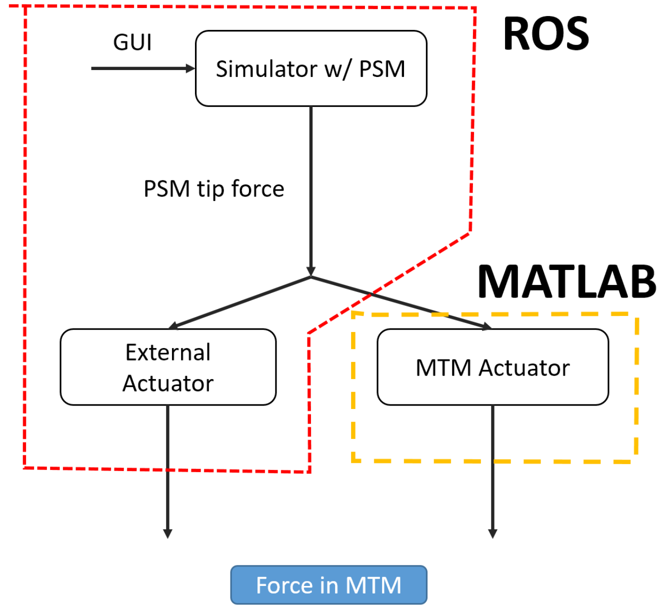

Fig. 7: Two ways for processing measured force in simulation.

Another area of consideration is to teleoperate the PSM when the MTM is manipulated. While generating a haptic feedback force is complicated by itself, we need to also consider the simultaneous operation of the MTM. The problem is now involves both haptic feedback and human manipulation/teleoperation. When a command is sent to the PSM joints, haptic information that interacts with the MTM should not be sent.

C. Actuators

Three linear actuators are necessary to provide AOH Feedback for an arbitrary collision of the simulated PSM end-effector. By correctly adjusting the phase of oscillation for each actuator, haptic feedback can originate from any direction as discussed in Section II-A. The idealized mechanism proposed here will produce zero net force[1]. TL-002-14R High-Bandwidth Vibrotactile Transducers (Figure 8) are chosen due to low price and availability. They have 16×29 mm cylindrical form factor, 11 g weight, and 50-500 Hz bandwidth.[7] The TL-042-14R voice coil motors are designed for haptic feedback applications and are used in Culbertson's project.

D. Waveform Generation

A ROS package was created to generate the asymmetric vibration waveform from the feedback force vector. It contains the `force2wave` and the `wave2sound` nodes (Figure 23).

[1] Asymmetric force oscillations with zero net force, however, can produce motion if the linear actuator that is driving the oscillation rests on a surface. If the peak force exceeds the surface friction the actuator will move (discontinuously) across the surface.

Fig. 8: TL-002-14R High-Bandwidth Vibrotactile Transducer[7].

a) From Force to Waveform Parameters: The purpose of the `force2wave` node is to to convert a feedback force vector to waveform parameters for each vibration actuator. This node first transforms the force from PSM tip frame into MTM gripper frame, then applies a function to the feedback force to generate the vibration waveform parameters, such as amplitude and frequency.

The function that maps from force to amplitude is a sigmoid function spanning from -1 to 1 (Equation 1). By tuning the gain a, different "softnesses" of the output can be achieved.

$$f(x) = \frac{2}{1+e^{-ax}} - 1 \tag{1}$$

b) Generate Audio Output from the Waveform Parameters: The `wave2sound` node listens for the waveform parameters for one channel and outputs the corresponding waveform to the computer sound card. Each vibration actuator requires a `wave2sound` node.

The audio signal was generated from a NumPy array with Python sound device library. The waveform consists of a steady voltage section followed by a ramp section, as described in Dr. Culbertson's paper[3]. Figure 9 shows the audio waveform generated from the internal audio card (channel 1 and 2). A USB audio card can be used for controlling a 3rd Haptuator. Note that the waveform appears deformed because of the DC-blocking capacitor in the output circuit. This is desirable because DC current in the voice coil motor does not generate motion, but heats up the coil.

c) Amplification: The audio signal was amplified with a Extron XPA1002 audio amplifier before being fed into the voice coil motor. Figure 10 shows the voltage input and current output waveform of the audio amplifier. The current output was measured using a $6.456\,\Omega$ current sense resistor in series with the voice coil motor. The output waveform appeared to be deformed due to the DC-blocking circuit in the signal path, but it preserved the important sharp rise and slow fall features.

This approach enables low latency signal generation with minimal hardware.

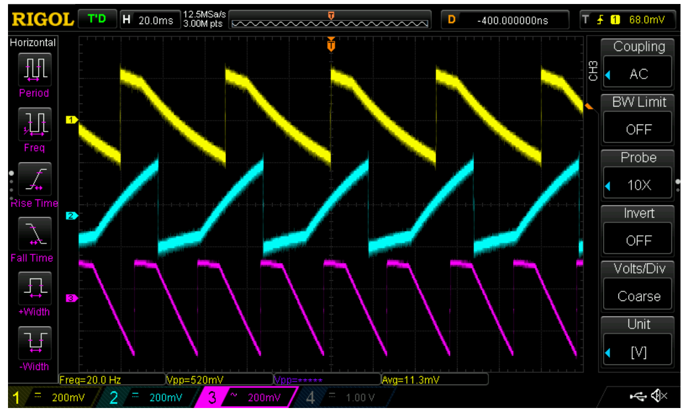

Fig. 9: Audio waveform output from computer and USB audio card.

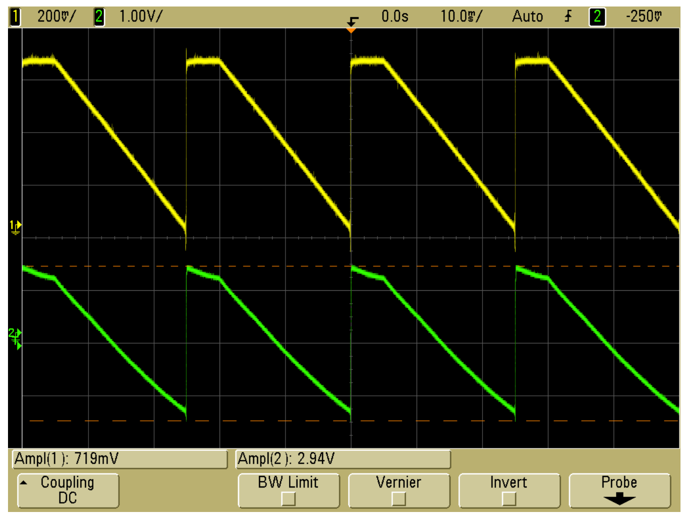

Fig. 10: Extron audio amplifier voltage waveform input (channel 1) and current output (channel 2), haptic feedback direction = left.

E. Mechanical Design

There were two iterations of the mechanical design to hold the Haptuators, which we decided to refer to as the Haptic Module to indicate the assembled part. The design requirements of the Haptic Modules are that they have to be as light-weight as possible, and ensure that the most accurate vibratory feedback gets transferred to the user's fingers for the shearing sensation. A lightweight module ensures that the skin-shearing is maximized due to conservation of momentum within system of the user's hand and the Haptuator. The first iteration of the Haptic Module that was designed for three-axis directional feedback is displayed in Figure 11 and Figure 12.

Upon initial testing, there are several flaws to Haptic Module 1's design. As annotated in Figure 12, the axis of Haptuator vibration, indicated with the dashed lines, did not intersect with the point where the user's fingers land. Since directional

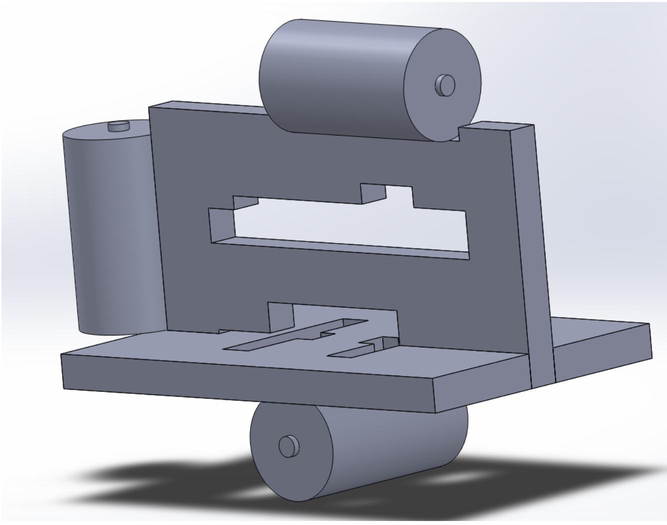

Fig. 11: CAD model of Haptic Module 1 with three axis directional feedback.

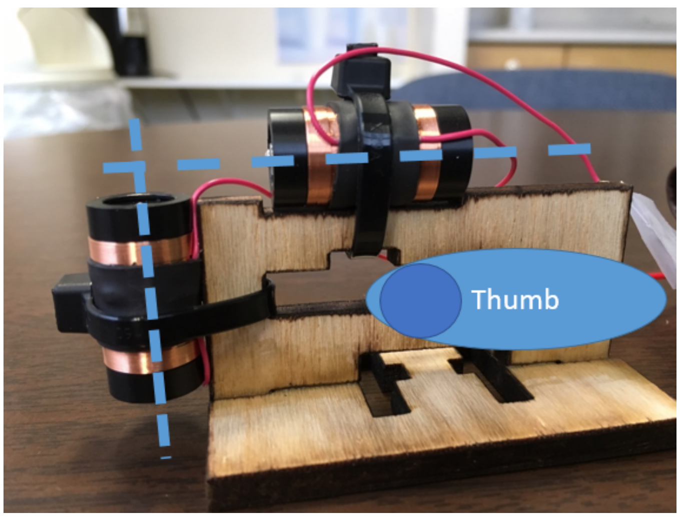

Fig. 12: Assembled Haptic Module 1 with annotated axis of vibration and finger placement.

haptic feedback is established through the shear force on the user's skin, this offset creates a rotational vibration around the user's finger tips instead of creating the desired shearing sensation. Furthermore, the third Haptuator was lost, forcing us to simulate planar haptic feedback.

Thus, the second iteration of the Haptic Module, dubbed the Haptic Module 2, was designed. The CAD model is displayed in Figure 13.

As indicated with the dashed line in Figure 14, both axes of vibration now point directly to the point of contact with the finger tips. Although it cannot be seen in this image, there is a small indent where the axes intersects to indicate the user on where to grip the haptic module for best results. Iteration

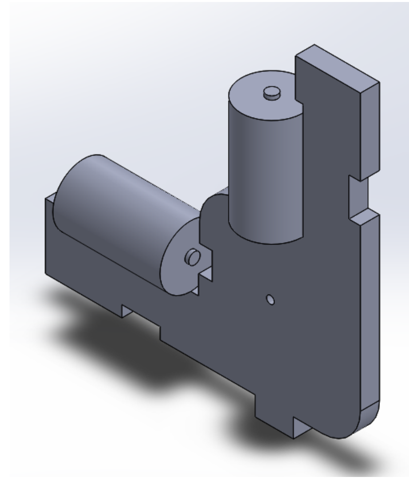

Fig. 13: CAD model of Haptic Module 2 with two axis directional feedback.

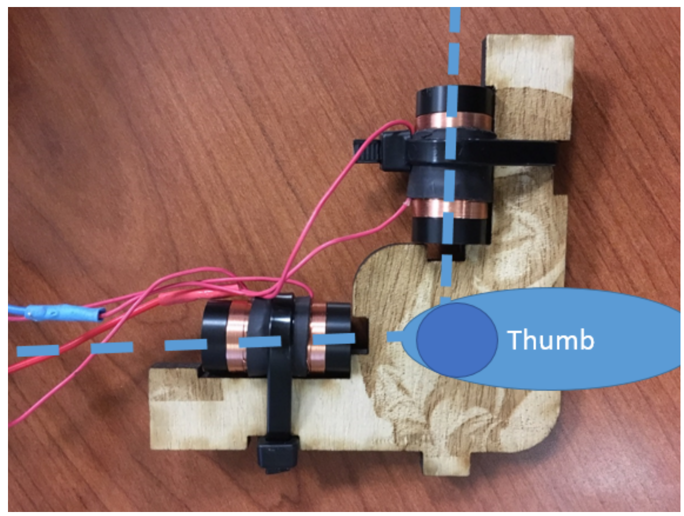

Fig. 14: Assembled Haptic Module 2 with annotated axis of vibration and finger placement.

2 was designed for expandability, where a platform could be added to provide aligned third axis vibrational feedback, as can be seen from the additional connector module on the bottom of the wooden piece.

IV. Results

By collecting force norms from simulation of touching spherical object in Rviz, wrenches are translated into asymmetric vibration so that the sensation of force can be felt, both directions and amplitude. Moving PSM to on the sphere surface will generate norms in different directions. We do survey with people. When the first time to hold the haptic module, and it will be not obvious to feel the directions. After holding the module for a while, people can clearly feel the direction change.

One qualitative result is that the haptuators do not produce enough acceleration. The Haptuator Redesign used in this project has an acceleration output of 1G at 50Hz. Compare it's frequency response in Figure 16 with the response from larger haptuators in Figure 17. This information can be found from Tactile labs [7].

V. Discussion

A. System

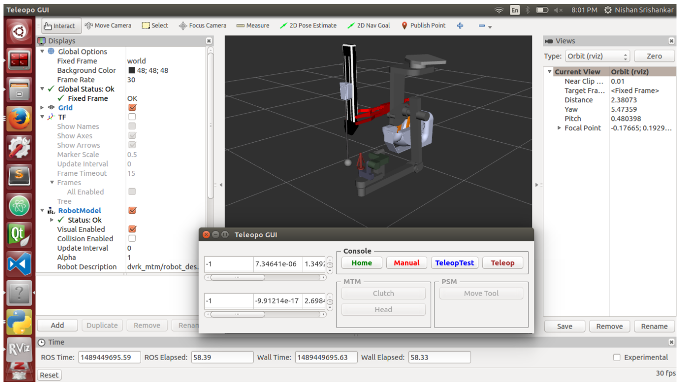

Fig. 15: RVIZ Simulation of the da Vinci Research Kit.

Figure 15 shows the simulation of the PSM/MTM teleoperation that has been implemented. This was installed following this procedure which was adapted from the WPI-AIM lab Github and the JHU CISST-SAW Github installatio guides. We plan on also utilizing the WPI dVRK haptics package to get force information. The waveform generation node must be run on a computer using Ubuntu 16.04 with ROS Kinetic. Installation requirements for the asymmetric signal generation node can be found at this Github profile.

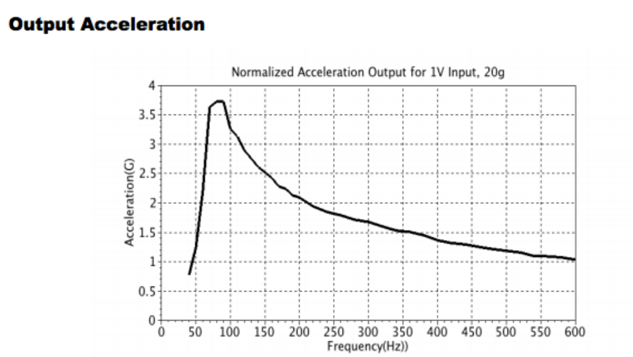

Fig. 16: Haptuator Re-design Frequency Response.

B. Future Hardware Design Improvements

There are several critical improvements that need to be made to the Haptic Module's design to improve its functionality. First

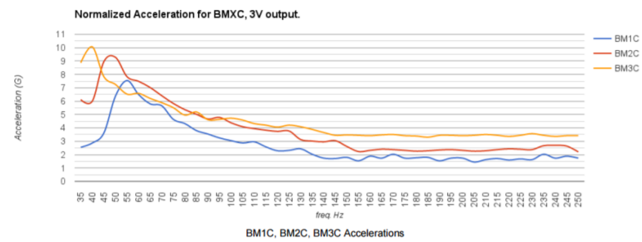

Fig. 17: BMX Series Frequency Response.

of all, as indicated with the red circles in Figure 18, there are several points of slack that attenuate the force transfer from the Haptuator's vibration to its mount and to the user's fingers. The Haptuators do not sit flush against the mount, and are clamped in place with zip ties. This means that when it vibrates, the Haptuators could slip back and forth along the zip tie but not actually make contact with the mount, and thus resulting in a loss of vibratory resolution.

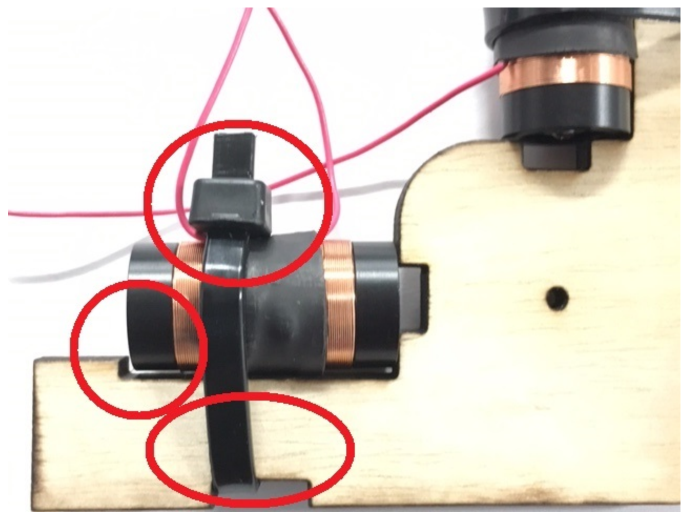

Fig. 18: Undesirable slack in Haptic Module 2 design.

Figure 19 displays the sketch of a Haptic Module 3 that we propose would help improve the accuracy of the feedback. The new design would be a 3D-printed monocoque frame, with the main Haptuator mount recessed so that the actuators could fit snugly in, as opposed to the current design which is manufactured from two dimensional wood. Furthermore, the new design would incorporate end-caps to secure the Haptuators in place using zip ties parallel to its axis of rotation.

C. Future Integration with MTM

A future system could control the MTM's actuators to generate the desired directional haptic feedback via asymmetric oscillation. Given a a force vector from the collision detection library, the magnitude of each component needs to be decomposed into joint commands. The asymmetric sine wave

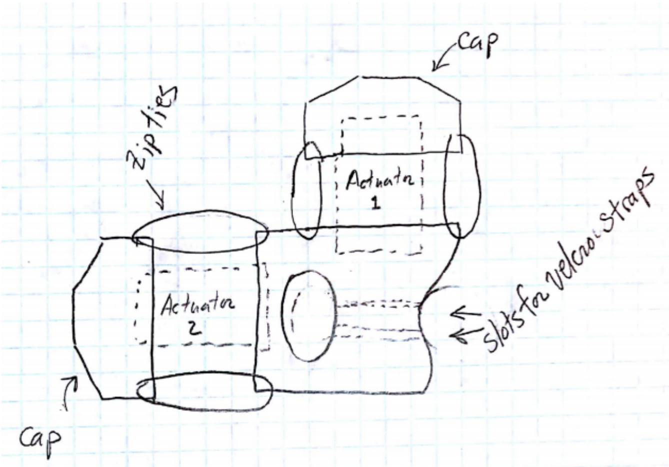

Fig. 19: Sketch of future Haptic Module 3 design with press-fitting Haptuator mounts.

used in Asymmetric Vibrations for Directional Haptic Cues [2] describes the Cartesian trajectory needed to create the skin shearing sensation that Dr. Culbertson has described in [3]. Unfortunately, the equation set 1 in [2] was missing a phase offset which results in a discontinuous waveform. The corrected version is below in Equation 2.

$$\text{Position} = \left\{ \begin{array}{lll} \text{if} & t \leq \omega_1 & -cos(\frac{t\pi}{\omega_1}) \\ \text{else} & & -cos(\frac{t\pi}{\omega_2} + \phi) \end{array} \right\} \quad (2)$$

$$\text{where} \left\{ \begin{array}{l} \omega_1 = \pi + \pi\Delta \\ \omega_2 = \pi - \pi\Delta \\ \phi = \pi - \pi\frac{\omega_1}{\omega_2} \end{array} \right\}$$

By tuning the parameter Δ, the transition point can be tuned to create a steep rise and a slow fall, which generates an upwards force sensation, or a slow rise and a steep fall, generating an downwards force sensation. Δ should be tuned to provide the most effective sensation. Based on Dr. Culbertson's conclusions, the total period of this piece-wise waveform should be *0.025sec*, which corresponds to 40Hz.

Given an arbitrary force vector, we can decompose the desired Cartesian trajectory (Figure 20) into joint commands as seen in Figures 21 and 22. Using ROS, a controller can subscribe to the current joint positions and compute the current position of the MTM gripper using forward kinematics. To create the haptic sensation, it is desired to command an incremental oscillation about the current position of the MTM's gripper. For the fastest implementation, inverse velocity kinematics can be used to transform the Cartesian velocity profile into joint velocity commands. It is only necessary to perform the inverse velocity kinematics on the first three joints of the MTM so the Jacobian is square and invertible.

In future work, the dynamics of the arm will need to be considered so that a closed loop velocity controller can be most effective. In this future work, the last four joints will need feed-forward commands to attenuate their inertial response to the vibrations of joints 1, 2 and 3. This way, the orientation of the gripper will not change during haptic feedback. The MTM console will also be responsible for filtering any motions above a cut-off frequency. However, we do not believe that the MTM hardware is not capable of commanding the required profile. To accurately generate the 40Hz waveform we expect that we need at least 10 points along the waveform. The encoders, and the RC-422 interface cards run well above 400Hz (2.5ms period). The Maxon RE-025 series motors in joints 1-4, however, have mechanical time constants of about 4-6ms [8]. The smaller RE-013 series motors in the wrist have a mechanical time constant of 13ms. These limitations will prevent successful generation of the desired waveform in joints 1-3 and ineffective attenuation of resulting motion about joints 4-7.

D. Future Surgical Applications

For the haptic module, actuators with larger masses would make the force sensation more realistic. Because mounting large Haptuators on the MTM wrist is difficult due to geometric constraints, a stand-alone haptic module is the best option. With a redesigned haptic module that can generate more shearing at the finger-skin interface and a motion capture system to record motion of the haptic-module, full teleoperation of the PSM could be achieved. This would allow a user, possibly a surgeon, to perform RMIS with effective haptic feedback but without the constraints of a console.

References

[1] A. M. Okamura, "Haptic feedback in robot-assisted minimally invasive surgery," *Frontiers in Robotics and AI*, vol. 19, 2009.

[2] H. W. Tappeiner, R. L. Klatzky, B. Unger, and R. Hollis, "Good vibrations: Asymmetric vibrations for directional haptic cues," in *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 285–289, March 2009.

[3] H. Culbertson, J. M. Walker, and A. M. Okamura, "Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement," in *2016 IEEE Haptics Symposium (HAPTICS)*, pp. 27–33, April 2016.

[4] G. Fischer, "Automation and Interventional Medicine (AIM) Robotics Research Laboratory at WPI." http://aimlab.wpi.edu/, 2016. [Online; accessed 12-Feb.-2017].

[5] A. Munawar and G. Fischer, "A surgical robot teleoperation framework for providing haptic feedback incorporating virtual environment-based guidance," *Frontiers in Robotics and AI*, vol. 3, p. 47, 2016.

[6] da Vinci Research Kit. http://research.intusurg.com/dvrkwiki/index.php?title=Main_Page, 2016. [Online; accessed 12-Feb.-2017].

[7] TactileLabs, "High-bandwidth vibrotactile transducer." http://tactilelabs.com/wp-content/uploads/2012/07/HaptuatorRedesignSpec_v1.0.pdf, 2012. [Online; accessed 12-Feb.-2017].

[8] Maxon RE-025 Series. http://www.maxonmotorusa.com/medias/sys_master/root/8820814839838/16-158-EN.pdf, 2016. [Online; accessed 1-May.-2017].

APPENDIX A
MATLAB PLOTS

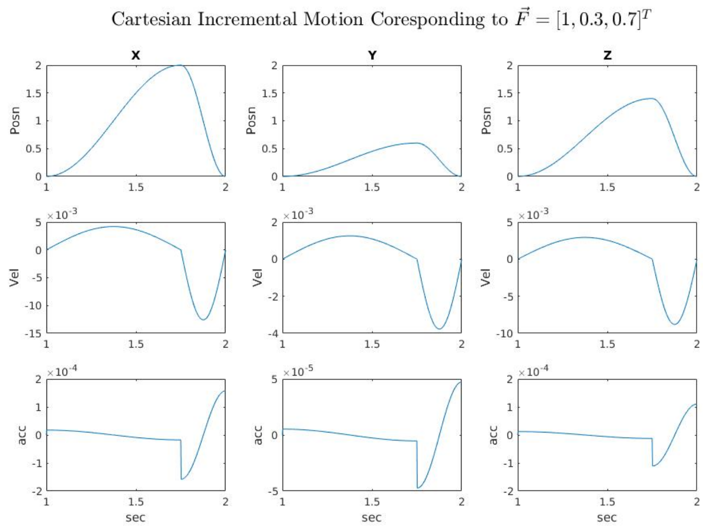

Fig. 20: Cartesian Trajectory.

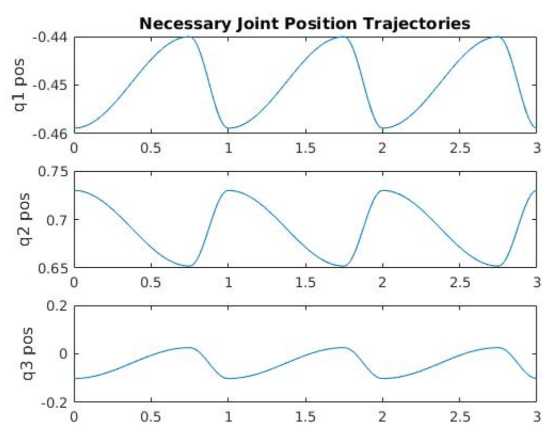

Fig. 21: Joint Position Profile.

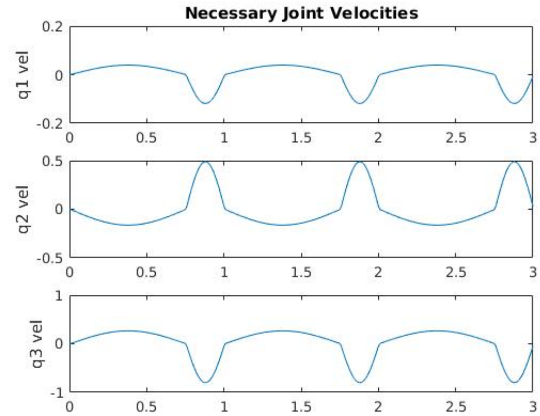

Fig. 22: Joint Velocity Profile.

APPENDIX B
ADDITIONAL FIGURES

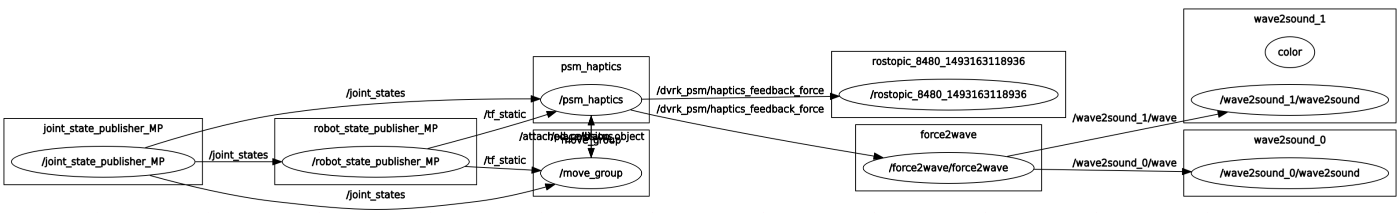

Fig. 23: ROS RQT-graph.