Towards Asymmetric Oscillatory Haptic Feedback through the dVRK Platform

Saraj Pirasmepulkul, Nolan Poulin, Nishan Srishankar, Keshuai Xu, and Ruibo Yan

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 1

II Prior Arts 1
   II-A Asymmetric Vibrations - CMU . . . . . . 1
   II-B Asymmetric Vibrations - GRASP . . . . 1
   II-C dVRK Gazebo Simulation - WPI . . . . 2

III Methodology 2
   III-A Systems Level Design . . . . . . . . . . 2
   III-B Simulation . . . . . . . . . . . . . . . . 2
   III-C Actuators . . . . . . . . . . . . . . . . . 3
   III-D Waveform Generation . . . . . . . . . . 3
   III-E Mechanical Design . . . . . . . . . . . 4

IV Results 5

V Discussion 6
   V-A System . . . . . . . . . . . . . . . . . . . . . . . . 6
   V-B Future Hardware Design Improvements 6
   V-C Future Integration with MTM . . . . . . 6
   V-D Future Surgical Applications . . . . . . 7

References 7

Appendix A: Matlab Plots 8

Appendix B: Additional Figures 9

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 standalone 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 18 ms.
Fig. 1: Asymmetric sinusoid vibration input described in Reference [2].

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

Fig. 3: Driving current waveform.

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.

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 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. 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 \(16 \times 29\) 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.
a) From Force to Waveform Parameters: The purpose of the force2wave node is 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 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.

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

b) Generate Audio Output from the Waveform Parameters: The wave2sound node listens for 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 an 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.

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
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 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

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 installation 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. 15: RVIZ Simulation of the da Vinci Research Kit.](image)

**Output Acceleration**

![Normalized Acceleration for 3V Input, 20g](image)

![Fig. 16: Haptuator Re-design Frequency Response.](image)

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 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.](image)

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.

![Fig. 17: BMX Series Frequency Response.](image)

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
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.

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

(2)

where

$$\begin{cases} \omega_1 = \pi + \pi \Delta \\ \omega_2 = \pi - \pi \Delta \\ \phi = \pi - \pi \frac{\omega_1}{\omega_2} \end{cases}$$

By tuning the parameter $\Delta$, 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. $\Delta$ 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 0.025 sec, which corresponds to 40Hz.

By tuning the parameter $\Delta$, 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. $\Delta$ 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 0.025 sec, which corresponds to 40Hz.

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**


Appendix A
Matlab Plots

Cartesian Incremental Motion Corresponding to $F = [1, 0.3, 0.7]^T$

Fig. 20: Cartesian Trajectory.

Fig. 21: Joint Position Profile.
Fig. 22: Joint Velocity Profile.

APPENDIX B
ADDITIONAL FIGURES

Fig. 23: ROS RQT-graph.