RICE UNIVERSITY

Development of an Educational Device and Accompanying Laboratory Series for Instruction in an Undergraduate Engineering Course

by

Kevin Bowen

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APPROVED, THESIS COMMITTEE:

Marcia K. O’Malley, Assistant Professor, Chair, Mechanical Engineering and Materials Science

Fathi H. Ghorbel, Professor, Mechanical Engineering and Materials Science

Satish Nagarajaiah, Professor, Civil and Environmental Engineering

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ABSTRACT

Development of an Educational Device and Accompanying Laboratory Series for Instruction in an Undergraduate Engineering Course

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The literature in engineering education research suggests that a cohesive series of laboratory exercises improves the learning and retention of the material presented in a laboratory course. The literature presents various devices that serve as the focus of a cohesive laboratory series. These devices and their accompanying laboratory series are designed to engage the students and generate enthusiasm in the course. One such device is the Haptic Paddle: a low cost single degree-of-freedom force-reflecting joystick that has enjoyed successful implementations in laboratory courses at other academic institutions. This thesis presents an adaptation of the Haptic Paddle and its accompanying laboratory series to meet specific goals for implementation in the laboratory component of the MECH 343: Modeling Dynamic Systems course offered at Rice University. Additionally, the device was developed to be an attractive platform for dissemination to colleagues who are interested in collaborating in engineering education research.
Acknowledgments

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I would like to thank Andy Deck and the National Instruments team for their generosity in providing hardware and technical support for this work. Thanks also goes to the National Science Foundation for its financial support through the grant NSF DUE-0411235.
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Chapter 1
Introduction

Providing students with a high quality of education is an ever-present goal at higher education institutions. Recent trends in the academic engineering field have shown a vigor in improving the quality of engineering education. A growing number of institutions are offering graduate programs in engineering education to students who conduct structured scientific research in order to better learn how to teach engineering [1,2]. Correspondingly, institutions are increasingly receptive to hiring graduates of such programs and incorporating their fresh perspectives into their curriculums.

The tools of an engineering instructor include laboratory devices with which students are able to investigate theoretical concepts learned in class lectures. The utility of these devices, however, goes beyond applications in instructional laboratory exercises. They provide a platform that education researchers can employ in their work. The goal of the research is to develop devices that best demonstrate course concepts and increase student learning. Dissemination of these devices improves the collaboration of fellow education researchers and thereby effect a greater impact on the engineering education community.

1.1. Motivation

The undergraduate mechanical engineering curriculum at Rice University offers courses that present material in various focus areas within the discipline. These focus areas include Aerospace Engineering, Computational Engineering, Fluid Mechanics and Thermal Science, Solid Mechanics and Materials, and System Dynamics and Control
(SDC). Students are required to take basic level courses that introduce the concepts of the various focus areas. Students are then required to select and take a few courses from a listing of higher level courses. The concepts that form the basis of the SDC area are taught in the course MECH 343: Modeling Dynamic Systems. This cornerstone course has a laboratory component included to enhance the course's impact. To maximize the educational benefit of the laboratory component, it is desired to implement an educational device and accompanying series of laboratory exercises that have the following features:

- Present the students with a cohesive series of exercises that build upon each other to reach an end goal.
- Integrate haptics into the laboratory series.
- Present the students with exercises focused on SDC and introductory electrical engineering material.
- Implement the device and accompanying laboratory exercises in a cost effective manner.
- Develop a device that is attractive to engineering education researchers.

The desire for a cohesive series of exercises arises from the fact that the exercises of typical laboratory series often do not correlate well to course instruction nor to each other. The disjointed nature of these exercises has students repeat steps and concepts without a progression towards an end goal, thereby lessening the potential impact of the laboratory component. This can be remedied by the development and implementation of a device that can serve as the test bed for a cohesive series of laboratory exercises that ties closely to lecture content to reinforce material. While it is difficult to objectively measure the value added by a such a series, implementations at other institutions have received positive feedback from students. Students have expressed increased enthusiasm towards course material and many feel that their laboratory experience positively
impacted their learning [3,4]. Additionally, when surveyed as to the impact of lectures, readings, and homework assignments on learning, students showed a marked increase from previous years in how they felt readings contributed to the learning experience. This potentially indicates that a progressive laboratory course encourages independent work on the part of the student, thereby showing improved confidence in the learning of the material [3]. One cohesive series in particular has had strong student feedback. The Haptic Paddle, a single degree-of-freedom force-feedback joystick, was developed for implementation as the focus in a series of laboratory exercises in a system dynamics and controls course at Stanford University. In one student’s words, it was “one of the better labs I’ve done because each built on the previous one and supported the course material well. Very helpful [5].”

Haptics refers to the sense of touch, and haptic interfaces are tactile or force-feedback manipulators which allow a user to feel and interact with virtual or remote environments. The virtual aspect of haptic systems enables them to physically display a rich assortment dynamic systems. Mechanical system parameters such as spring and damping constants can be changed in real time, allowing students to interact with an infinite number of systems, even unstable systems that have negative spring and damping constants! The implementation of haptic systems as a teaching tool has enjoyed great success as it has increased student interest through the ability to make textbook material more accessible [6]. In some cases students will share their experiences with others in the class, and even with those who are not taking the course [7]. The aforementioned Haptic Paddle is another example of a successful use of haptic devices for education.
The desire for the exercises to focus on SDC and introductory electrical engineering material arises from the fact that the undergraduate curriculum has required laboratory classes that fall within many of the focus areas, however there is no laboratory specific to the SDC area. Also missing is a required, or even suggested, course in introductory electrical engineering. In addition, senior students take a required capstone design course and many of the projects offered fall within the SDC area. A practical laboratory course specific to SDC and electrical engineering will better prepare those who take on a capstone project in the SDC area.

This thesis presents the development of a device that satisfies the stated goals for instruction in the MECH 343 course and dissemination to the education research community. Also presented in this thesis are the device’s accompanying series of laboratory exercises and supporting software and hardware.

The intention is to develop a device that will be used for several years. With several students using the device over these years, the cost of implementing the device could be high if a conscious effort is not made to make it cost effective. A cost effective solution also improves the device’s attractiveness for the final goal of dissemination.

A final goal in developing the device was to provide a platform that would be attractive to other education researchers. Dissemination of information about the device will provide a pool of colleagues who are all working with the same device and thereby facilitate the discovery of instruction methods that improve instruction.
1.2. Terminology

Throughout this thesis, several variables and acronyms will be used to discuss the developed educational device and its accompanying laboratory series. These terms are listed alphabetically for reference and are found in Tables 1.1 and 1.2.

<table>
<thead>
<tr>
<th>Variable:</th>
<th>Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta )</td>
<td>Angular displacement of the paddle</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Time constant of a first order system</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Either angular velocity or natural frequency of a second order system, dependent on context</td>
</tr>
<tr>
<td>( b_{eq} )</td>
<td>Lumped parameter damping constant of the Haptic Paddle system</td>
</tr>
<tr>
<td>( B_m )</td>
<td>Damping constant of the motor bearings</td>
</tr>
<tr>
<td>( B_{net} )</td>
<td>Net magnetic field applied to the Hall-effect sensor</td>
</tr>
<tr>
<td>( B_{spin} )</td>
<td>Damping constant of the experimental setup for the motor spindown test</td>
</tr>
<tr>
<td>( b_{virt} )</td>
<td>Virtual damping constant effected using PD control</td>
</tr>
<tr>
<td>( D )</td>
<td>Distance between the center of mass and the attachment point of the strings in the bifilar pendulum setup</td>
</tr>
<tr>
<td>( f_m )</td>
<td>The force output at the paddle handle due to the motor’s torque output</td>
</tr>
<tr>
<td>( g )</td>
<td>Acceleration constant due to gravity, 9.81 m/s(^2)</td>
</tr>
<tr>
<td>( h )</td>
<td>Length of the strings in the bifilar pendulum setup</td>
</tr>
<tr>
<td>( i_{arm} )</td>
<td>Armature current through the motor</td>
</tr>
<tr>
<td>( J_{cm} )</td>
<td>Rotational inertia of the paddle component about its center of mass</td>
</tr>
<tr>
<td>( J_m )</td>
<td>Rotational inertia of the motor rotor</td>
</tr>
<tr>
<td>( J_p )</td>
<td>Rotational inertia of the paddle component about its pivot point</td>
</tr>
<tr>
<td>( J_{spin} )</td>
<td>Rotational inertia of the experimental setup for the motor spindown test</td>
</tr>
<tr>
<td>( K_{BP} )</td>
<td>Equivalent spring constant of the bifilar pendulum system</td>
</tr>
<tr>
<td>( k_{eq} )</td>
<td>Lumped parameter spring constant of the Haptic Paddle system</td>
</tr>
<tr>
<td>( K_i )</td>
<td>DC motor torque constant</td>
</tr>
<tr>
<td>( K_v )</td>
<td>DC motor voltage constant</td>
</tr>
<tr>
<td>( k_{virt} )</td>
<td>Virtual spring constant effected using PD control</td>
</tr>
<tr>
<td>( l_x )</td>
<td>Distance between paddle pivot point and the handle</td>
</tr>
<tr>
<td>( m_{eq} )</td>
<td>Lumped parameter mass of the Haptic Paddle system</td>
</tr>
<tr>
<td>( m_p )</td>
<td>Mass of the paddle components</td>
</tr>
<tr>
<td>( R_a )</td>
<td>Armature resistance of the motor</td>
</tr>
<tr>
<td>r_{cm}</td>
<td>Distance between the center of mass and the pivot point of the paddle component</td>
</tr>
<tr>
<td>r_{cs}</td>
<td>Radius of the Capstan spool</td>
</tr>
<tr>
<td>r_{sp}</td>
<td>Radius of the paddle sector pulley</td>
</tr>
<tr>
<td>R_l</td>
<td>Load resistor used as a dynamic brake</td>
</tr>
<tr>
<td>T</td>
<td>Torque output from the motor</td>
</tr>
<tr>
<td>V_c</td>
<td>Control voltage sent to the motor</td>
</tr>
<tr>
<td>V_{emf}</td>
<td>Back electro-motive force generated by the rotating motor shaft</td>
</tr>
<tr>
<td>x</td>
<td>The linear displacement of the paddle handle</td>
</tr>
<tr>
<td>x_{sp}</td>
<td>The set point for the displacement of the paddle handle used in PD control</td>
</tr>
</tbody>
</table>

Table 1.1. Variables used in Haptic Paddle laboratory exercises.

<table>
<thead>
<tr>
<th>Acronym:</th>
<th>Definition:</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>Analog input</td>
</tr>
<tr>
<td>AO</td>
<td>Analog output</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>ELVIS</td>
<td>Educational Laboratory Virtual Instrument Suite</td>
</tr>
<tr>
<td>EMF</td>
<td>Electro-motive force</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical user interface</td>
</tr>
<tr>
<td>PC</td>
<td>Personal computer</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed circuit board</td>
</tr>
<tr>
<td>PCI</td>
<td>Peripheral Component Interconnect</td>
</tr>
<tr>
<td>PD</td>
<td>Proportional derivative</td>
</tr>
<tr>
<td>PSS</td>
<td>Precision shoulder screw</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse-width modulation</td>
</tr>
<tr>
<td>PXI</td>
<td>PCI eXtensions for Instrumentation</td>
</tr>
<tr>
<td>RTOS</td>
<td>Real-time operating system</td>
</tr>
<tr>
<td>SDC</td>
<td>System dynamics and control</td>
</tr>
<tr>
<td>SIP</td>
<td>Single inline package</td>
</tr>
<tr>
<td>TA</td>
<td>Teaching Assistant</td>
</tr>
<tr>
<td>VI</td>
<td>Virtual instrument</td>
</tr>
</tbody>
</table>

Table 1.2. Acronym list

1.3. Proposed solutions

To meet the challenges set forth, the laboratory device was chosen to be an adaptation of the aforementioned Haptic Paddle device developed at Stanford University.
The device is depicted in Figure 1.1 [8]. Also developed at Stanford and further developed at Johns Hopkins University was a cohesive laboratory series to accompany the Haptic Paddle. The material covered in this laboratory series matches well to the material covered in the MECH 343 course. The multi-domain nature of haptic devices makes them well suited for study in both dynamic systems and control and electrical engineering. Additionally, the Haptic Paddle ties these concepts together with other subsets of mechanical engineering including assembly, system analysis, and calibration. During the progression of the laboratory series, students study the Haptic Paddle component by component and use results from previous exercises to explain what they observe in later exercises to ideally gain a better understanding of the Haptic Paddle and dynamic systems in general. As discussed earlier, the implementation of this device was well received by the students at Stanford.

An alternative low-cost device that would allow component by component study of the system in a laboratory series was developed at the University of Michigan. This device is depicted in Figure 1.1 [7]. This device, known as the “iTouch,” functions much in the same way as the Haptic Paddle. However, this device requires students to fabricate voice coil actuators, which was undesirable for the MECH 343 course. One of the laboratory exercises discussed in Chapter 3 involves performing a spin-down test of the DC motor that is the actuator for the Haptic Paddle system. The concepts demonstrated in this exercise are not as easily demonstrated with a voice coil actuator. Also, documentation of this device and its accompanying laboratory series was not as readily available as that of the Haptic Paddle.
Figure 1.1. Instructional haptic devices: the original Haptic Paddle (L) [8] and the iTouch [7].

The original Haptic Paddle design and accompanying laboratory series developed were adapted for several reasons. The primary reason in adapting the original design was to enable repeated use from year to year, thereby reducing the device's long-term cost. Changes were also made to improve functionality, versatility, and ease of assembly and use. These adaptations are further discussed in Chapter 2. The primary reason in adapting the laboratory series was to tailor the exercises to the adapted design and to align the series to the MECH 343 course. Changes were also made to improve the educational impact of the laboratory series. These adaptations are further discussed in Chapter 3.

The consistent use of a data acquisition (DAQ) system to affect inputs to and measure and record outputs from the experimental setups will improve the cohesion of the laboratory series. LabVIEW, a commercially produced graphical programming language (National Instruments Corporation, Austin, TX), is a primary choice for applications in engineering education. The software tool has great versatility in programming virtual instruments that have all of the function needed for a laboratory exercise. It has been successfully implemented for instruction in several engineering disciplines, including applications that are multidisciplinary [9]. Several academic
institutions have site licenses of LabVIEW, which will facilitate the dissemination of laboratory exercises to those institutions. LabVIEW is not necessary to the experiments, thus its use will not deter dissemination to institutions who do not have a license for the software. The DAQ hardware selected to compliment this use of LabVIEW is presented in Chapter 4.

1.4. System Overview

Throughout the series of laboratory exercises, the Haptic Paddle is used in a number of configurations that facilitate investigation of individual components. Each experimental setup differs from the next. Specific details of each experimental setup are discussed with the presentation of the adapted laboratory series in Chapter 3. Most setups employ National Instruments DAQ hardware to affect inputs to the experimental systems and measure and record system outputs. As discussed in the previous section, National Instruments LabVIEW software accompanies the use of this hardware to provide students with a control interface. The supporting software and hardware are covered in more detail in Chapter 4.

1.5. Outline of thesis

The outline of this thesis is as follows: Chapter 1 introduces the motivation for the work done and the reasoning for the decision to adapt the Haptic Paddle and its accompanying laboratory series. Chapter 2 presents the hardware adaptation of the Haptic Paddle. Chapter 3 presents the adaptation of the laboratory series to accompany the Haptic Paddle. Chapter 4 presents the supporting software and hardware used to control the Haptic Paddle and provide data measurement and recording in laboratory exercises.
Chapter 5 presents significant results of this work. Chapter 6 presents conclusions and suggests future directions to further improve upon this work.
Chapter 2
Hardware Adaptation

2.1. Desirable aspects of the original design

There are many aspects of the Haptic Paddle design developed at Stanford that are attractive for its use in a system dynamics course. Foremost is the ability to assemble the device in progressive stages. This ability enables students to investigate the various components of the Haptic Paddle system in a cohesive series of lab exercises that culminates in an exploration of the system as a whole. Additionally, the system is easy to assemble and thus students tend to enjoy assembling the device in its various stages as opposed to being frustrated by the process. Particularly attractive is the system’s low-cost. The cost per unit is approximately $20. This cost does not include the price of the surplus DC motor, which is widely variable, nor does it include the cost of manufacture in dollars and man hours. The size of the production run is not stated in the reference [10]. The device’s low-cost makes it much more feasible to provide each individual lab group with its own unit. The design of the adapted Haptic Paddle strived to maintain these attractive aspects.

2.2. Desired improvements in adapted design

While the original Haptic Paddle design had many desirable aspects, there are many ways in which the design could be improved upon. The adaptation of the original design made the following improvements:
• Enabled repeated use from year to year, thereby reducing the device’s long-term cost.
• Linearized output of the Hall-effect sensor.
• Improved manufacture and symmetry of the paddle component.
• Improved functionality to ease sensor calibration.
• Improved attachment and tensioning of the cable used for power transmission.
• Provided adaptability to varying thicknesses of the primary material of construction.
• Incorporated electrical connections that can be quickly and easily connected.

The greatest desired improvement is the ability to disassemble assembled units so that they may be reused in subsequent years. The original design primarily used glue in assembly, thus brand new units were needed every year somewhat offsetting the attractiveness of the device’s low cost. Implied in designing the device for long term reusability is making it robust to withstand repeated use. The design of a robust system required a greater manufacture effort to produce units, but a conscious effort was taken to streamline production and minimize manufacturing steps. Documentation of this manufacture is discussed later in this chapter and attached in Appendix A. The other improvements are discussed in greater detail in the following section.

2.3. Solutions to achieve design criteria

The adapted design was influenced in part by the design of the Impulse Engine 2000, a commercially produced two degree-of-freedom force-reflecting joystick (Immersion Corporation, San Jose, CA). A listing of the components used in the adapted design are available in Appendix A. The specifics of the adapted design choices are discussed subsequently.
2.3.1. Material, actuator, and sensor selection

The primary material chosen for the adapted design was cast acrylic, which is also the primary material used in the original design. This low-cost material can be readily etched or cut in thicknesses up to half an inch on laser cutter systems and easily machined, thus reducing manufacture time and cost. It holds fastener threads well and is durable. A disadvantage of the material is that it is prone to shattering if dropped from a sufficient height.

Both the original and adapted designs employ a permanent magnet DC motor to provide actuation. DC motors are widely used in industrial applications, easy to control, and can often be found surplus for very low cost. A Pittman Lo-Cog 9434 15.1V DC motor was selected as the motor to actuate the adapted design because of its suitable performance characteristics and availability at a local surplus store. The manufacturer’s datasheet is available at [17]. The 15.1V is not listed in the manufacturer’s datasheet, thus specifications specific to the motor were interpolated and are attached in Appendix B. Any Pittman 9000 series motor can be used with the adapted design with the exception of motors that have a custom housing.

Both the original and adapted designs employ a ratiometric, linear Hall-effect sensor to read the angular position of the paddle component. The voltage output of these sensors varies linearly with the strength of the magnetic field that is applied perpendicularly to the sensor. This sensor is reliable, easy to calibrate, and inexpensive. The output of the sensor in the original design was noticeably sigmoidal over the range of the Haptic Paddle’s workspace, thus a cubic function was employed to calibrate the sensor.
For the adapted design, it was desired for the sensor to have a linear output over the range of the Haptic Paddle’s workspace. Sensor samples were obtained and various configurations and proximities of magnet to sensor were experimented with until a linear relationship was achieved. The final configuration is depicted in Figure 2.1. $B_{net}$ represents the net magnetic field applied to the sensor. From the geometry shown, it is apparent that the magnetic field applied perpendicularly to the sensor is proportional to the sine of the paddle position $\theta$. The workspace of the Haptic Paddle is sufficiently small to allow use of the small angle approximation, thus the magnetic field applied perpendicularly to the sensor is proportional to $\theta$ and a linear relationship is achieved. An Allegro 1322 EUA Hall-effect sensor was selected as the sensor for the adapted design. The device’s datasheet is available at [18].

![Diagram of magnet-sensor arrangement](image)

**Figure 2.1.** Depiction of magnet-sensor arrangement to demonstrate applicability of small angle approximation. Figure adapted from [11].

### 2.3.2. General design for repeated use

To provide for repeated assembly and disassembly, fasteners were largely employed in the adapted design and the use of glue was almost completely eliminated.
The single use of glue is presented later in this chapter. The need for students to use glue and wait for it to dry has been completely eliminated, thus the assembly of the device is cleaner and faster.

2.3.3. Adapted paddle component design

The paddle component serves multiple purposes. One major purpose is to provide the user a handle to grasp and interact with the system. Another major purpose is to transmit the input torque of the system’s actuator to the handle. A Capstan cable drive is employed to transmit the torque to the paddle about a pivot point. The transmitted torque is then levered about the pivot point to produce a tangential force at the handle. As an integral part of the cable drive, the paddle must have a means of securing and tensioning the cable. The paddles of the original and adapted designs are juxtaposed in Figure 2.2.

Figure 2.2. The original (L) [8] and adapted designs juxtaposed for comparison.
The most significant change from the original design is the placement of the handle and the sector pulley opposite of each other about the pivot point. With this modification, the paddle can be fabricated from a single piece of material. An additional benefit is an increase in the distance between the handle and the pinch point of the cable drive. The previous geometry did not prevent users from resting their fingers on the sector pulley, thus it was possible for the resting finger to come in contact with the Capstan drive shaft and get pinched between it and the sector pulley [12]. It must be noted that in the original design the center of mass of the paddle was above the pivot point, thus making it an inverted pendulum. The instability of the inverted pendulum was a desirable trait as it demonstrates classical concepts in system dynamics and control. In the adapted design, the center of mass of the paddle has moved below the pivot point thus making the device stable. If desired, the adapted design can easily be made unstable by adding a mass to the handle to move the center of mass above the pivot point. This is another benefit of the adapted design because the original design cannot be made stable by mechanical means.

Changes were also made to the paddle’s cable attachment and tensioning aspects. In the original design, a nylon screw inserted into a washer is used to secure a cable end by threading the screw into a tapped hole and tightening it down to trap the cable between the washer and the sector pulley. In the adapted design, a cable end is threaded through a hole and a nylon screw is inserted into the hole to secure the cable, thus simplifying the attachment of the cable. These holes and screws (one for each end of the cable) can be seen in Figure 2.2. The holes are sized to ensure that the cable is well secured when the screws are inserted. A second tensioning slit was added to provide the paddle with greater
symmetry. Additionally, the original design relied on the material’s elasticity to provide tension in the cable. The gap in the tensioning slit was not rigidly held, thus the flexure of the material could allow for slack in the cable’s tension. A tensioning set screw close to the radius of the sector pulley was added in the adapted design to rigidly maintain the gap of the tensioning slit, as seen in Figure 2.2.

To improve the paddle’s functionality, the adapted design takes advantage of the material’s ability to be etched by laser cutter systems. In one of the exercises in the accompanying lab series, students must move the paddle to a position and measure the angular position for sensor calibration. To do this on the original device, students had use a protractor which could be frustrating to get an accurate position reading. The adapted device has the protractor etched onto the face of the paddle to facilitate the calibration process. Figure 2.2 shows the calibration tick marks along the sector pulley that serve this function.

2.3.4. Components along the rotational shaft

The rotational shaft provides the axis of rotation through the paddle’s pivot point. Various components are secured along the shaft to provide robustness, ease of assembly, and adaptability to differing thicknesses of cast acrylic material. Views of the adapted design showing the components along the rotational shaft are shown in Figure 2.3.

The varying thickness of cast acrylic material presents a design challenge. Recall that one of the motivations in developing this device is to provide a platform for education research that can be largely disseminated. Cast acrylic material is typically found at the cheapest prices through local vendors, thus it is very likely that Haptic Paddle systems will be constructed with material purchased from a significant number of
vendors. The actual thickness of the half inch cast acrylic material is rarely consistent from vendor to vendor, thus the adapted design must address this issue.

![Diagram of components](image)

Figure 2.3. Top(L) and zoomed back views of the adapted design showing components along the rotational shaft.

Consistent with the general design choice to use fasteners as a primary means of assembly, a precision shoulder screw (hereafter PSS) was selected to provide the rotational shaft. Unlike a shaft that has grooves for retaining rings, the threads of the PSS provide the adjustment necessary to address varying thicknesses of cast acrylic material. In the top view, the head of the PSS can be seen through the transparent magnet cap. It is inserted into the other components and fastens to the acorn nut. Flanged ball bearings were chosen to replace the bronze bushings of the original design to improve robustness. Washers were chosen to as an inexpensive off-the-shelf component to provide spacing. The use of numerous thin spacers helps to adjust to varying thicknesses of material by simply adding or subtracting a spacer. The assembly of components along the rotational shaft must fit snugly to prevent play, however the fit must not be too snug or else the ball
bearings will bind. Placing lock washers between the ball bearings greatly assists finding the balance between too snug and not snug enough.

A magnet must be affixed to the PSS for position sensing. To accomplish this, a component is made from quarter inch cast acrylic to hold the magnet. This “magnet cap” press fits to the head of the PSS with a slight interference fit and also holds the magnet with a slight interference fit. The magnet cap is designed such that the center of the magnet is along the axis of rotation, as can be seen in the back view of Figure 2.3.

2.3.5. Robust electrical connections

Units of the original design were not used for more than a few exercises, thus the mechanical robustness of the electrical connections was not a concern. Alligator clips were commonly used to connect to frail leads. The adapted design provides robust connections that are quicker and easier to connect than alligator clips. The Hall-effect sensor is housed in a small 3-pin single inline package (SIP). A 3-pin SIP header with wire wrap leads provides an interface to connect the frail Hall-effect leads to a 3-pin SIP connector. The thicker wire wrap leads of the SIP header provide a durable connection that the SIP connector can easily be slid onto and off of repeatedly. The SIP header is glued to a piece of perforated board for mounting to the rest of the device. Note that this is the only use of glue in the system. The two pieces were glued together as part of the unit’s manufacture and are presented to the students as a single “Hall mount” component.
Banana jacks were integrated into the mechanical design to fasten the Hall mount to the device, as well as providing a simple, mechanically robust connection between the motor leads and the amplifier leads. Figure 2.4. shows a picture of these connections.

![Diagram showing connections](image)

Figure 2.4. A picture displaying the robust and easily connected electrical connections.

2.4. Consumable components

While most components were designed or selected to withstand years of use, some components must be replaced from time to time. The cable becomes kinked and warped through use and tends to fray when stored. This component must be replaced annually. The Hall-effect sensor has frail leads that tend to break with repeated use. Also, the sensor can be burned if connected improperly or polarized if stored close to a magnet for too long a period. Many of these sensors must be replaced either annually or biannually. All consumable components can be replaced for less than $1.50 per unit.
2.5. Performance and cost of the adapted design

The adapted design is capable of providing a peak force of approximately 10N at the handle of the paddle component when given a 2A supply at stall conditions. This force magnitude is comparable with commercially available haptic devices. The workspace of the Haptic Paddle is approximately ±35° from its vertical position, which is sufficiently small to allow small angle approximations that are made to linearize the system’s model in the accompanying lab series.

For a production run of 25 units, the cost per unit is approximately $28. This cost does not include the price of the surplus DC motor, which is widely variable. Manufacture steps such as drilling holes into laser cut parts and tapping them required approximately one man hour at $10 per hour (the rate paid to undergraduate workers).

2.6. Documentation for dissemination

Several documents have been written to facilitate dissemination of the Haptic Paddle hardware. These documents include a bill of materials, CAD models, detailed design drawings, a procedure for manufacturing components, and a document presenting the components of the system and assembly instructions. These documents are available on the internet [13] and are attached in Appendix A.
Chapter 3
Laboratory Series Adaptation

3.1. Laboratory series developed for original design

The original laboratory series was developed for an undergraduate course at Stanford University in dynamic systems and control and many of the concepts covered are the same as those in covered in the MECH 343 course. The original series has undergone its own series of revisions. The series presented subsequently was used for instruction at Johns Hopkins University in the Spring of 2002. In general, equations of motion and mathematic relationships relevant to the concepts covered in lab were either provided in the handout or prompted in the post-lab exercise. Pre-lab exercises consisted of an ungraded quiz presented at the beginning of the exercise and awarded points based on a “good faith” completion effort. The handouts and solutions were provided courtesy of Allison Okamura who developed the Haptic Paddle at Stanford and has implemented it in her courses of instruction at Johns Hopkins University. The laboratory series presented later in this Chapter was adapted largely from the subsequently presented laboratory series.

3.1.1. Lab 1 - Motor Spin-Down Test

This exercise presents the students with a real-world homogeneous first-order dynamic system. The setup for the exercise involves a DC motor, the same as that used to actuate the Haptic Paddle, with an extra mass attached to the shaft and mounted to a stand. This setup is depicted in Figure 1.1. Note that the stand is assembled with the
motor for the students prior to the exercise. Students ramp the motor velocity to an initial speed and then remove power to the motor to observe the subsequent spin-down. The system is modeled as a first-order system due to the viscous damping of the lubricants in the motor’s bearings. This viscous damping is assumed to dominate the Coulomb friction of the motor. The post-lab assignment focuses primarily on developing the equation of motion and the use of the system’s time constant to characterize the motor’s damping.

![Motor and Stand](image)

**Figure 3.1. Setup of spin-down test showing motor mounted to stand [8].**

### 3.1.2. Lab 2 – Haptic Paddle System Components

In this two part exercise, the students investigate additional aspects of the Haptic Paddle system as well as partially assembling the system. In the first part of the exercise, students characterize the motor’s torque constant and its Coulomb friction. To characterize the motor’s torque constant, students hang weights off of a pulley to apply a known torque. A current is then passed through the motor to balance the weight. The slope of the torque-current relationship provides the value of the motor’s torque constant. To characterize the motor’s Coulomb friction, students determine the minimum of current
required to spin the motor from rest. The motor’s torque constant is then used to determine the amount torque required to spin the motor from rest. This torque amount is taken as the motor’s Coulomb friction.

In the second part of this exercise, the students use a bifilar pendulum to determine the rotational inertia of the paddle component [14]. Figure 3.2 depicts the bifilar pendulum with the paddle as the hanging mass. This setup can be modeled as an undamped second order system with the equivalent spring constant determined from system parameters. Students displace the pendulum from equilibrium and observe the natural frequency of the subsequent motion. Students can then use the characteristic second order equation to determine the paddle’s rotational inertia from the parameters they have observed.

![Figure 3.2. A bifilar pendulum with the paddle as the hanging mass [8].](attachment:image.png)
3.1.3. Lab 3 – Equivalent Systems

In this exercise, students completed the assembly of the Haptic Paddle with the exception of the position sensor and learned how to calibrate the Hall-effect sensor. As a post-lab exercise, students used lumped parameter modeling to develop the second-order equation of motion for the paddle. In the calibration portion of the exercise, the students observe that the sensor output is nonlinear with respect to the paddle position. A calibration file has been written for them to perform a best fit cubic curve of the data. They simply enter observations of the paddle’s position and the corresponding sensor output into the file and are then provided with calibration constants for later use.

3.1.4. Lab 4 – Feedback Control

In this exercise, students run a C executable that employs a proportional derivative (PD) controller to display a virtual second-order system on the Haptic Paddle. Students are able to instantaneously change spring and dashpot coefficients and physically observe the effect of the change by grasping the handle and feeling the force output from the Haptic Paddle. Students also record data for a step response input to the system. They adjust the virtual spring and dashpot coefficients to effect underdamped, critically damped, and overdamped type responses. The post-lab exercise focuses on feedback control concepts that are beyond the scope of the MECH 343 class and thus were not used in the adapted laboratory series, nor are they presented here.

3.1.5. Lab 5 – Coupled Dynamic Systems

In this exercise, students interact with virtual multi-degree-of-freedom systems to better understand modal analysis, the effects of damping on such systems, and state space
feedback control of such systems. These concepts are beyond the scope of the MECH 343 class thus were not used in the adapted laboratory series, nor are they presented here.

3.2. The adapted laboratory series

The primary goal in adapting the Hopkins laboratory series was to tailor the exercises to the adapted design and to align the series to the MECH 343 course. The adaptation also sought to improve the series by expanding the background information presented in the handouts as well as requiring pre-lab assignments. Pre-laboratory assignments focused on developing equations of motion and deriving mathematical relationships that would be used post-laboratory. Hopefully the expanded background information and pre-laboratory assignments will provide students with a better sense of the purpose of the exercise and its procedures while they are performing the procedures, as opposed to the previous series in which most of the model development was performed post-laboratory.

In addition to the Haptic Paddle laboratory series, the MECH 343 course also has a Matlab and Simulink simulation exercise and two laboratory exercises that have strong electrical engineering influence. In one laboratory exercise the students investigate first and second-order dynamic electrical circuits and make analogies to the mechanical domain. In the other laboratory exercise the students investigate operational amplifier (op-amp) circuits and their use to perform basic mathematical operations. Parts of the adapted laboratory series attempt to connect to concepts covered in these labs to improve the cohesiveness of the entire series' progression.

The adapted series handouts and solutions are attached in Appendix C. The first exercise in the adapted series is Lab 4 because it follows the aforementioned exercises.
3.2.1. Lab 4 – Actuator Characteristics

Investigations of pertinent aspects of the Haptic Paddle’s actuator were logistically collected into a single two part exercise that consisted of the motor spin-down test and the characterization of the motor’s torque constant. In the first part of the exercise, students partially assemble the Haptic Paddle and attach a mass to the motor shaft for the spin-down test. The background information in the exercise handout presents the students with the electric circuit model of a DC motor as a voltage source \( V_{\text{emf}} \) and a resistance \( R_a \) in series as shown in Figure 3.3. Also represented in the figure are the control voltage sent to the motor \( V_c \) and the armature voltage \( V_{\text{arm}} \). The armature voltage is measured and recorded by a LabVIEW virtual instrument (VI) that communicates with a DAQ card. The use of LabVIEW and DAQ hardware is discussed in Chapter 4. The setup for this exercise is shown in Figure 3.4. The equations that form the basis of DC motor operation are as follows:

\[
T = K_i i_{\text{arm}} \tag{3-1}
\]

\[
V_{\text{emf}} = K_i \omega \tag{3-2}
\]

\( T \) represents the rotor torque generated by a current passing through the motor’s armature, which is equal to the torque constant \( K_i \) multiplied by the current \( i_{\text{arm}} \). The modeled voltage source is commonly called a back Electro Motive Force (EMF) and will have the same sign as the velocity of the rotor. This back EMF is equal to the speed or voltage constant \( K_v \) multiplied by the angular velocity \( \omega \) of the rotor.
The series developed for the original design makes the assumption that the viscous damping of the lubricants in the motor bearings dominates the Coulomb friction of the motor. However, this is a poor assumption for the motor used in the adapted
design. To ensure that the spin-down test will demonstrate first-order behavior, a dynamic brake was added in series with the motor to add electrical damping to the system. This dynamic brake is essentially a load resistor $R_l$. With the switch in position 1, students ramp the motor speed to an initial value using a 15 volt power supply that is trimmed through a potentiometer. The students then flip the switch to position 2 to engage the dynamic brake. The initial velocity of the motor coupled with the electromechanical characteristics of the motor results in a braking torque that is presented to the students in the handout as:

$$ T = \left( \frac{K_r K_v}{R_l + R_a} \right) \omega $$ \hspace{1cm} (3-3)

In the pre-lab exercise, students use a free body diagram to derive the equation of motion and the resulting time response equation:

$$ J_{spin} \ddot{\omega} + B_{spin} \omega = 0 \hspace{1cm} (3-4) $$

$$ \omega(t) = \omega(0) e^{-\frac{B_{spin}}{J_{spin}}} \hspace{1cm} (3-5) $$

The parameter $J_{spin}$ is the sum of the rotor and the spinning mass inertias, which they determine during the exercise, while $B_{spin}$ is the sum of the damping due to the bearing lubricants and the effect of they dynamic brake. The students then use the first-order characteristic equation to determine the relationship for the system’s time constant:

$$ \tau = \frac{J_{spin}}{B_{spin}} $$ \hspace{1cm} (3-6)

In the post-lab exercise, students determine the time constant of the first order system and use the value of $J_{spin}$ they determined to characterize $B_{spin}$. From the
characterized damping constant, the students can subtract out the effect of dynamic braking, expressed in equation (3-3), to determine the damping of the bearing lubricants. Also in post-lab, students are prompted to consider the analogy of this first-order system to the electrical-first order system they investigated earlier in the semester to tie the exercises together.

In part two of this exercise, students incrementally assemble more of the Haptic Paddle to provide the setup for the characterization of the motor’s torque constant. The paddle component and the cable drive transmission are attached in the assembly. The setup places the Haptic Paddle on its side and masses are attached to the handle, as shown in Figure 3.5. Unlike the series developed for the original design, this exercise has the students use the cable transmission. This way the students can directly observe how the torque output of the motor results in a force at the handle. The setup also uses the electric circuit shown in Figure 3.3. The switch is kept in position 1 and a Fluke Digital Multimeter is used to measure the current required to balance the applied weight. Students record the mass applied and the corresponding current to balance it for a range of masses. In post-lab, students determine the resulting torque applied to the motor by the mass and produce a torque versus current plot. This plot expresses equation (3-1), thus the slope of the line characterizes the motor’s torque constant. This post-lab exercise is the same as that of the corresponding exercise of Lab 2 in the original series.
Figure 3.5. Setup for torque constant characterization.

The characterization of the motor's Coulomb friction was eliminated from the adapted laboratory series. This is largely because there was no feedback control used to compensate for the friction in either laboratory series. Also, it was difficult to obtain consistent values even on individual Haptic Paddle systems. The value of the Coulomb friction will also change once the drive cable is attached and tensioned.

The characterization of the motor's voltage constant could be added to this exercises procedure, however it could make the length of the exercise prohibitively long. Also, characterizing the voltage constant is not as relevant to the system because the output of the Haptic Paddle is a force, not a velocity. For educational rigor, there is a prompt in the post-lab exercise that leads the students to the conclusion that the two constants must equal one another. To do this they must equate the electrical power input to the motor to the mechanical power output from the motor.
3.2.2. Lab 5 – Sensor Calibration and System Inertia

This two-part exercise was condensed from two exercises because each part employs the small angle approximation which is an analytical tool presented in the course. In part one of this exercise, students use a bifilar pendulum to determine the rotational inertia of the paddle component. The background information in the handout presents the students with the undamped second-order equation of motion:

\[ J_{cm} \ddot{\theta} + K_{BP} \theta = 0 \]

(3-7)

The rotational inertia \( J_{cm} \) is that of the paddle component about its center of mass while \( K_{BP} \) is the equivalent spring force due to gravity. In the pre-lab exercise, the students use the force body diagram and system parameters to determine the equivalent spring constant:

\[ K_{BP} = \frac{m_p g D^2}{4h} \]

(3-8)

The mass of the paddle is represented by \( m_p \) and the parameters \( D \) and \( h \) are the lengths depicted in Figure 3.1. The students then use the second-order characteristic equation to determine the relationship for the rotational inertia dependent on the observed free response natural frequency \( \omega \):

\[ J_{CM} = \frac{m_p g D^2}{4h \omega^2} \]

(3-9)

Finally, through the use of the parallel axis theorem and the measurement of the distance \( r_{cm} \) between the center of mass and the paddle’s pivot point, students can determine the rotational inertia of the paddle about its pivot point \( J_p \):

\[ J_p = m_p r_{cm}^2 + J_{CM} \]

(3-10)
The general procedure and post-lab exercises are similar to that of Lab 2 developed for the original design. A setup specific to the bifilar pendulum was developed for use in the exercise. This setup is shown in Figure 3.6. A balance bar is included in the setup for determining the paddle’s center of mass. Yarn is used for the strings and is taped to the paddle. Binder clips with holes drilled in their back sides are employed to secure the yarn and provide easy adjusting of the yarn’s length. The binder clips sit in a slot on the hang bar that allow their position to be adjusted laterally so that the yarn can hang vertically.

Figure 3.6. Bifilar pendulum employed in System Inertia lab.

In part two of this exercise, students complete the assembly of the Haptic Paddle and calibrate the Hall-effect sensor. A multi stage op-amp circuit is used to condition the output of the sensor and the output of the conditioning circuit is read by a VI that communicates with a DAQ card. The signal conditioning circuit is discussed in Chapter 4. Unlike the exercise for the original design, the procedure of this exercise has the
students generate their own calibration file by entering the data into Microsoft Excel and applying a best fit linear curve. As discussed in Chapter 2, the adapted design ensures that the sensor output stays within a linear range, thus the post-lab exercise prompts the students to address how the small angle approximation provides for their linear data. The post-lab exercise also prompts students to derive an op-amp circuit that does the same conditioning as the signal conditioning circuit to tie this exercise to the one in which students investigate op-amp circuits.

3.2.3. Lab 6 – Virtual and Teleoperation Systems

In this exercise, students run a VI that communicated with a DAQ card and employs a PD controller to effect a virtual second-order system. The background information in the exercise handout presents the students with the lumped parameter model equation of motion for the Haptic Paddle system and the equation of motion for the implemented virtual second-order system:

\[ m_{eq} \ddot{x} + b_{eq} \dot{x} + k_{eq} x = f_m \]  \hspace{1cm} (3-11)

\[ m_{eq} \ddot{x} + b_{virt} \dot{x} + k_{virt} (x - x_{sp}) = 0 \]  \hspace{1cm} (3-12)

The lumped parameter model expresses the system relative to the displacement \( x \) of the paddle handle with the force input \( f_m \) transmitted from the motor. In the pre-lab exercise, students use energy methods to determine the relationships expressing the lumped parameters and subsequently calculate their numerical values:

\[ m_{eq} = \frac{J_p}{l_x^2} + J_m \left( \frac{r_{sp}}{r_{CS}} \right)^2 \]  \hspace{1cm} (3-13)

\[ b_{eq} = B_m \left( \frac{r_{sp}}{r_{CS} l_x} \right)^2 \]  \hspace{1cm} (3-14)
\[ k_{eq} = \frac{m_p g r_{cm}}{l_x^2} \]  \hfill (3-15)

The parameters \( J_m \) and \( B_m \) are the mechanical inertia and damping of the motor, respectively. The parameters \( r_{sp} \) and \( r_{cs} \) are the radii of the sector pulley and capstan spool, respectively, used in the cable transmission. The parameter \( l_x \) is the distance from the paddle’s pivot point to its handle.

During the exercise, students are able to enter virtual spring and dashpot coefficients, \( k_{v_{irt}} \) and \( b_{v_{irt}} \) respectively, to achieve underdamped, critically damped, and overdamped second order response behavior. The students are also able to use the VI to impart step inputs to the system, by using a set point \( x_{sp} \), and record the step responses. To improve the fidelity of the virtual environments, the VI was run on the LabVIEW real-time operating system (RTOS) to improve loop rates. The RTOS is discussed in Chapter 4. The procedure for this part of the exercise is much the same as that of Lab 4 developed for the original design. Because feedback control is not within the scope of the MECH 343 course, students are presented with only a high level overview of PD control. To demonstrate the abilities of haptic device’s, the VI was also programmed to effect common events such as hitting a wall, traversing over a bump or divot, and moving within a viscous fluid. To further demonstrate the abilities of haptic devices, a second VI was written to effect a teleoperation system. Students are able to explore both traditional master slave teleoperation as well as haptic teleoperation depicted in Figure 3.7. The post-lab exercise focuses on the recorded step responses for the under, critically, and overdamped behavior displayed by the virtual environment represented by equation (3-12). Students employ the logarithmic decrement method to determine the experimental
values of the damping ratio and natural frequency of the underdamped response. They are able to compare these experimental values to the expected values corresponding to the known $m_{eq}$ and their selected $k_{virt}$ and $b_{virt}$. Also for the critically damped response, students are also able to determine if they should have expected to observe critically damped behavior due to the value of damping ratio corresponding to the known $m_{eq}$ and their selected $k_{virt}$ and $b_{virt}$.

Figure 3.7. Depiction of master-slave (above) and haptic teleoperation schemes employed in Teleoperation Systems lab.
Chapter 4
Supporting Software and Hardware

The implementation of the original design and laboratory series used a custom made board that communicated with a PC via a parallel port connection. A C executable ran on the PC to affect inputs to and read and record outputs of the system. Discussed subsequently are the supporting software and hardware choices made for the implementation of the adapted design and laboratory series in the MECH 343 course.

4.1. LabVIEW software

As discussed in Chapter 1, LabVIEW is a powerful programming software that has demonstrated repeated success in educational applications. Specific to the adapted lab series presented in this thesis, LabVIEW adequately provides compatibility with DAQ hardware, performance, intuitive Graphical User Interface (GUI), and a real time add-on package. LabVIEW also offers a Real-Time Operating System (RTOS) designed specifically to run LabVIEW programs in real-time. LabVIEW programs called Virtual Instruments (VIs) were written for the motor spin-down, sensor calibration, and virtual and teleoperation systems exercises.

The VIs written for the adapted lab series were capable of reading and writing analog signals as appropriate to the exercise. Necessary controls, indicators, and displays are incorporated into the VI front panel display. When needed, recording of data was built into the VI. All mathematical modeling was performed within the VIs. The VIs for the virtual and teleoperation systems exercise were written to run in the LabVIEW RTOS. Front panel displays and block diagram codes are attached in Appendix D.
4.2. Data Acquisition Hardware

The data acquisition (DAQ) hardware selected had to be compatible with the LabVIEW software and capable of digital to analog and analog to digital conversions (DAC and ADC respectively). DAC and ADC are also referred to as analog out and analog in (AO and AI), respectively, in this thesis. National Instruments commercially produces a broad range of DAQ devices that are compatible with LabVIEW. The 6070E DAQ card is one such device. It has 16 ADC and 2 DAC 12-bit channels which are sufficient for the needs of the adapted lab series. The card also has 8 digital input/output channels (DIO), two timers, and two counters that are available if needed by future modifications to the lab series. The datasheet for this device is available at [19]. The 6070E card is installed in a PXI industrial computer chassis. For most purposes, this computer functions as a regular personal computer that runs the Windows operating system. It has a large number of PCI card slots, which provides the ability to install a number of computer controllable laboratory devices. This ability makes the hardware very useful for both the adapted lab series and for research work. The PXI computer readily boots into the LabVIEW RTOS for easy setup in the final exercise. A typical setup showing the Haptic Paddle and data acquisition system is given in Figure 4.1. The PXI computer with 6070E card is also part of a larger system designed for education known as ELVIS (Educational Laboratory Virtual Instrument Suite) [15]. The ELVIS system is used in the earlier MECH 343 lab exercises, which improves the continuity of these exercises with the Haptic Paddle labs.
4.3. Actuator amplifier

The actuator requires an amplifier that can interface with the DAQ system and deliver the necessary power to drive the actuator. A LM12CLK power operational amplifier was wired as an inverting amplifier with unity gain to provide the actuator amplifier. The circuit schematic is shown in Figure 4.2. The op-amp is powered by a bipolar power supply as shown in the schematic. The datasheet for the LM12CLK is available at [20].
Figure 4.2. Amplifier circuit schematic showing connections to the motor and the DAQ card.

Figure 4.3. Conditioning circuit schematic showing connections to the sensor and the DAQ card.
4.4 Sensor signal conditioning

The Hall-effect sensor outputs a voltage in the range of 0-5 volts that is linear with the paddle position. The 6070E card has an ADC range of ±10 volts with 12 bits of resolution over the range. To take full advantage of the card’s resolution, a signal conditioning circuit was wired to linearly amplify the sensor’s output to have the same ±10 volt range as the card. The conditioning circuit employs a series of op-amps to buffer the signal and amplify it to the desired range. The circuit also uses a differentiating op-amp stage to provide a voltage proportional to the paddle’s velocity. Analog differentiation is preferred over digital differentiation because it is not affected by software loop rates and reduces software calculations thereby increasing loop rates. The signal conditioning circuit is shown in Figure 4.3.
Chapter 5

Results

The following discussion addresses the results of the work done to meet the goals set forth in Chapter 1.

5.1. Repeatable use of adapted design

As stated in Chapter 1, repeated use was the primary goal in adapting the original design of the Haptic Paddle. New units were manufactured for use in the Fall 2006 MECH 343 course. Every unit survived use during the series of exercises. At the completion of the course, every unit was disassembled and the individual components were examined for structural integrity. Each and every non-consumable component is sufficiently sound for use for at least another semester and possibly several more. The two year cost of the adapted design is approximately $30 per unit, compared to approximately $40 per unit for the original design. Longer term use of the adapted design will provide even greater cost savings.

5.2. Student performance

The adapted Haptic Paddle labs were first implemented at Rice in the Fall 2005 semester. The final exercise had not yet incorporated teleoperation and thus focused on exploring virtual systems with haptics. The adapted design was incorporated with LabVIEW software and DAQ hardware to display virtual environments, however the system required further development before it could record data at sampling rates sufficient for analysis. As a result, students were given a demo of virtual systems
displayed on the Haptic Paddle and then they used the Impulse Engine 2000 to explore virtual systems and record data for analysis. The report submission prompts and grading rubric were the same as the virtual systems exercise included in the Fall 2004 lab series.

Assessment of the performance of the two classes is presented subsequently. It should be emphasized that this assessment was for the same lab experiment, conducted at the end of the course, in each year. The differences in years were the content of the earlier laboratory experiments, and the careful incorporation of course concepts closely tied to lecture material in the Haptic Paddle laboratory series (Year 2). It is expected that Year 2 students would have better conceptual understanding because they have seen the concepts repeated in exercises throughout the semester, and have learned the material in an exploratory fashion rather than following strict laboratory guidelines of the procedures [16]. Figure 5.1 charts the student performance in laboratory notebook submissions. The darker colored bars reflect rubric points graded for conceptual knowledge rather than factual knowledge shown by the lighter colored bars. The rubric points graded are listed below the figure.
Figure 5.1. Student performance showing marked improvement with the implementation of the Haptic Paddle laboratory series [16].

**First-order System**
1. Student describes concept of mass-damper system.
2. Student documents output signal.
3. Student recognizes differences between system output for different parameter values.
4. Student describes that behavior of mass-damper system follows equation.
5. Student identifies the importance of the time constant.
6. Student relates the time constant to the damping in the system.

**Second-order System**
7. Student describes concept of mass-spring-damper system.
8. Student documents output signal.
9. Student understands and computes the system parameters using log-decrement method.
10. Student documents system behavior and explains correctly.
11. Student relates behavior of second order system to equation (damping coefficient and natural frequency).
12. Student describes the change in behavior of the response with varying damping coefficients.

**General**
13. Student identifies the human-supplied input as an impulse.
14. Student relates the measured output to impulse response of the system.
15. Student describes concepts of haptic system.
16. Student correctly uses measurement equipment.
It is clear from Figure 5.1 that there are significant gains in student understanding of concepts after completing the haptic paddle laboratory series. Such improvements included conceptual understanding of mass-damper systems, importance of time constant, relation of time constant to the damping in the mechanical system, concept of mass-spring-damper system, and concept of a haptic system (largest gain). Negligible gains/losses (not significant) were seen on the concepts regarding the behavior of the mechanical system following the characteristic equation, that the change in behavior varied with damping, that the input given by the student was an impulse, and that the measured output was the impulse response. In addition, basics like correctly using equipment, using log-decrement method, and observing experiment output, all clearly outlined in experimental procedures, did not vary significantly from year to year.

5.3. Student survey

For the Fall 2006 semester, the device and its supporting software and hardware were sufficiently developed to allow students to explore virtual systems and record data from those systems for analysis. Teleoperation systems were also incorporated into the exercise. The Fall 2006 class was the first at Rice to fully experience the Haptic Paddle and its accompanying laboratory series. The adapted laboratory series is still relatively new and fresh, which also means that there are several opportunities for improvements that can be made to the series. At the conclusion of the course, the students were surveyed to gauge opinions regarding the laboratory series. The opinions were asked with the scale of Strongly Disagree, Disagree, Slightly Disagree, Slightly Agree, Agree, and Agree. Students also provided suggestions for haptic environments to render and general comments about how the lab could be improved. Of the 46 students who took the course,
29 responded. The opinions relevant to the work presented in this thesis and the two strongest responses to each are as follows:

1. I feel the lab material was well aligned with class material in the order it was presented: 38% Agree, 28% Slightly Agree.

2. I feel this lab contributed to my learning experience in the class: 41% Agree, 38% Slightly Agree.

3. I enjoyed the lab exercises: 32% Slightly Agree, 29% Agree.

4. I enjoyed assembling the Haptic Paddle: 48% Agree, 31% Slightly Agree.

5. I felt a sense of ownership of my team’s Haptic Paddle: 45% Slightly Agree, 31% Agree.

![Fall 2006 Student Survey Results](image)

**Figure 5.2. Student opinion survey results**

Review of the full results charted in Figure 5.2 shows that 79% of the class felt that the lab contributed to their learning experience, as well as 86% enjoyed assembling the Haptic Paddle, and 79% felt a sense of ownership of their team’s Haptic Paddle. These results demonstrate that the Haptic Paddle is an engaging device that provides the students enjoyment while they learn. Areas for improvement include increasing student
enjoyment of the laboratory exercises and better alignment with the course material in the order it is presented in lecture.

In the Spring of 2007, a select number of undergraduate students from the Fall 2006 class were recruited to be involved with a thorough review of the adapted laboratory series. The focus of the review was to address the issues brought forth by the survey. Particular attention was paid to the order that material was presented, expanding the background information presented in the handouts, developing more constructive pre-lab exercises, and improving the detail of the procedures, thereby reducing the mystery of what the students were investigating and why. Improved clarity of post-lab exercise prompts was also attended to. The exercise handouts attached in Appendix C are the latest versions that incorporate the edits made in this review. Another product of this review was feedback given to the instructor of the course for suggestions as to how to modify lecture material so that it better aligned with the laboratory material.

5.4. Grading rubrics

The laboratory time and grading demands of the MECH 343 laboratory component are great enough to require four teaching assistants (TAs). During the Fall 2005 semester, loosely defined rubrics were used to grade student work and it became apparent (largely through the student feedback) that better structured rubrics were needed to homogenize the grading of the different TAs. Additionally, no solution manual had been created for the non-Haptic Paddle exercises which caused an increased variance in grading. For non-Haptic Paddle exercises, new rubrics were adapted from the previous ones; these rubrics included solutions and had a defined number of points to be awarded for each answer. Solution rubrics were also generated for the Haptic Paddle exercises.
The availability of these rubrics facilitated discussion among the TAs as to how to award credit for answers. This discussion and these rubrics significantly reduced the variance of grading among the TAs in the Fall 2006 semester as evidenced by student feedback regarding this issue.

The Spring 2007 review of the exercise handouts included a review of their respective solution rubrics. The solution rubrics attached in Appendix C are the latest versions that incorporate the edits made in this review.

5.5. Dissemination of adapted design

As discussed in Chapter 2, documentation of the adapted design and its manufacture has been prepared to facilitate dissemination. The most current version of these documents have been posted on the internet at the Mechatronics and Haptic Interfaces Lab’s website [13]. At the time this thesis was written, there has not yet been an aggressive campaign to disseminate the information. This is expected once the latest round of revisions to the adapted laboratory series discussed in the previous section is complete.

The adaptation of the original design and the implementation of a LabVIEW based laboratory series have been presented in the conference proceedings of the 14th Symposium on Haptic Interfaces for Virtual Environments and Teleoperation (HAPTICS ’06) [12], which included an oral presentation of the work and a hardware demonstration of the Haptic Paddle system, and the 2006 ASEE Annual Conference & Exposition: Excellence in Education [16], which included a poster presentation of the work.

Despite the lack of a campaign, information has been disseminated to several institutions. Hardware units have been sent to Todd Murphey, assistant professor of
electrical and computer engineering at the University of Colorado, and to Panos Antsaklis, professor of electrical engineering at the University of Notre Dame. Information has also been sent to Allison Okamura, associate professor of mechanical engineering at Johns Hopkins University, Edward Colgate, professor of mechanical engineering at Northwestern University, and John Hollerbach, professor of computer science and research professor of mechanical engineering at the University of Utah. Note that many of these are professors in disciplines other than Mechanical Engineering, thus demonstrating the broad appeal of the device.

Information will also be shared with Gangbing Song, associate professor of mechanical engineering at the University of Houston which is predominantly attended by minority students. Due to the university’s location in the same city as Rice University, it was possible to give a demonstration of the Haptic Paddle in a senior level controls course instructed by Dr. Song in the Spring of 2006. Students were able to physically interact with a second-order mass spring damper system and feel the effect of changing spring and damping constants. Students were then able to observe how changing these constants could affect whether the system’s free response behavior to a step input was under, critically, or overdamped. Afterwards, the students were surveyed for their opinions on the demonstration. The scale of opinions asked was 1—not effective/familiar, 2—somewhat effective/familiar, 3—effective/familiar, 4—very effective/familiar. Figure 5.3 lists the questions asked on the left with the responses graphed to the right. The number in the bar represents the average response with the lines showing one standard deviation. The survey results show a strong positive response to the demonstration’s effectiveness in presenting the Haptic Paddle as an electromechanical system, in presenting underdamped
versus critically damped versus overdamped behavior, and in motivating learning about haptics. There was also a positive response to the demonstration's effectiveness in presenting the concept of haptic feed back and how the implementation of a control system can affect a change in system behavior.

![Haptic Paddle Demonstration Survey — March 2006](image)

**Figure 5.3.** Student survey of Haptic Paddle demonstration in Dr. Song's MECE 4372 Spring 2006 course.

### 5.6. Educational outreach

The Haptic Paddle has also been used for workshop exercises in educational outreach to grade school students. In October of 2006, the Haptic Paddle was a part of the Sally Ride Science Festival, an event aimed at increasing interested in science and engineering among middle-school aged girls. Event attendees were able to assemble the device and then use it to interact with virtual environments and in teleoperation. In January of 2007, the device was a part of the Winter Intersession at the Kipp Academy
for high school students. The Winter Intersession is a four-day seminar in which students are able to attend workshops of their choosing. The Haptic Paddle was used in a workshop entitled "Robots, Physics, and You." Students were able to assemble the Haptic Paddle, received an introduction to haptics, and learned how haptics enabled them to explore concepts taught in their physics classes. In March of 2007, the device was a part of the Rice Austin College Expo. Students from Austin High School, which is predominantly attended by minority students, that are interested in the engineering professions attend this event, which is put on by Rice’s local chapter of the Society of Hispanic Professional Engineers. Event attendees received an introduction to robotics and haptics and were able to use the Haptic Paddle to interact with virtual environments and in teleoperation.

The use of the device in these outreach programs further demonstrates its appeal.
Chapter 6
Conclusions and Future Work

Educators can maximize the effectiveness of their laboratory courses by selecting laboratory devices of great utility. The development of devices that can be accompanied by a cohesive lab series have shown strong potential for improving quality of education. Haptic devices have also shown this strong potential. The Haptic Paddle is one such device that has successfully married these two qualities. VIs written in LabVIEW software are fully capable of providing the needs of laboratory exercises and have been shown to be very effective in educational settings.

The adapted design of the original Haptic Paddle significantly reduces the device’s cost. As discussed in Chapter 5, cost benefits are realized within two years. Improvements were also made to the device’s functionality, versatility, and ease of assembly and use. The adapted laboratory series to accompany the adapted design has also shown to be successful through student performance gains and positive student survey feedback. Continued improvements to the laboratory series are expected to bring increased positive feedback in future student surveys.

To affect a greater impact on the engineering education community, documentation has been prepared to facilitate the dissemination of this device to the education research community. The aim of this dissemination is to make the Haptic Paddle a popular platform for use in engineering education research. Despite the lack of an aggressive campaign to disseminate information about the device, several institutions have already requested information and units. Those who have requested information
include individuals not only from mechanical engineering departments, but also from
counter science and electrical engineering departments. This dissemination speaks to
the broad appeal of the device.

Future work includes further development of the supporting hardware to improve
dissemination. Currently only schematics of the amplifier and signal conditioning circuits
are available for dissemination. The ultimate goal is to be able to provide the files
necessary to have these circuits manufactured by a PCB fabricator, thereby improving
cost and manufacture time.

The replacement of the current actuator amplifier with a PWM driven H-bridge is
under consideration. The use of the power op-amp requires the use of a bipolar power
supply that has sufficient current capacity to drive the motor, whereas the H-bridge only
requires a unipolar supply with sufficient current capacity. Unipolar supplies are more
widely available at lower costs, thus an H-bridge solution will drive down cost.

Embedded microprocessing presents an alternative to the DAQ and control
hardware presented in this thesis. The use of a microprocessor to control the Haptic
Paddle system will make the device more popular where the high cost of products such as
the 6070E card have deterred their purchase. Microprocessors are compatible with
programming in standard languages, including LabVIEW. They are also capable of
communicating with executables, written in standard languages including LabVIEW,
running on regular personal computers.

The work and results presented demonstrate the utility of the Haptic Paddle as an
ideal subject of a cohesive laboratory series, a promising platform for engineering
education research among collaborators, and even an engaging device that can foster interest in the sciences and engineering among the youth.
References


   http://upload.wikimedia.org/wikibooks/en/9/9a/Fldbarmgnt.png


   http://mems.rice.edu/~mahi/research/Haptic%20Paddle/ccli.html


Appendix A
Dissemination Documentation [13]

A.1. Kit Information

HAPTICS

Haptics (pronounced HAP-tiks) is the science of applying touch (tactile or kinesthetic) sensation and control to interaction with computer applications. The word derives from the Greek *haptein* meaning "to fasten." By using manually controlled input/output devices (joysticks, data gloves, or other devices), users can receive feedback from computer applications in the form of felt sensations via the hand or other parts of the body. In combination with a visual display, haptics technology can be used to train people for tasks requiring hand-eye coordination, such as surgery and space ship maneuvers. It can also be used for games in which you feel as well as see your interactions with images. For example, you might play tennis with another computer user somewhere else in the world. Both of you can see the moving ball and, using the haptic device, position and swing your tennis racket and feel the impact of the ball.

THE HAPTIC PADDLE

The Haptic Paddle is a low cost, single degree-of-freedom force feedback joystick capable of providing a peak force of about 10N at its handle. It is an ideal tool for the demonstration of electromechanical system properties and concepts covered in undergraduate engineering courses.
HAPTIC PADDLE COMPONENTS

Part 1: Paddle

Parts 2-4: Paddle Frame
<table>
<thead>
<tr>
<th>Part Name</th>
<th>Picture</th>
<th>Part Name</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall Effect Mount</td>
<td></td>
<td>Hall Effect Sensor</td>
<td></td>
</tr>
<tr>
<td>3/8&quot; OD x 3/16&quot; ID Washers x 6</td>
<td></td>
<td>Precision Shoulder Screw</td>
<td></td>
</tr>
<tr>
<td>PMDC Motor</td>
<td></td>
<td>Capstan Spool</td>
<td></td>
</tr>
<tr>
<td>#10 Lock Washers x 4</td>
<td></td>
<td>Flanged Ball Bearings x 2</td>
<td></td>
</tr>
<tr>
<td>Motor Wires with banana plugs and quick connect terminals</td>
<td></td>
<td>Banana jacks, one red, one black</td>
<td></td>
</tr>
<tr>
<td>Cable</td>
<td></td>
<td>Acorn Nut</td>
<td></td>
</tr>
<tr>
<td>Magnet Cap</td>
<td></td>
<td>Magnet</td>
<td></td>
</tr>
</tbody>
</table>

Fasteners:

8 x #10-24 x ½" socket head cap screws (SHCS)
4 x #6-32 x 5/8" flat head screws (FHS)
2 x #6-32 x ¼" nylon round head screws (RHS)
1 x #8-32 x 3/8" set screw (SS)
1 x 1/16" x 3/8" spring pin
Haptic Paddle Assembly

The following sub sections are for progressively assembling the Haptic Paddle throughout the lab series written to accompany the device. Skip to the last sub section “Full Haptic Paddle Assembly” if you wish to assemble the entire device from complete disassembly.

Actuator Characteristics Lab: Part I

The assembly for Part I of the exercise is shown by the following pictures. Follow the steps below for this assembly.

1. Use the eight SHCS to fasten together the Paddle Base, Paddle Support, and Side Supports as shown above. Keep the screws a little loose until all have been threaded, then snug them. Do not over tighten the screws!
2. The Capstan Spool has already been affixed to the motor shaft through the use of the spring pin. Use the four FHS to fasten the motor to the Paddle Support.
3. Use the motor wires to connect the motor leads together. The red banana plug fits into the hole on the side of the black banana plug.
4. Do not use pliers for this step! Spin the provided mass onto the Capstan Spool. Leave a small space between the mass and the Paddle Support.
5. Use the provided nut driver to tighten the nut against the mass. Give it a final tightening and hold the weight to prevent it from rotating.
Actuator Characteristics Lab: Part II

The attachment of the Paddle is shown by the following pictures. Follow the steps below for this assembly.

1. Begin with the assembly from Part I of the exercise.
2. Place one ball bearing on the precision shoulder screw (PSS); the flanged side should meet the head of the screw. Place four lock washers on the PSS.
3. Insert the PSS and flanged bearing on the back side of the Paddle Support.
4. Place the second ball bearing on the PSS and insert it into the Paddle Support.
5. In the following order, place two washers, the Paddle, four washers, and the acorn nut on the PSS. The Paddle tensioning slit should be on the left side when viewed from the front of the device.
6. Tighten the acorn nut to remove axial play of the bearings relative to the Paddle Support. Using an Allen wrench on the head of the PSS and holding the acorn nut with your fingers provides good tightness. Do not over-tighten the nut; it will impede the free swinging of the paddle.
7. If the Paddle comes in contact with the Capstan Spool, use the provided sandpaper to sand the Paddle until it swings freely past the Capstan Spool. Take care not to snap off the leg with the tensioning slit in it.
8. Continue assembly to attach the cable.
The following picture is a bottom view of the cable wrapped on the Capstan Spool.

9. Thread the cable through the right cable attachment hole on the Paddle.
10. With the cable towards the middle of the Paddle, jam a RHS into the attachment hole.
11. Rotate the Paddle counter clockwise until the arc of the sector pulley is just right of the Capstan Spool.
12. Run the cable along the Paddle pulley and wrap it around the three threads that are about even with the top face of the Paddle.
13. Rotate the Paddle clockwise and thread the cable through the left cable attachment hole. Hold the cable to the pulley to keep it taut.
14. Squeeze the tensioning slit and jam a RHS into the attachment hole.
15. Rotate the Paddle clockwise as far as it will go.
16. Screw the #8 SS into the tensioning slit until it is snug to the inside of the slit.
17. Rotate the Paddle back and forth to ensure that the cable runs smoothly. If it does not, it may be because the cable is too loose. If so, tighten the tensioning set screw with the Paddle rotated all the way clockwise.
18. Cut off the excess cable.
Hall Effect Calibration Lab

The assembly for the Hall Effect Calibration Lab is shown by the following pictures. Follow the steps below for this assembly.

1. Start with your assembly from the Actuator Characteristics Lab.
2. Remove the 4 SHCS from the Base, turn it around, and refasten the SHCS. **Do not over tighten the screws!**
3. Slide the magnet into the Magnet Cap. It is easier to slide it in on the side etched with the “M”. The magnet should be centered.
4. Push the Magnet Cap onto the PSS. This should be a slight press fit. Use a minimum amount of force to try and rotate the Magnet Cap. The fit is good if the Cap resists rotating. If the Cap is loose and rotates easily, put a piece of paper towel or tissue paper in the Cap and push it on.
5. The proper length for the Hall-effect sensor leads is such that the sensor is positioned directly below the magnet. Determine the proper length for the leads and cut them. Note: the leads of the Hall-effect may have already been cut to the proper length.
6. Insert the Hall-effect sensor into the Mount. **Note the trapezoidal cross section of the Hall-effect sensor!** The narrower side of the sensor should be facing upwards.
7. Fasten the Mount to the Side Supports with the red and black banana jacks. As you tighten the banana jacks, push the Mount downwards so that it hangs as low as its clearance holes will allow.
Full Haptic Paddle Assembly

1. Use the eight SHCS to fasten together the Paddle Base, Paddle Support, and Side Supports as shown on Page 2. Keep the screws a little loose until all have been threaded, then snug them. Take care not over tighten the screws!
2. The Capstan Spool has already been affixed to the motor shaft through the use of the spring pin. Use the four FHS to fasten the motor to the Paddle Support.
3. Refer to the picture on page 5 for steps 3 through 8. Place one ball bearing on the precision shoulder screw (PSS); the flanged side should meet the head of the screw. Place four lock washers on the PSS.
4. Insert the PSS and flanged bearing on the back side of the Paddle Support.
5. Place the second ball bearing on the PSS and insert it into the Paddle Support.
6. In the following order, place two washers, the Paddle, four washers, and the acorn nut on the PSS. The Paddle tensioning slit should be on the left side when viewed from the front of the device.
7. Tighten the acorn nut to remove axial play of the bearings relative to the Paddle Support. Using an Allen wrench on the head of the PSS and holding the acorn nut with your fingers provides good tightness. Do not over-tighten the nut; it will impede the free swinging of the paddle.
8. If the Paddle comes in contact with the Capstan Spool, use sandpaper to sand the Paddle until it swings freely past the Capstan Spool. Take care not to snap off the leg with the tensioning slit in it.
9. Refer to the picture on page 6 for steps 9 through 18. Thread the cable through the right cable attachment hole on the Paddle.
10. With the cable towards the middle of the Paddle, jam a RHS into the attachment hole.
11. Rotate the Paddle counter clockwise until the arc of the sector pulley is just right of the Capstan Spool.
12. Run the cable along the Paddle pulley and wrap it around the three threads that are about even with the top face of the Paddle.
13. Rotate the Paddle clockwise and thread the cable through the left cable attachment hole. Hold the cable to the pulley to keep it taut.
14. Squeeze the tensioning slit and jam a RHS into the attachment hole.
15. Rotate the Paddle clockwise as far as it will go.
16. Screw the #8 SS into the tensioning slit until it is snug to the inside of the slit.
17. Rotate the Paddle back and forth to ensure that the cable runs smoothly. If it does not, it may be because the cable is too loose. If so, tighten the tensioning set screw with the Paddle rotated all the way clockwise.
18. Cut off the excess cable.
19. Refer to the picture on page 7 for the remaining steps. Slide the magnet into the Magnet Cap. It is easier to slide it in on the side etched with the “M”. The magnet should be centered.
20. Push the Magnet Cap onto the PSS. This should be a slight press fit. Use a minimum of force to try and rotate the Magnat Cap. The fit is good if the Cap resists rotating. If the Cap is loose and rotates easily, put a piece of paper towel or tissue paper in the Cap and push it on.
21. The proper length for the Hall-effect sensor leads is such that the sensor is positioned directly below the magnet. Determine the proper length for the leads and cut them.

22. Insert the Hall-effect sensor into the Mount. Note the orientation of the Hall Effect so that you know which lead is which.

23. Fasten the Mount to the Side Supports with the red and black banana jacks. The holes in the Mount are oversized to allow play in the distance between the magnet and the Hall Effect. The closer the Hall, the greater the voltage changes as the Paddle rotates. This can cause problems with DAQ saturation, depending on the signal conditioning of the sensor.

THE PADDLE ACTUATOR

A Pittman LO-COG® 9434 15.1VDC brushed servomotor provides actuation for the Haptic Paddle. See the attached data sheet for the motor specifications. The 15.1 VDC winding is not listed, thus an Excel file with interpolated properties relevant to the Paddle lab series is also attached.

THE PADDLE POSITION SENSOR

The Allegro 1322 EUA is a ratiometric Hall Effect Sensor that requires a 5V supply and provides a voltage output proportional to the applied magnetic field in the range of 0-5V. The ratiometric characteristic makes the Hall Effect a suitable sensor for measurement of angular displacement. See the attached datasheet for specifics on this device.

A.2. Manufacture Document

Preface: Please review these procedures with your technician. Drawings are attached at end of document. The drawings in the PDF version of this document are not as clear as the originals, which are available at the following link:
http://mems.rice.edu/~mahi/research/Haptic%20Paddle/ccli.html

Per kit, laser cut the following parts per appended drawings: Paddle Base, Paddle Support (**see note on drawing), Side Support x 2, Paddle, Magnet Cap (**see note on drawing). Note the small radii at 90° corners (we found this feature to produce cleaner corners on parts produced from our laser cutter).

Examples of laser cut layouts are appended after the technical drawings. If you would like either our .dxf or .ai (Adobe Illustrator) files, please contact Dr. Marcia O'Malley (omalleym@rice.edu).

In general, is it is most time efficient to do step one to all parts, then to proceed to step 2 for all parts, and so forth.
Paddle Base:

1. Laser cut part. Rice logo to be added in laser cutter software (i.e. Adobe Illustrator).
2. Place scrap metal backing on paddle base (to prevent from boring all the way through).
3. Using a drill press and socket bore, counterbore the Paddle Base for #10 SHC screw at locations shown in the drawing so that the screw heads are flush with the paddle base. **Note:** Counterbore up on the side opposite of the etched logo.

Paddle Support:

1. Laser cut part (**see note on drawing**).
2. Place scrap metal backing on paddle support (to prevent from boring all the way through).
3. Counterbore the four corner holes of the paddle support for #10 SHC Screws as shown in the drawing so that the screw heads are flush with the paddle base.
4. Countersink the four holes surrounding the motor shaft hole for #6 Flathead Screws (**see note on drawing**) as shown in the drawing so that the screw heads are flush with the paddle support. **Note:** Counterbore and countersink in the *same* direction.
5. Using a ½” reamer, ream through the ½” holes located at the center top and center bottom (**see note on drawing**) of the paddle support as shown in the drawing.

Side Supports:

1. Laser cut two parts. The laser cut parts have score lines cut into them to assist in lining up the holes to be drilled, as shown in the drawing.
2. Use a Vernier height gage on a ground flat surface to etch a line at one half the material thickness to cross these score lines. These crosses mark where to drill the holes. **Note:** Measure the width of your material because it may not be exactly .500” inches.
3. On a mill, line up the long side of the part to drill the marked hole ½” deep with a #25 bit (center bit first). After drilling the marked hole, move the part 3” over and place a second hole as shown on the drawing.
4. Line up the short side of the part to drill the marked hole ½” deep with a #25 bit (center bit first). After drilling the marked hole, move the part 2” over and place a second hole as shown on the drawing.
5. Line up the back side of the part to drill the marked hole 5/8” deep with a #29 bit (center bit first).
6. Tap the appropriate holes with #10-24 and #8-32 taps.

Paddle:

1. Laser cut part. The laser cut part has score lines cut into it to assist in lining up the holes to be drilled, as shown in the drawing. The laser cut part has a thin sliver that fits in the slit that assists in drilling the hole for the tensioning set screw.
2. Use a Vernier height gage on a ground flat surface to etch a line to cross these score lines. The .135” dimension on the drawing assumes .500” thick material. Measure material and use (=.135-(.500-t)/2) for appropriate dimension. These crosses mark where to drill the holes. **Note:** When looking at the bottom of the Paddle, the holes should be on the bottom right and upper left as shown in the drawing.

3. Use the height gage to etch a line at one half the material thickness on the leg with the slit. This will assist in lining up the hole for the tensioning set screw.

4. On a mill, line up a hole on the arc to be drilled. There are etch marks on the Paddle face to assist vertical alignment of the hole. When drilling the hole on the slit side, make sure that the part is firmly clamped in the device. Drill through with a bit about half the size of a #29 (0.136”) bit, using a center bit first. Be gentle to prevent cracking the material when you exit the other side. Drill through with a #29 bit.

5. On the leg with the slit, line up the hole using a center bit giving as little clearance as possible between the bit and the arc. Drill to the thin sliver with a bit about half the size of a #29 (0.136”) bit. You will be able to see when you get through to the thin sliver. Drill to the thin sliver with a #29 drill.

6. On the hole at the center of the Paddle, ream through with 3/16” reamer.

7. Tap the hole for the tensioning set screw with an #8-32 tap. If you run the tap too far, it will widen the slit and snap the leg. Use a finishing tap to prevent this.

8. **Note:** due to tolerance of the laser cutter, there may be a slight interference between the Paddle and the Capstan Spool when the Haptic Paddle is assembled. A simple way to fix this is to hold a piece of sand paper over the Capstan Spool and work the Paddle back and forth until there is free motion.

**Magnet Cap:**

1. The cap is laser cut in two parts (**see note on drawing**). Assemble the parts by pushing the B part into the A part on the side opposite the etched ring.

2. The purpose of the .040” inch fillets on the A part are for easier insertion (thickness of tab on B is actually less than slot in A due to tolerance of laser cutter).

**Hall Mount:**

1. The Hall Mount consists of Vector Board (“Punchboard”) made of epoxy glass and a Single Inline Package (SIP) header. Print out the attached drawing and place it underneath the Vector Board. Trace the outlines of the parts and mark the locations for the holes that give clearance for the SIP header and the banana connectors. The two holes for the banana connectors should be centered between a region of four holes on the Vector Board.

2. Using a sheet metal shearer, cut the Vector Board into the 3”x .6” sections.

3. Using a punchboard vise and a 1/16” drill bit, drill the three holes for the pins of the SIP header. These three holes should already line up with the existing three holes of the Vector Board.

4. Use a 1/16” drill bit to drill starter holes for the two banana connector holes. Then work your way up to a final size of a 1/4” bit.

5. Using a razor blade, cut off a 3-pin SIP header.
6. Glue the SIP header so that the pins are on the pretty (shiny) side of the Vector Board.

**Capstan Spool:**

1. The Capstan Spool is machined from 3/8"-24 all-thread.
2. On a ban saw, cut parts to 1 ¼" long.
3. Mount part on a lathe with a 3/8" collet chuck. Use a stop tool so that you have a face to reference.
5. Chamfer part and use file to remove sharp edge.
6. Flip part around and machine face until part is 1" long.
7. Use a parting tool to remove threads about .3" along the part face. Use file to remove sharp edge.
8. Ream part with 5/32" reamer (**see note on drawing). Center drill and drill with appropriate drill first.
9. On a mill, mount part with a V-block.
10. Drill a hole with a 1/16" bit, center bit first, as shown on the drawing. The hole goes completely through the part.
11. By hand, ream hole again with 5/32" reamer (**see note on drawing).
12. Affix Spool to motor shaft with 1/16" spring pin
13. Use 3/8"-24 die to clean threads on Spool. If the motor shaft extends out the backside of the motor, it is helpful to use the collet chuck on the lathe to secure the motor rotor.

**A.3. Manufacture Drawings**

Drawings are on subsequent pages
To scale laser cut outline on Sheet 2.

MATERIAL: 1/2" Acrylic
Note: The dimensions of the through hole and screw holes depend on the motor selection. Make sure your dimensions are appropriate to your motor.

To scale laser cut outline on Sheet 2.

MATERIAL: 1/2" Acrylic
Drill with #29 Bit and Tap #8-32 X 0.25" Deep

Score Lines to Assist in Lining up Holes by Eye

*See note*

Note: Score Lines are .010" wide by .005" deep.

MATERIAL: 1/2" Acrylic

To scale laser cut outline on Sheet 2.
Laser Cut to φ0.17"
Ream Thru with 3/16" Reamer

Drill with #29 Bit x .25" Deep
and Tap #8-32
Place as close to outer radius as possible

Score Lines to Assist in Lining up Holes by Eye
** see note

Breakaway part to ease removal from sheet after laser cutting

Drill Thru with #29 Bit 2 Places

0.50

0.010" wide by .005" deep.

To scale laser cut outline on Sheet 2.

MATERIAL: 1/2" Acrylic
Note: Dimensions are dependent on thickness of material and tolerance of laser cutter. Part B is inserted on opposite side of etch on Part A.

MATERIAL: 1/4" Cast Acrylic
Template is for a 6" x 4" perforated board.
Note: This dimension is specific to the motor selection. Make sure to use the dimension appropriate to your motor.

MATERIAL: 3/8"-24 All-Thread
## A.4. Bill of Materials

<table>
<thead>
<tr>
<th>Part #</th>
<th>Part Name</th>
<th>Qty</th>
<th>Material</th>
<th>Description</th>
<th>Vendor</th>
<th>Vendor Part #</th>
<th>Cost/Kit</th>
<th>Mfg Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Paddle</td>
<td>1</td>
<td>Cast Acrylic</td>
<td>1/2&quot; sheet</td>
<td>Laird Plastics (local)</td>
<td></td>
<td>$3.97</td>
<td>Laser Cut and then machined</td>
</tr>
<tr>
<td>2</td>
<td>Paddle Base</td>
<td>1</td>
<td>Cast Acrylic</td>
<td>1/2&quot; sheet</td>
<td>Laird Plastics (local)</td>
<td></td>
<td></td>
<td>Laser Cut and then machined</td>
</tr>
<tr>
<td>3</td>
<td>Paddle Support</td>
<td>1</td>
<td>Cast Acrylic</td>
<td>1/2&quot; sheet</td>
<td>Laird Plastics (local)</td>
<td></td>
<td></td>
<td>Laser Cut and then machined</td>
</tr>
<tr>
<td>4</td>
<td>Side Support</td>
<td>2</td>
<td>Cast Acrylic</td>
<td>1/2&quot; sheet</td>
<td>Laird Plastics (local)</td>
<td></td>
<td></td>
<td>Laser Cut and then machined</td>
</tr>
<tr>
<td>5</td>
<td>Magnet Cap</td>
<td>1</td>
<td>Cast Acrylic</td>
<td>1/4&quot; sheet</td>
<td>Laird Plastics (local)</td>
<td></td>
<td></td>
<td>Laser Cut in 2 parts</td>
</tr>
<tr>
<td>6</td>
<td>Base Fasteners</td>
<td>8</td>
<td>Steel/SS</td>
<td>10-24 x 1/2&quot; Socket Head Cap Screw</td>
<td>Coastal Fastener (local)</td>
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<td>$0.43</td>
<td>As Purchased</td>
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<td>7</td>
<td>Precision Shoulder Screw</td>
<td>1</td>
<td>SS</td>
<td>3/16&quot; Shoulder x 1 1/4&quot; long, 8-32 thread</td>
<td>McMaster Carr 93985A209</td>
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<td>8</td>
<td>Flanged Ball Bearing</td>
<td>2</td>
<td>SS</td>
<td>3/16&quot; ID x 1/2&quot; OD</td>
<td>McMaster Carr 57155K302</td>
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<tr>
<td>9</td>
<td>Lock washer</td>
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<td>SS</td>
<td>#10</td>
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<td>$0.03</td>
<td>As Purchased</td>
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<tr>
<td>10</td>
<td>Washer</td>
<td>6</td>
<td>SS</td>
<td>3/16&quot; ID x 3/8&quot; OD, pack of 250</td>
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<td>$0.17</td>
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<tr>
<td>11</td>
<td>Acorn Nut</td>
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<td>Steel/SS/Brass</td>
<td>8-32 thread, pack of 100</td>
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<td>As Purchased</td>
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<tr>
<td>12</td>
<td>Capstan Spool</td>
<td>1</td>
<td>Steel</td>
<td>3/8&quot;-24 all thread, 36&quot; long</td>
<td>McMaster Carr 98838A031</td>
<td>$0.10</td>
<td></td>
<td>Machined</td>
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<td>13*</td>
<td>Capstan Fastener*</td>
<td>1</td>
<td>SS</td>
<td>1/16&quot; x 3/8&quot; spring pin</td>
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<td>As Purchased</td>
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<td>14</td>
<td>Cable</td>
<td>15&quot;</td>
<td>SS wire</td>
<td>1x7 bare leader, 60lb break</td>
<td>Cut Rate Fishing Supply (local)</td>
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<td>$0.14</td>
<td>Cut to length</td>
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<td></td>
<td>Description</td>
<td>Quantity</td>
<td>Material/Type</td>
<td>Description</td>
<td>Supplier</td>
<td>Unit Cost</td>
<td>Unit Count</td>
<td>Remarks</td>
</tr>
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<td>------------</td>
<td>------------------</td>
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<tr>
<td>16</td>
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<td>#8-32 x 3/8&quot;</td>
<td>Coastal Fastener (local)</td>
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<td>As Purchased</td>
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<td>17</td>
<td>DC Motor</td>
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<td>Surplus Store</td>
<td>$5.00</td>
<td></td>
<td>As Purchased</td>
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<td>18*</td>
<td>Motor Fasteners*</td>
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<td>Steel/SS</td>
<td>6-32 x 3/8&quot; flat head</td>
<td>Coastal Fastener (local)</td>
<td>$0.01</td>
<td></td>
<td>As Purchased</td>
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<tr>
<td>19</td>
<td>Wire to motor</td>
<td>2</td>
<td></td>
<td>4&quot; long, 1 black, 1 red, 16AWG</td>
<td>Lab Stock</td>
<td></td>
<td></td>
<td>Cut to length</td>
</tr>
<tr>
<td>20*</td>
<td>Quick Disconnect Terminal*</td>
<td>2</td>
<td></td>
<td>Insulated, female, 14-16 AWG, .187&quot; tab</td>
<td>Jameco 489694</td>
<td>$0.22</td>
<td></td>
<td>Crimped to motor wire</td>
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<tr>
<td>21</td>
<td>Red Banana Plug</td>
<td>1</td>
<td></td>
<td>Solderless, set screw secures lead</td>
<td>EPO (local)</td>
<td>$1.00</td>
<td></td>
<td>As Purchased</td>
</tr>
<tr>
<td>22</td>
<td>Black Banana Plug</td>
<td>1</td>
<td></td>
<td>Solderless, set screw secures lead</td>
<td>EPO (local)</td>
<td>$1.00</td>
<td></td>
<td>As Purchased</td>
</tr>
<tr>
<td>23</td>
<td>Banana Jack Set</td>
<td>1</td>
<td></td>
<td>1 Red, 1 Black</td>
<td>Jameco 71239</td>
<td>$0.85</td>
<td></td>
<td>As Purchased</td>
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<tr>
<td>24</td>
<td>Magnet</td>
<td>1</td>
<td></td>
<td>1/8&quot; diameter by 1/8&quot; long, nickel plated</td>
<td>Dexter Magnetic Technologies PN335HC0125B</td>
<td>$2.00</td>
<td></td>
<td>As Purchased</td>
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<tr>
<td>25</td>
<td>Hall Effect</td>
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<td></td>
<td>Allegro A1322EUA, 3 Pin SIP</td>
<td>Newark InOne 88H0374</td>
<td>$1.35</td>
<td></td>
<td>As Purchased</td>
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<tr>
<td>26</td>
<td>Hall Mount</td>
<td>1</td>
<td>Epoxy glass perf board</td>
<td>4.5&quot; x 6.5&quot;, .1&quot; spacing</td>
<td>Digikey V1042-ND</td>
<td>$0.50</td>
<td></td>
<td>Scored, snapped, holes drilled</td>
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<tr>
<td>27</td>
<td>SIP Header</td>
<td>1</td>
<td></td>
<td>3 leads, wirewrap pins</td>
<td>Jameco 104053</td>
<td>$0.20</td>
<td></td>
<td>Glued to hall mount</td>
</tr>
</tbody>
</table>

*Parts are specific to motor selection

Total $31.36
Appendix B

Interpolated datasheet for Pittman 9434 15.1V winding

<table>
<thead>
<tr>
<th>Rated VDC</th>
<th>Kt(oz.in/A)</th>
<th>Kv(V/krpm)</th>
<th>Ra(Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provided in Pittman Bulletin LCM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.58</td>
<td>1.91</td>
<td>0.83</td>
</tr>
<tr>
<td>19.1</td>
<td>4.07</td>
<td>3.01</td>
<td>1.89</td>
</tr>
<tr>
<td>24</td>
<td>5.17</td>
<td>3.82</td>
<td>2.96</td>
</tr>
<tr>
<td>30.3</td>
<td>6.5</td>
<td>4.81</td>
<td>4.62</td>
</tr>
<tr>
<td>Interpolated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.1</td>
<td>3.24</td>
<td>2.39</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Table B.1. Motor properties provided by manufacturer and interpolated for unlisted rating

![Pittman 9434 Motor Properties](image)

Figure B.1. Data curve fits to determine unknown motor properties.
Appendix C

Laboratory Handouts and Solutions

C.1. Lab #4 – Actuator Characteristics handout

Additional documentation available on course website and provided in lab:
Haptic Paddle Kit Information
Pittman Bulletin LCM
Pittman 9434 15.1V Specs

THE HAPTIC PADDLE

The Haptic Paddle is a low cost, single degree-of-freedom force feedback joystick capable of providing a peak force of about 10N at its handle. It is an ideal tool for the demonstration of electromechanical system properties and concepts covered in undergraduate engineering courses. Over the course of the remaining lab exercises, you will investigate components of the system so that you can better understand your interaction with the complete system in the final exercise. A short demonstration video at the beginning of the lab procedure will provide further introduction to the system.

THE HAPTIC PADDLE ACTUATOR

In this lab exercise, you will characterize parameters of the Haptic Paddle actuator. Specifically, you will characterize the actuator’s viscous damping in Part I and torque constant in Part II. Part I of this exercise provides an example of a homogeneous first order electromechanical system. A Pittman LO-COG® 9434 15.1V DC motor provides actuation for the Haptic Paddle system.

BASICS OF A DC MOTOR

DC Motors are one of the most widely used actuators in industry. A DC motor is effectively a torque transducer that converts electric energy into mechanical energy. In electrical circuits, DC motors are often modeled as a voltage source and a resistance in series as shown in Figure 1. The electromechanical component of the motor that is modeled by this voltage source and resistance is known as the armature. Current that flows through the armature from the positive to negative lead will generate a torque on the motor rotor that acts in the positive direction of rotor spin, and vice versa for current that flows from the negative to positive lead. This torque is expressed as
\[ T = K_i i_{arm} \]  

where \( T \) is the motor torque (Nm), \( K_i \) is the torque constant of the motor (Nm/A), and \( i_{arm} \) is the armature current (amperes). \( K_i \) is sometimes listed as \( K_e \) in motor data sheets. The modeled voltage source is commonly called a back Electro Motive Force (EMF) and will have the same sign as the velocity of the rotor. This back EMF is expressed as

\[ V_{emf} = K_v \omega \]  

where \( V_{emf} \) denotes the back EMF (volts), \( K_v \) is the speed constant or voltage constant (V*sec/rad) and \( \omega \) is the rotor velocity (rad/sec) of the motor. \( K_v \) is sometimes listed as \( K_e \) in motor data sheets.

Equations (1) and (2) form the basis of DC motor operation.

**Viscous Damping and Dynamic Braking**

The viscous damping of the motor is due to lubricants in its ball bearings. The equations presented subsequently make the assumption that this damping is the dominant resistance compared to other disturbances, e.g. coulombic friction. To ensure this assumption is valid, we will enhance the viscous damping by applying a dynamic brake. Dynamic braking is applied by connecting a spinning DC motor to a load resistor \( R_l \) so that the load resistor will dissipate the kinetic energy stored in the rotor and the load inertias. Figure 1 shows the dynamic braking circuit used for this exercise.

![Figure 1. Dynamic Braking Circuit](image-url)
The switch shown in the top of Figure 1 toggles between the spin-up (position 1) and spin-down (position 2) states for the motor. The DC motor is modeled as a voltage source and a resistance, \( V_{enf} \) and \( R_a \) respectively, in series. \( R_a \) is sometimes listed as \( R_l \) in motor data sheets. \( V_c \) is the control voltage sent to the motor by the amplifier. Measuring devices are used to measure the armature voltage and current, \( V_{arm} \) and \( i_{arm} \) respectively. The armature current is measured only when the switch is in the spin-up position. When the switch is in the spin-down position, the back EMF of the spinning rotor produces a current of

\[
i_{arm} = \frac{V_{enf}}{R_l + R_a} = \frac{K_v \omega}{R_l + R_a}
\]

(3)

The current in turn causes a braking torque of

\[
T = K_i i_{arm} = \left( \frac{K_i K_v}{R_l + R_a} \right) \omega = B_{DB} \omega
\]

(4)

Equation (4) shows that the braking torque is proportional to the motor velocity, which is a property of viscous damping. Also, it can be seen from (4) that the damping effect can be easily adjusted by changing the load resistor.

**TRANSMISSION OF MOTOR POWER TO END EFFECTOR**

Robotic machines, such as haptic devices, often use transmissions to transmit power from their actuators to their end effectors. An end effector is a part of the robot that interacts with its surrounding environment or a user. The Haptic Paddle employs a Capstan cable drive to transmit the power of its actuator to affect a force at the Paddle handle where the user grasps. The cable drive effectively acts as a gear transmission to impart a torque on the Paddle component about its pivot point. This torque is then levered about the pivot point to produce the output force at the handle.

**EXPERIMENTAL SYSTEM AND EQUIPMENT**

- The Haptic Paddle Actuator with attachments including a dynamic brake and load mass for part I and the Haptic Paddle transmission and mass attachments for part II
- Components of the Haptic Paddle system including the Power Amplifier (Amp)
- Various tools for assembly of Haptic Paddle
- PXI industrial computer with 6070E data acquisition (DAQ) card and connector block
- Fluke DMM
- Calipers or rulers
- C-clamp

Figure 2 on the next page gives an overview of the experimental set-up for Part I. The experimental setup for Part II is the same with the exception of the actuator and its
attachments. Figure 3 gives an overview of the actuator setup for Part II. Note that the Capstan Spool, Paddle pivot point, and the hole in the Paddle handle are all inline.

Figure 2. Experimental Set-up for Part I

Figure 3. Experimental Set-up for Part II
PRE-LAB ASSIGNMENT

Part I

1. Consider the dynamic braking circuit. For the switch in the spin-down position, draw the free body diagram of the motor rotor and derive the equation of motion for the system considering the following variables and parameters (coulombic friction is ignored):
   - \( J_{\text{spin}} \), the sum of the inertia of the cylindrical mass and the inertia of the motor rotor (provided in the motor spec sheet)
   - \( B_{\text{spin}} \), the sum of the damping due to dynamic braking, \( B_{\text{DB}} \), and the damping due to lubricants in the bearings, \( B_{\text{m}} \)
   - \( \omega \), the angular velocity of the motor

2. Solve the equation of motion to determine an expression for \( \omega(t) \) in terms of \( J_{\text{spin}} \) and \( B_{\text{spin}} \), assume \( t_0 = 0 \).

3. What is \( \tau \), the time constant, in terms of \( J_{\text{spin}} \) and \( B_{\text{spin}} \)? When \( t = \tau \), what is the numerical value of the ratio \( \omega(t)/\omega(0) \)?

4. For the switch in the spin-down position, derive the equation for \( V_{\text{emf}} \) in terms of \( V_{\text{arm}}, R_{\text{a}}, \text{and } R_{\text{f}} \).

Part II

5. Draw the free body diagram of the Capstan Spool-Paddle coupling considering only moments about the pivot point and the following variables and parameters (variables and parameters not included are considered negligible):
   - \( F_w \), the weight of the mass attached at the Paddle handle
   - \( T_m \), the motor torque generated
   - \( r_{cs} \), the radius of the Capstan Spool
   - \( r_{sp} \), the radius of the Paddle sector pulley (center of pulley is Paddle pivot point)
   - \( l_s \), the distance from the Paddle pivot point to the center of hole in the handle

6. What is the relationship \( N \) describing the effective gear ratio of the transmitted motor torque via the cable drive? Assume no slipping of the cable.

7. Under static conditions where the Capstan Spool, Paddle pivot point, and handle are all inline, derive the equation for \( T_m \) in terms of the other parameters and variables listed.

LABORATORY PROCEDURE

Affix your pre-lab assignment into your notebook and then have it initialed by the TA.
It is suggested that you read the Results to Report section before carrying out the lab procedure.
Watch the video “Mech 343 Haptic Paddle Demo” in the folder “Mech 343 Labs” from the Desktop.

Part I: Characterizing the viscous damping
a) Assemble your Haptic Paddle as detailed for this part of the exercise in the Haptic Paddle Kit handout and then C-clamp it to the table.

b) Take appropriate measurements of the provided mass for determining its rotational inertia. For the purposes of this exercise, assume that the Capstan Spool, jam nut and mass are a single homogeneous disk. The mass of the Capstan Spool and jam nut together is 18 gm.

c) The black dots on Figure 1 represent banana jacks. Use the wire with two banana plugs to connect the brake to the Fluke DMM at the appropriately labeled banana jack on the brake and the “10A” jack on the DMM. Connect the red wire labeled “Motor Power” from the Power Supply and Amplifier (hereafter Amp) to the appropriately labeled banana jack on the brake. Connect the black wire labeled “Motor Power” from the Amp to the “Com” jack on the DMM. Use the red and black motor wires to connect the motor to the dynamic brake at the appropriately labeled banana jacks.

d) The channels named in this and following steps refer to the terminal positions on the DAQ connector block. Connect the wire from the Amp with the flag “AO” to channel 22 on the connector block, and the wire with the flag “GND” to channel 55. These connections provide for the DAQ to send a control signal to the Amp. Use an alligator clip and jumper wire to connect the red motor banana plug to channel 68. The hole on the side of the banana plug provides a good place to bite with the alligator clip. Be sure that the alligator clip has a good connection to the jumper wire. This connection provides for the DAQ to read $V_{arm}$ (the black motor lead is common to ground which you have already connected to channel 55).

e) To control the system, you will use a LabVIEW virtual instrument (VI). Open “Actuator Characteristics Lab” in the folder “Mech 343 Labs\Haptic Paddle Labs” from the Desktop. This VI enables you to control $V_c$ as well as reading and recording $V_{arm}$. Be aware that the input “$V_c$” to the VI is not an actual measurement of $V_c$.

f) Before you turn on any power button, make sure the switch on the dynamic brake is flipped to the spin-down position. Have the TA check your set-up before proceeding. Then, turn on the Amp.

g) Run the VI by clicking the white arrow in the upper left corner of the screen. Make sure that “$V_c$” is set to zero and press “Motor Power” (it should turn green).

h) Flip the switch on the dynamic brake to the spin-up position and set “$V_c$” to 9.5 volts. Once the motor speed has stabilized, flip the switch on the brake to the spin-down position to engage the brake and observe the response.

i) Set “$V_c$” back to zero.

j) Now you will record the first-order decay you just observed. Enter your team name in the “Team Name” field. Flip the switch on the brake to the spin-up position. Again, set “$V_c$” 9.5 volts. Once the motor speed has stabilized, hit “Record Data” (it should turn green). Soon thereafter, flip the switch on the brake to the spin-down position. After the motor has stopped spinning, hit “Write Data to File” to store the data. Hit “Record Data” again to stop the recording.

k) Set “$V_c$” back to zero and turn off the power to the Amp.

l) Your data file has been saved in the Mech 343 Labs folder. Check it to ensure your data is good (shows exponential decay). Save your file to your USB flash drive and remove the file from the computer. It is your responsibility to get a copy of the file from your lab mates if you do not have your own flash drive. Notify the TA if no one
in your group has a flash drive. Important: The Motor Test VI records \( V_{arm} \) and time – it should be apparent which is which.

Part II: Characterizing the Torque Constant

a) Disconnect the motor from the circuit. Remove the C-clamp and then remove the mass. You will need to connect the motor leads to each other in order to remove the mass.

b) Assemble your Haptic Paddle as detailed for this part of the exercise in the Haptic Paddle Kit handout and then C-clamp it to the table. Reconnect the motor to the circuit. The dynamic brake is not used for this part of the exercise; it simply provides a means of connecting the motor to the circuit.

c) Measure and record \( r_{sp} \) and \( l_x \). \( r_{co} \) is difficult to measure because of the threads on the Capstan Spool – it’s value is 4.3 mm.

d) Use a minimum of 250 gm to apply a known torque to the Paddle by attaching the provided weights (mass of weight is stamped on it) to the hole in the Paddle handle. The mass of the hex bolt with the washer and spacer is 22 gm. The mass of the thread and spacer is 12 gm.

e) Turn the Fluke DMM to the ammeter setting. Be sure that it is reading DC current. Press the yellow (Fluke 175 model) or blue (Fluke 83III model) button if the display shows AC. If the DMM turns off during the exercise, press this button to turn it back on.

f) Turn on power to the Amp. Flip the switch on the brake to the spin-up position. Determine the minimum amount of current required to balance the weight by adjusting "Vc" in the VI (current through the motor is directly proportional to Vc in static conditions). **START WITH A SMALL VOLTAGE V \( \approx 0.5 \) V.** Record the current reading on the DMM once you balance the Paddle in a horizontal position. Set “Vc” to zero after you record the current.

g) Collect 4 more data points of weight applied versus the current required to balance it. Remember to use a minimum of 250 gm and to set “Vc” to zero after each recording.

h) Use a scatter plot in Excel to ensure your data is linear.

i) Turn off the power to the Amp and disassemble the circuit. Use masking tape to label your Haptic Paddle with your team’s name and put it away in the proper drawer.

**RESULTS TO REPORT**

- Provide a plot of your spin-down test with time on the x-axis and rotor velocity (rad/sec) on the y-axis. Be judicious in your choice of \( \omega(0) \) so that it is a good representation of the initial velocity. After you select your initial data point, time shift your data so that \( t_0 = 0 \). There are a significant number of data points for this plot, thus it is only necessary to show a sample calculation as to how you achieved your plotted values.

- Use the ratio \( \omega(t) / \omega(0) \), calculated as a part of the pre-lab assignment, and your plot of \( \omega \) vs. \( t \) to mark the point \( t = \tau \) on the plot and give a numerical value of \( \tau \).

- Determine a numerical value of \( B_{spin} \). Include units. Also determine a numerical value of \( B_m \), the damping constant of the motor.
• In Matlab, generate an array of points $\alpha(t)$, where $t$ varies from 0 to $3\pi$, incremented at 0.03 seconds. Use the numerical values you determined for $B_{spin}$ and $J_{spin}$ to generate this array. Provide a second plot with your new $\alpha(t)$ over your original data. It is not necessary to include your array of points; a sample calculation for a single point is sufficient.
• Provide a plot showing motor torque (Nm) vs. current for the data you collected. Determine $K_f$ from the plot.
• Convert $K_v$ provided in the datasheet to have the same units as $K_f$. In your discussion, justify the relationship you observe between $K_v$ and $K_f$. Hint: consider power.

**ADDITIONAL ITEMS TO ADDRESS IN THE DISCUSSION SECTION**

• Explain why you were directed to connect the motor leads together to assist in attaching the mass.
• In what ways are the first-order dynamic system and its time response observed in this exercise analogous/dissimilar to the first-order dynamic system and its time response of the RC circuit observed in Lab #2?
• In what ways is the time constant observed in this exercise analogous/dissimilar to the time constant of the RC circuit observed in Lab #2?
• Motors commonly have a 10% tolerance for their voltage and torque constants. Compare your derived value for $K_f$ to the motor datasheets.

**BONUS DISCUSSION**

• Explain the sudden drop in $V_{arm}$ when you flipped the switch on the dynamic brake.
• With the switch in the spin-up position, how could you experimentally characterize the voltage constant? Present the equations necessary to do this, as well as the outputs that need to be recorded.

**REFERENCES**

C.2. Lab #4 – Actuator Characteristics solutions

Total: ___/ 40

___ Meets Honest Effort Attempt Completes all sections. Makes valid attempt at addressing prompted results and discussion items.

Table of Contents is up-to-date: ___/1 TOC is to have Lab Title, Abstract, Results, Discussion, and Conclusion

___(-1 per) Fails to follow general guidelines: missing title page for lab, abstract not on its own page, use of pencil, loose or folded paper, use of staples or other bulky means of affixing loose paper, sloppily affixed paper, uses both sides of notebook, messy work, sections out of order, other sloppy work

Specify which guidelines are not followed

Abstract: ___/2.5
(5) Identifies experimental system
Haptic Paddle Actuator and attachments including a dynamic brake and spinning mass for Part I and Haptic Paddle transmission and mass attachments for Part II
(5) Conveys experiment's purpose
To characterize the motor's damping and torque constant.
(5) Summarizes equipment, setup, and procedure
A LabVIEW VI, DAQ card, and Power Amplifier were used to send power to the experimental system. The same VI, DAQ card, and a Fluke DMM were used to record outputs of the system. In Part I, A spin-down test was performed to characterize the motor’s damping. In Part II, known torques were applied to the system and balanced to characterize the motor’s torque constant.
(5) Includes important results
Observed first order decay in spin-down test and determined time constant, which provided for characterization of motor damping.
Observed torque-current relationship, which provided for characterization of torque constant.
(5) Includes important conclusions
The important conclusions stated here should be consistent with those presented in the conclusion section.
Pre Lab Assignment
Part I: ___ / 6
(1) Draws correct FBD

(1) Generates EOM
\[ \sum T = I \alpha \]
\[ J_{\text{spin}} \dot{\omega} = -B_{\text{spin}} \omega \]
\[ J_{\text{spin}} \dot{\omega} + B_{\text{spin}} \omega = 0 \]

(1) Derives expression for \( \omega(t) \)
The general solution presented in class provides:
\[ \omega(t) = \omega(0) e^{-t B_{\text{spin}} / J_{\text{spin}}} \]

(1) Derives \( \tau \) as a function of \( J_{\text{spin}} \) and \( B_{\text{spin}} \)
The characteristic equation present in class is
\[ \dot{\omega} + \frac{1}{\tau} \omega = 0 \]

\[ \Rightarrow \tau = \frac{J_{\text{spin}}}{B_{\text{spin}}} \]

(1) Determines the value of the ratio \( \omega(\tau) / \omega(0) \)
\[ \frac{\omega(\tau)}{\omega(0)} = e^{-\tau/\tau} = e^{-1} \]

(1) Derive the equation for \( V_{\text{enf}} \) in terms of \( V_{\text{arm}} \)
From Kirchhoff’s loop law:
\[ V_{\text{enf}} - V_{\text{arm}} - i_{\text{arm}} R_a = 0 \]
\[ V_{\text{enf}} - i_{\text{arm}} (R_a + R_l) = 0 \]

\[ \Rightarrow V_{\text{enf}} = \frac{V_{\text{arm}} (R_a + R_l)}{R_l} \]
Part II: ___/3

(1) Draws correct FBD with parameters labeled

(1) Determines $N$

*Gear ratio is the ratio of the radii, thus $N = r_p / r_{cs}$*

(1) Derives the equation for $T_m$

*For static conditions, the moments about the pivot point equal zero*

\[ \sum T = 0 \]

\[ T_m N = F_w l_x \]

\[ T_m = \frac{F_w l_x r_{cs}}{r_p} \]

(+) Points recovered for corrected Pre-Lab Assignment

*Students can receive up to half credit of missed points for correcting any incorrect answers in their Pre-Lab Assignment.*

System, equipment, setup, and procedure: ___/3

(.5) Lists Experimental System and Equipment

*System: The Haptic Paddle Actuator with attachments including a dynamic brake and load mass for part I and the Haptic Paddle transmission and mass attachments for part II*

*Equipment:*

- Components of the Haptic Paddle system including the Power Amplifier (Amp)
- Various tools for assembly of Haptic Paddle
- PXI industrial computer with 6070E data acquisition (DAQ) card and connector block
- Fluke DMM
- Calipers or rulers
- C-clamp
Experimental setup
(1) Correctly describes setup
*A LabVIEW VI running on the PXI computer communicates with the 6070E DAQ card. The DAQ sends a control voltage to the amp which sends a voltage to the experimental system. The DAQ is also used to read the armature voltage. A Fluke DMM is used to read armature current.*
(1) Schematic correctly depicts setup

(.5) Procedure

Results
Give only partial credit if student does not cleanly present calculations:
Student displays equation symbolically, then enters in numerical values with units, and final value has units and is either underlined or boxed.
Give only partial credit if student does not properly present plots:
Charts are properly labeled and well done (including calculations if applicable)
Part I: ___/6
(1) Produces plot of $\omega$ vs $t$

![Motor Speed vs Time Plot](image)
Sample calculation is to accompany plot:

\[ \omega = \frac{V_{\text{emf}}}{K_r} = \frac{V_{\text{arm}}(R_a + R_l)}{K_rR_l} \]
\[ \omega = \frac{7.134V(1.22\Omega + 5\Omega)}{0.0228V/\text{rad/s} \times 5\Omega} = 389 \text{ rad/s} \]

(1) Determines \( \tau \) from plot

On the plot, student marks the velocity and time at which \( \omega(t) = \omega(0)e^t \). 2.5 seconds is a typical time constant.

(1) Correctly calculates \( J_{\text{spin}} \) for determining \( B_{\text{spin}} \)

\[ J_{\text{spin}} = J_{\text{mass}} + J_{\text{rotor}} \]
\[ J_{\text{spin}} = \frac{1}{2} mr^2 + J_{\text{rotor}} \]
\[ J_{\text{spin}} = \frac{1}{2} \cdot 35 \text{ kg} \cdot (0.35 \text{ m})^2 + 4.16 \times 10^{-6} \text{ kg} \cdot \text{m}^2 \]
\[ J_{\text{spin}} = 2.19 \times 10^{-4} \text{ kg} \cdot \text{m}^2 \]

(1) Determines value for \( B_{\text{spin}} \)

\[ B_{\text{spin}} = \frac{J_{\text{spin}}}{\tau} \]
\[ B_{\text{spin}} = \frac{2.19 \times 10^{-4} \text{ kg} \cdot \text{m}^2}{2.5 \text{ s}} \]
\[ B_{\text{spin}} = 8.76 \times 10^{-5} \text{ Nm/s} \]

Units may also be expressed as kg\( \cdot \)m\(^2\)/s.

(1) Determines value for \( B_m \)

\[ B_m = B_{\text{spin}} - B_{\text{DB}} \]
\[ B_m = B_{\text{spin}} - \frac{K_rK_v}{R_a + R_l} \]
\[ B_m = 8.76 \times 10^{-5} \text{ Nm/s} - \frac{0.228 \text{ Nm/A} \cdot 0.228 \text{ V/s/rad}}{1.22\Omega + 5\Omega} \]
\[ B_m = 4.02 \times 10^{-6} \text{ Nm/s} \]
(1) Produces theoretical plot of $\omega$ vs $t$

![Theoretical Expectations and Experimental Results](image)

Sample calculation is to accompany plot:

$$\omega(t) = \omega(0)e^{-t\frac{B_{\text{spin}}}{J_{\text{spin}}}}$$

$$\omega(t) = 389 \frac{rad}{sec} \cdot e^{-0.16 \sec \cdot 8.76 \times 10^{-5} \text{Nm/s}/2.19 \times 10^{-4} \text{kg/m}^2}$$

$$\omega(t) = 365 \frac{rad}{sec}$$

Part II: __/3
(1) Produces plot of $T_m$ (in Nm) vs $i_{\text{arm}}$

![Applied Torque vs. Current](image)

$$y = 0.0208x + 0.0056$$

$$R^2 = 0.9959$$
Tabulated data is to accompany plot:

<table>
<thead>
<tr>
<th>Measured parameters</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>l_x (m)</td>
<td>r_cs (m)</td>
<td>r_sp (m)</td>
<td>g (m/s²)</td>
<td></td>
</tr>
<tr>
<td>0.0635</td>
<td>0.0043</td>
<td>0.0762</td>
<td>9.81</td>
<td></td>
</tr>
<tr>
<td>Applied Current (A)</td>
<td>Applied Mass (kg)</td>
<td>Calculated Applied Torque (Nm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.732</td>
<td>0.584</td>
<td>0.0205</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.313</td>
<td>0.36</td>
<td>0.0127</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.544</td>
<td>0.469</td>
<td>0.0165</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.915</td>
<td>0.699</td>
<td>0.0246</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.132</td>
<td>0.84</td>
<td>0.0295</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sample Calculation is to accompany tabulated data:

\[
T_m = \frac{F_w l_x r_{cs}}{r_{sp}} \cdot \frac{0.584\text{kg} \cdot 9.81\text{m/s}^2 \cdot 0.0635\text{m} \cdot 0.0043\text{m}}{0.0762\text{m}} = 0.0205\text{Nm}
\]

(1) Determines \(K_t\) from plot

\(K_t\) is the slope of the line. \(K_t = 0.0228\text{Nm/A} \pm 10\%\).

(1) Converts given \(K_v\) to same units as \(K_t\)

\[
K_v = \frac{2.39V}{krpm} \cdot \frac{1\text{krrevs}}{1000\text{revs}} \cdot \frac{1\text{rev}}{2\pi \text{rads}} \cdot \frac{60\text{s}}{1\text{min}} \cdot \frac{J}{V \cdot A \cdot s} \cdot \frac{141.6\text{oz} \cdot \text{in}}{1\text{J}}
\]

\[
K_v = 3.23 \frac{\text{oz} \cdot \text{in}}{A}
\]

Discussion

Part I: \(\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\) /10

(1) Provides first order EOM

\[
J_{spin}\ddot{\omega} + B_{spin}\dot{\omega} = 0
\]

(1) Provides time response equation

\[
\omega(t) = \omega(0)e^{-t\frac{B_{spin}}{J_{spin}}}
\]

OR

\[
\omega(t) = \omega(0)e^{-t/\tau} \text{ where } \tau = J_{spin}/B_{spin}
\]

(1) Discusses utility of time constant

The time constant can be observed from the time response and then used with known system parameters to determine unknown system parameters.

(1) Explains differences between theoretical and experimental plots
The imbalance of the spinning mass and electric signal noise contribute to the roughness of the curve. Coulombic friction brings the system to a stop much sooner than theoretical expectations (which actually approaches but never reaches zero).

(1) Explains procedure direction to connect the motor leads
With the motor leads connected, the electronic circuit is a loop with $V_{emf}$ and $R_a$ in series. A positive spin of the rotor produces a current that flows from the negative to positive motor lead. This current produces a torque that acts in the negative direction of rotor spin.

(1) Recognizes dissimilarity of dynamic systems
The motor spin-down is an inertia-damper system while the RC circuit is a spring-damper system.
(1) Recognizes dissimilarity of time responses
The state variable of the spin-down is velocity while the state variable of the RC circuit is charge (position).

(1) Recognizes similarity of time responses
Both display $e^{-rt}$ exponential decay
(1) Recognizes dissimilarity of time constant
The time constant of spin-down is inertia/damping. The time constant of the RC circuit is damping/spring.

Part II: __/4
(1) Provides equation expressing torque as a function of current
$T = K_t i_{arm}$

(1) Discusses how torque constant was characterized
Data was taken to produce a torque vs. current curve. The slope of the curve provides $K_t$.

(1) Compares $K_t$ to that provided in the spec sheet
Recognizes that $K_t$ is within tolerance of value listed in data sheet. If the student has an erroneous value for $K_t$ due to incorrect calculations, the student should recognize the errors and correct them.

(1) Justifies $K_t - K_v$ relationship
The relationship is $K_t = K_v$. Consider power input to and output from the motor:

$P_{in} = i_{arm} V_{emf}$

$P_{out} = T_m \omega$

$P_{in} = P_{out}$

$i_{arm} V_{emf} = T_m \omega$

$\frac{T_m}{K_t} K_v \omega = T_m \omega$

$\Rightarrow K_t = K_v$
Bonus Discussion: +

(+2) Explains sudden drop in $V_{arm}$
For the switch in the spin-up position, current flows from the positive to the negative motor lead. From Kirchhoff's loop law:

$$V_{arm} - V_{emf} - i_{arm} R_a = 0$$

$$\Rightarrow V_{arm} = V_{emf} + i_{arm} R_a$$

For the switch in the spin-down position, current flows from the negative to the positive motor lead. From Kirchhoff's loop law:

$$V_{arm} - V_{emf} + i_{arm} R_a = 0$$

$$V_{emf} - i_{arm} (R_a + R_f) = 0$$

$$\Rightarrow V_{arm} = \frac{V_{emf} R_f}{R_a + R_f}$$

When the switch is flipped, the change in current is near instantaneous because there is no inertial load in the circuit. The rotor speed, and thereby $V_{emf}$, holds constant in this instant due to the inertia of the spinning mass. In the instant of the switch flip, $V_{arm}$ changes from a value greater than $V_{emf}$ to a value that is less than $V_{emf}$. Even in ideal conditions where $i_{arm}$ is equal to zero when the switch is in the spin-up position, $V_{arm}$ will change from a value equal to $V_{emf}$ to a value that is less than $V_{emf}$.

(+2) Details how to experimentally characterize voltage constant
With the switch in the spin-up condition, $K_v$ can be expressed by the following relationship

$$V_{arm} - V_{emf} - i_{arm} R_a = 0$$

$$V_{emf} = V_{arm} - i_{arm} R_a$$

$$K_v \omega = V_{arm} - i_{arm} R_a$$

$$K_v = \frac{V_{arm} - i_{arm} R_a}{\omega}$$

The student should get readings of $V_{arm}$, $i_{arm}$, and $\omega$ for different values of $V_c$. These readings can be used to calculate $K_v$ for the different values of $V_c$. The calculated values of $K_v$ should be averaged to arrive at a final value for $K_v$. The setup for this exercise provides for readings of $V_{arm}$ and $i_{arm}$. A tachometer is needed to measure $\omega$.

Conclusion: ___/1.5

(5) States a correct conclusion derived from Results and Discussion
(1) States bulk of important conclusions
The observed time constant of a time response is useful for characterizing unknown parameters of a first order system.
The torque constant of a motor can be characterized by the slope of its torque-current curve.
The relationship $K_i = K_v$ is fundamental due to power conservation.
C.3. Lab #5 – Sensor Calibration and System Inertia handout

Additional documentation available on course website and provided in lab:
Haptic Paddle Kit Information
Allegro A1322 Datasheet

FURTHER INVESTIGATION OF THE HAPTIC PADDLE SYSTEM

In Part I of this lab exercise, you will characterize the rotational inertia of the Paddle component by the use of a bifilar pendulum. In Part II of this lab exercise, you will learn how to calibrate the system’s position sensor. An Allegro A1322 ratiometric linear Hall-effect sensor, which outputs a voltage proportional to an applied magnetic field, and a permanent magnet are used to determine the Paddle’s angular position. You will notice during the exercise that the magnet has a cylindrical shape. Its poles go from North to South along the cylindrical axis.

A BIFILAR PENDULUM

A bifilar pendulum consists of a mass that is suspended by two vertical strings as seen in Figure 1. The strings have equal length \( h \) and are attached to the hanging mass at a distance \( D/2 \) from the center of mass. The parameter \( r_{cm} \) is the distance from the center of mass to the pivot point of the Paddle component. For sufficiently small angular deflections about the axis through the center of mass, the system can be modeled as the second order system:

\[
J_{cm} \ddot{\theta} + K_{BP} \dot{\theta} = 0
\]

where \( J_{cm} \) is the inertia about the center of mass and \( K_{BP} \) is the equivalent spring constant due to the force of gravity and system parameters. The damping of the system is negligible and therefore ignored. By observing the natural frequency of the system, it is possible to determine \( J_{cm} \) for the suspended mass.
Figure 1. A bifilar pendulum with the Paddle component as the hanging mass.

**WORKSPACE AND SENSOR CALIBRATION**

A robot's workspace is the space in which it is capable of moving its end effector. In order to move properly, the robot must know where it is within its workspace. Devices called sensors send signals to the robot's control system that provide information relating to the robot's position. As stated earlier, a Hall-effect sensor and magnet are used to sense the Haptic Paddle's position. If you wish to learn more about the Hall-effect, information is readily available on the internet. The sensor outputs a constant voltage in the range of 0-5 volts which varies linearly with the strength of the magnetic field applied perpendicularly to the sensor by the magnet. In order to take full advantage of the analog to digital resolution of the DAQ, the sensor output is input to a signal conditioning circuit (SCC) that uses a series of op-amp stages to linearly amplify the 0-5 volt signal to a ±10 volt signal. The linear relationship between the amplified signal and the strength of the perpendicularly applied magnetic field must be determined in order for the Haptic Paddle control software to properly know the angular position of the Paddle component.
EXPERIMENTAL SYSTEMS AND EQUIPMENT

- Bifilar Pendulum with Paddle component as hanging mass
- Haptic Paddle Sensor with magnet and signal conditioning circuit (SCC)
- Ruler
- Stopwatch
- PXI industrial computer with data acquisition (DAQ) card and connector block

PRE LAB ASSIGNMENT

1. Derive an expression for the equivalent spring constant $K_{BP}$ in terms of the parameters $m_p$ (the mass of the Paddle component), $g$, $D$, and $h$. Assume that the vertical motion of the Paddle component is negligible. Hint: when you rotate the Paddle about the axis through its center of mass, you can draw a pair of right triangles relating the current positions of the string and the length $D/2$ to their respective equilibrium positions. Note that these two triangles have a common leg.

Result: $K_{BP} = m_p g D^2 / 4h$

2. Use the previous result to derive an expression for $J_{cm}$ in terms of the same parameters and the natural frequency $\omega$.

3. Use the previous result to derive an expression for the moment of inertia $J_p$ about the axis through the Paddle’s pivot point.

LAB PROCEDURES

Part I: Characterizing the Rotational Inertia of the Paddle Component

a) Place a piece of masking tape on the Paddle (a spare Paddle is provided so that you do not have to disassemble your Haptic Paddle) such that it goes from the handle, over the pivot point, and to the bottom of the sector pulley.

b) Balance the Paddle on the bar of the bifilar pendulum to determine the approximate center of mass. Then mark two points, each an equal distance $(D/2)$, from the center of mass, at which you will hang the Paddle. Record the distance $D$. Record the distance $r_{cm}$ from the center of mass to the pivot point. The mass of the Paddle is 57.2 grams.

c) Tape the yarn to the Paddle at the marked points and use binder clips to adjust the length and position of the strings. The strings should be equal in length and hanging vertically. The Paddle should be flat in the horizontal plane. Measure the length $h$ of the strings from the binder clips to the top of the Paddle.

d) Deflect the Paddle to an initial angular displacement about its center of mass (less than $30^\circ$ so that the small angle approximation holds) and let it go to allow it to swing freely. Record the time it takes to make 20 oscillations. Repeat this twice more.

e) Remove your Paddle from the string and discard the used tape.
Part II: Position Sensor Calibration

a) Assemble the Haptic Paddle as detailed in the Haptic Paddle document for the Hall Effect Calibration lab.

b) From the signal conditioning circuit (SCC), connect the 3-wire SIP terminal to the sensor pins on the Haptic Paddle. **Ensure that the “Up” label on the connector is Up.**

c) The channels named in this step refer to the terminal positions on the DAQ connector block. From the SCC, connect the wire with the flag “Pos” to channel 68 on the connector block, the wire with the flag “GND” to channel 67, and the wire with the flag “5V” to channel 8. These connections provide for the DAQ to read the amplified sensor output and to provide a 5V signal to the SCC. Have the TA come and check your setup. Turn on the power to the SCC.

d) Open the “Hall Effect Calibration Lab” from the “Mech 343 Labs\Haptic Paddle Labs” folder on the Desktop. Run the VI by hitting the white arrow in the upper left corner.

e) The VI has a readout for the voltage output from the SCC. Put the paddle in the zero position and adjust the magnet cap so that the reading is within a half volt of zero. Then run the Paddle to the extents of the workspace to ensure that the DAQ does not saturate (output of conditioned signal is less than 10V).

f) Record 10 data points of the voltage readout versus the Paddle position in degrees. A few of the Paddle positions have been marked along the sector pulley.

g) Use Microsoft Excel to do a linear approximation of your data by plotting Paddle position vs. signaled voltage (chart data with scatter plot and add trend line, check option to show equation).

h) Enter the values you determined for A (slope) and B (y-intercept) into the VI. Compare positions of your Paddle to the Position readout in the VI to confirm the calibration of the sensor.

i) Hit the stop button to stop the VI. Turn off the power to the SCC. Save your calibration file to the folder named “Calibration files.”

j) Please detach the wires from the Hall mount and the DAQ connector block and store your Haptic Paddle.

**RESULTS TO REPORT**

- Provide the average value of $J_{cm}$ determined by the use of the bifilar pendulum. Use this result to determine $J_p$.
- Provide a plot of Paddle position vs. signal voltage for the sensor calibration. Include the linearized relationship you determined.
- Design a two stage op amp circuit that has the raw Hall-effect voltage and the DAQ 5V supply as inputs. The desired output of the circuit is a linear amplification of the raw Hall-effect voltage that is in the range of ±10V. Recall the op amp circuits from Lab #3 for your design. A bonus point will be awarded if you can design a circuit that performs the desired amplification in a single stage.
ADDITIONAL ITEMS TO ADDRESS IN THE DISCUSSION SECTION

- Why is it necessary that the initial displacement of the hanging mass of a bifilar pendulum not be too large?
- The background information for this exercise explains that the amplified Hall-effect signal varies linearly with the strength of the perpendicularly applied magnetic field. However, you observed that the amplified signal varies linearly with the Paddle angular position. Explain how the perpendicular component of the applied magnetic field is linear with the Paddle angular position. Use figures to assist your explanation. Your figures should include the magnet and its flux lines, the sensor, and show angle of displacement.

REFERENCES


C.4. Lab $5$ – Sensor Calibration and System Inertia solutions

Total: ___ / 24

___ Meets Honest Effort Attempt Completes all sections. Makes valid attempt at addressing prompted results and discussion items.

Table of Contents is up-to-date: ___ / 1 TOC is to have Lab Title, Abstract, Results, Discussion, and Conclusion

___ (-1 per) Fails to follow general guidelines: missing title page for lab, abstract not on its own page, use of pencil, loose or folded paper, use of staples or other bulky means of affixing loose paper, sloppily affixed paper, uses both sides of notebook, messy work, sections out of order, other sloppy work

Specify which guidelines are not followed

Abstract: ___ / 2.5

(.5) Identifies experimental system

In part I, bifilar pendulum with Paddle component as hanging mass. In part II, Hall-effect sensor, magnet, and SCC

(.5) Conveys experiment's purpose

In part I, determine rotational inertia of Paddle component. In part II, learn how to calibrate Hall-effect sensor

(.5) Summarizes equipment, setup, and procedure

In part I, student imparts an initial angular displacement of bifilar pendulum and records subsequent oscillations with a stopwatch. In part II, student positions magnet by positioning Paddle. Hall-effect output is input to a SCC whose output is read by a LabVIEW VI and DAQ.

(.5) Includes important results

Observed natural frequency of bifilar pendulum to determine $J_{cm}$ of the Paddle component. $J_p$ of the Paddle was subsequently determined using measured parameters.

Observed linear relationship of Paddle position to amplified Hall-effect signal and used it to calibrate the sensor.

(.5) Includes important conclusions

The important conclusions stated here should be consistent with those presented in the conclusion section.
Pre Lab Assignment: ___ / 4
(2) Correctly derives $K_{BP}$

Consider the Paddle deflected by an angle of $\theta$ from equilibrium shown by the blue line in above picture. The red lines represent the new position of the strings, which form an angle of $\phi$ with their equilibrium positions. The FBD is shown below where $F_t$ is the tension in the strings.

It is helpful to consider the following triangles where the middle triangle shows the component breakdown of the tension in the strings as the restoring force, $F_r$, and $m_pg/2$ as the balance of forces in the vertical direction.
Using Newton's second law:
\[ \Sigma T = J_{CM} \ddot{\theta} \]
\[ \Sigma T = -2F_r \frac{D}{2} \]
\[ \tan \phi = \frac{2F_r}{m_p g} \], by small angle approximation (SAA): \( \phi = \frac{2F_r}{m_p g} \)
\[ \sin \phi = \frac{y}{h} \], by SAA: \( \phi = \frac{y}{h} \)
\[ \sin \theta = \frac{2y}{D} \], by SAA: \( \theta = \frac{2y}{D} \)

Combining these produces:
\[ F_r = \frac{m_p g D^2}{4h} \theta \]
Thus the EOM is:
\[ J_{CM} \ddot{\theta} + \frac{m_p g D^2}{4h} \theta = 0 \text{, with } K_{BP} = \frac{m_p g D^2}{4h} \]

(1) Correctly derives \( J_{cm} \)
Consider the characteristic EOM:
\[ \ddot{\theta} + \omega^2 \theta = 0 \]
Thus:
\[ \omega^2 = \frac{K_{BP}}{J_{CM}} \]
\[ J_{CM} = \frac{m_p g D^2}{4h \omega^2} \]

(1) Correctly derives \( J_p \)
By the Parallel Axis THM:
\[ J_p = m_p r^2_{cm} + J_{CM} \]

(+) Points recovered for corrected Pre-Lab Assignment
Students can receive up to half credit of missed points for correcting any incorrect answers in their Pre-Lab Assignment.

System, equipment, setup, and procedure: ___/3

(.5) Lists Experimental System and Equipment
Systems:
Bifilar pendulum with Paddle component as hanging mass
Hall-effect sensor with magnet and signal conditioning circuit (SCC)
Equipment:
Ruler
Stopwatch
PXI industrial computer with data acquisition (DAQ) card and connector block
Experimental setup
(1) Correctly describes setup
In part I, a student imparted an initial condition on the bifilar pendulum. A second student observed the subsequent motion and used a stopwatch to take time measurements.
In part II, students positioned the magnet by positioning the Paddle. A LabVIEW VI running on the PXI computer communicated with the 6070E DAQ card to read the output of the signal conditioning circuit, which was used to linearly amplify the output of the Hall-effect sensor.
(1) Schematic correctly depicts setup

(5) Procedure

Results: __ / 5
Give only partial credit if student does not cleanly present calculations:
Student displays equation symbolically, then enters in numerical values with units, and final value has units and is either underlined or boxed.
Give only partial credit if student does not properly present plots:
Charts are properly labeled and well done (including calculations if applicable).
(1) Correctly calculates ω in determining J_{cm}
Averages 3 observed times to determine T_{avg}

\[ \omega = \frac{N_{oscillations} \times 2\pi \text{ rads/oscillation}}{T_{avg}} = \frac{20\text{ oscillations} \times 2\pi \text{ rads/oscillation}}{20.8\text{s}} \]

\[ \omega = 6.04 \text{ rad/s} \]
Student could alternatively calculate ω for each observed time and then average.
(1) Provides value of $J_{cm}$

$$J_{CM} = \frac{m_p g D^2}{4h\omega^2}$$

$$J_{CM} = \frac{0.0572 kg \times 9.81 m/s^2 \times (0.1 m)^2}{4 \times 0.256 m \times (6.04 rad/s)^2}$$

$$J_{CM} = 1.5 \times 10^{-4} \text{ kg} \times \text{m}^2$$

(1) Provides value of $J_p$

$$J_p = m_p r_{cm}^2 + J_{CM}$$

$$J_p = 0.0572 kg \times (0.023 m)^2 + 1.5 \times 10^{-4} \text{ kg} \times \text{m}^2$$

$$J_p = 1.8 \times 10^{-4} \text{ kg} \times \text{m}^2$$

(1) Provides plot of Paddle position vs. signal voltage

![Paddle Position vs. Voltage Signal](image)

<table>
<thead>
<tr>
<th>Voltage</th>
<th>-9.21</th>
<th>-6.51</th>
<th>-5.2</th>
<th>-2.71</th>
<th>-1.55</th>
<th>-0.4</th>
<th>2</th>
<th>3.2</th>
<th>5.98</th>
<th>7.59</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (deg)</td>
<td>-35</td>
<td>-25</td>
<td>-20</td>
<td>-10</td>
<td>-5</td>
<td>0</td>
<td>10</td>
<td>15</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>

(1) Provides linearized relationship of Paddle position vs. signal voltage

*This can be provided on plot as seen above.*
(1) Provides op amp amplification circuit
Student first inverts either Hall or 5V signal and then sums the two signals. Resistors should be selected so that the math is correct.

(+) Op amp circuit performs desired amplification in a single stage
This solution requires the student to do research and discover an op amp circuit not taught in lab:

Discussion: ___ / 6

(1) Provides EOM for bifilar pendulum
\[ J_{cm} \ddot{\theta} + K_{pp} \theta = 0 \]

(1) Discusses utility of system’s natural frequency
The natural frequency of the system can be observed from the system’s free motion response and then used with known system parameters to determine unknown system parameters.

(1) Discusses necessity of small initial displacement of hanging mass
A small initial displacement allows the use of the small angle approximation in deriving the equivalent spring constant of the system. Without this approximation, the EOM is nonlinear and determining \( J_{cm} \) from an observed \( \omega \) is not as straightforward.

(2) Explains how signal voltage has a linear relation to Paddle position
As explained in the handout, the amplified output of the Hall-effect sensor varies linearly with the strength of the magnetic field applied perpendicularly to the sensor. The rotation of the magnet about the pivot point has the result that its magnetic field applied perpendicularly to the Hall-effect sensor varies sinusoidally with Paddle position. The range of the Paddle’s workspace is sufficiently small to allow the small
angle approximation, thus the sinusoidal relationship approximates to a linear relationship.

(1) Employs figures in explanation
The left figure below shows the magnet at the zero Paddle position. Lines of magnetic flux emanate from the north pole and terminate at the south pole. The net magnetic field at the Hall-effect sensor is represented as $B_{net}$. It is apparent from the figure that $B_{net}$ is completely parallel to the sensor. The figure on the right shows the magnet position corresponding to a Paddle position of $\theta$. $B_{net}$ passes through the sensor at the same angle, thus the value of the magnetic field perpendicular to the sensor is $B_{net} \sin \theta$.

Conclusion: ___/1.5
(1.5) States a correct conclusion derived from Results and Discussion
(1) States bulk of important conclusions
The observed natural frequency of a time response is useful in characterizing unknown parameters of a second order system.
When properly used, the small angle approximation is useful in linearizing nonlinear systems.
The student learned how to calibrate the Hall-effect sensor.
C.5. Lab #6 – Virtual and Teleoperation Systems handout

The Complete Haptic Paddle Electromechanical System

In Part I of this lab exercise, you will explore virtual systems displayed on the Haptic Paddle. One of the virtual systems is a second order system implemented through the use of PD control. You will analyze this system through the use of the logarithmic decrement method. In Part II of this lab exercise, you will experience teleoperation of the Haptic Paddle.

Recall the following parameters and variables of the Haptic Paddle system from previous exercises:
- \( r_{cm} \), the distance from the Paddle component’s center of mass to the pivot point
- \( l_s \), the distance from the Paddle component’s pivot point to the center of the hole in the handle
- \( r_{sp} \), the radius of the Paddle component’s sector pulley
- \( J_p \), the inertia of the Paddle component about the pivot point
- \( m_p \), the mass of the Paddle
- \( r_{CS} \), the radius of the Capstan Spool
- \( J_{rotor} \), the inertia of the motor rotor
- \( B_m \), the damping in the motor
- \( R_o \), the armature resistance of the motor
- \( T_m \), the applied torque from the motor
- \( K_t \), the torque constant of the motor

You will also need to consider the following variables:
- \( \theta_p \), the angular displacement of the Paddle component from vertical. The positive direction is defined to be clockwise.
- \( \theta_m \), the angular displacement of the motor rotor. The zero position and positive direction are defined to be consistent with \( \theta_p \).
- \( x \), the horizontal component of the displacement of the hole in the Paddle component’s handle. The zero position and positive direction are defined to be consistent with \( \theta_p \).
- \( V_c \), the control voltage sent from the motor amplifier to the motor.

Lumped parameter modeling can be used to derive the equation of motion (EOM) for the Haptic Paddle mechanical system as

\[
m_{eq} \ddot{x} + b_{eq} \dot{x} + k_{eq} x = f_m
\]  

(1)

where the variable \( x \) is displacement defined above. The parameters \( m_{eq} \), \( b_{eq} \), and \( k_{eq} \) are the equivalent lumped parameters with respect to \( x \) due to inertial, damping, and stiffness elements of the mechanical system. The stiffness element of this system is due to the force of gravity. The force \( f_m \) is the equivalent lumped force experienced with respect to \( x \).
due to the input motor torque. To effect a virtual second order system, a LabVIEW Virtual Instrument (VI) has been programmed to control $f_m$ such that the EOM becomes

$$m_{eq} \ddot{x} + b_{virt} \dot{x} + k_{virt} (x - x_{sp}) = 0$$ (2)

where $b_{virt}$ and $k_{virt}$ are virtual parameters entered into the LabVIEW VI. A set-point value, $x_{sp}$, is input to the system and the control scheme outputs $f_m$ such that it is equal to the sum of a force proportional to the difference of the position and the set-point, a force proportional to the derivative of the position, and a force to balance the restoring force of the system. This control of $f_m$ is known as proportional-derivative (PD) control and is commonly used for position control. The VI has also been programmed to display haptic virtual environments in which the user moves the Paddle to input a position and the VI controls the motor to output a force corresponding to the interaction with the virtual environment.

**Teleoperation**

Teleoperation is the control of a machine from a remote location. Often times, the machine being teleoperated is a robot. In cases where the teleoperator, or input device, is also a robot, the teleoperator is known as the “master” robot and the teleoperated robot is known as the “slave” robot. The teleoperation scheme implemented in this exercise is depicted in the following figure.

The master is the ground reference for the slave. The virtual spring connecting the slave to the master is relaxed when $x_s$ equals $x_m$.

![Figure 1. Master – Slave Teleoperation](image)

If the master is a force feedback manipulator, such as the Haptic Paddle, then the user can haptically feel the remote environment of the slave via the master. Haptics enables this unique bimodal communication (communication goes both ways) and both robots are in effect a master and a slave grounded through their environment or user. The haptic teleoperation scheme implemented in this exercise is depicted in the following figure. A VI has been programmed to enable you to explore teleoperation of the Haptic Paddle.

![Figure 2. Haptic Teleoperation](image)
LABVIEW REAL-TIME OPERATING SYSTEM (RTOS)

Fast, even-timed calculation loop rates are critical to maintaining proper haptic environments. This exercise employs the LabVIEW RTOS to run loop rates faster than that achievable within LabVIEW for Windows. You will use a host computer running Windows to open and download a VI to the client RTOS machine. The VI will then run on the client machine and communicate with the host machine. The client machine also performs the data acquisition.

THE LOGARITHMIC DECREMENT METHOD

The logarithmic decrement method allows you to experimentally determine the values of $\zeta$ and $\omega_n$ for an under-damped system. The procedure is as follows:

f) Choose a section of your graph to work with. This section should go from one peak to another and include several cycles.

g) The logarithmic decrement is found using the equation $\delta = -\frac{1}{n} \ln \left( \frac{x_i}{x_{i+n}} \right)$, where $n$ is the number of cycles between peaks while $x_i$ and $x_{i+n}$ are the amplitudes of the peaks.

h) The damping ratio is then given by $\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}}$

i) Find the damped natural frequency, $\omega_d = \frac{2\pi}{p}$, where $p$ is the period (time/cycles)

j) Then use $\omega_d = \omega_n \sqrt{1 - \zeta^2}$ to find $\omega_n$.

EXPERIMENTAL SYSTEM AND EQUIPMENT

- Virtual and teleoperation systems displayed on the Haptic Paddle ($\times2$ for Part II)
- PXI industrial computer running Windows
- PXI industrial computer running LabVIEW RTOS with 6070E data acquisition (DAQ) card and connector block
- Haptic Paddle Power Supply and Amplifier ($\times2$ for Part II)
- Signal conditioning circuit (SCC) ($\times2$ for Part II)
- Kill switch

PRE-LAB ASSIGNMENT

1. Derive the linear relationship for both $\theta_p$ and $\theta_m$ and in terms of the system parameters and the variable $x$ listed on the first page of this handout.
2. From equation (1), derive relationships for $m_{eq}$, $b_{eq}$, and $k_{eq}$ in terms of the system parameters. It is helpful to use energy methods in determining these relationships.
Also derive the relationship for the input $f_m$ in terms of the system parameters and the input $T_m$.

3. Use these relationships to calculate numerical values for the equivalent parameters. Use metric units.

**BONUS PRE-LAB ASSIGNMENT**

1. Derive the expression for the controlled $f_m$ used to achieve equation (2) in terms of the equivalent parameters, the virtual parameters, $x$ and its derivative, and $x_{sp}$.

2. Use this expression to derive the relationship for $V_c$ in terms of the equivalent parameters, the virtual parameters, the system parameters, $x$ and its derivative, and $x_{sp}$.

**EXPERIMENTAL PROCEDURE**

**Part I: Virtual Systems**

a) From the SCC, connect the 3-wire SIP terminal to the sensor pins on the Haptic Paddle. Ensure that the “Up” label on the connector is up. Also connect the following wires to the connector block: flag “Pos” to channel 68, flag “Vel” to channel 33, flag “GND” to channel 67, flag “5V” to channel 8. These connections allow for the DAQ analog input channels 0 and 1 to read the amplified sensor voltage and its derivative and to send a 5 volt signal to the SCC, respectively.

b) From the Amplifier, connect the following wires to the connector block: flag “Vc” to channel 22, flag “GND” to channel 55. These connections allow for the DAQ to send control voltages to the Amplifier. Also connect the red and black banana plugs to their corresponding banana plugs on the Haptic Paddle.

c) From the Haptic Paddle power supply, use the wires with banana plugs on both ends to connect the red, black, and green banana jacks to their corresponding jacks on the Haptic Paddle circuit board. Use the wires from the kill switch to connect the corresponding yellow banana jacks such that the kill switch is in series with the power supply and the Haptic Paddle circuit board.

d) Have the TA check your setup. Turn on the power to the power supply.

e) On the host machine, open the “Virtual Systems Project” project in the “Mech 343 Labs\Haptic Paddle VI’s” folder from the Desktop.

f) In the project viewer, open the file “Virtual Systems Lab” for the appropriate remote system. Your client machine is labeled with its IP address.

g) Run the VI by hitting the white arrow in the upper left corner. It will take a few seconds to download the VI to the client machine.

h) Swing the Paddle to the extents of its workspace to make sure that you do not have saturation of the DAQ. Adjust the magnet cap and sensor position as necessary.

i) Open your calibration file from the “Calibration files” folder and calibrate the Hall-effect sensor. Calibrate the sensor with 5 data points throughout the workspace using similar procedure as that in Lab #5. Ensure that your calibration is correct.

j) Enter values for the equivalent system parameters $b_{eq}$ and $k_{eq}$ that you determined as part of the Pre-lab assignment. Also enter the value of the torque constant that you characterized in Lab #4.
k) Enter values into the controls for $k_{\text{virt}}$ and $b_{\text{virt}}$. Values of 500 N/m and 15 N*s/m are good initial values. Turn on the “Force-feedback” button.

l) Make sure no one is holding the Paddle and change the set-point control “x_sp (cm)” to a different value. Observe the response of the Paddle.

m) Experiment with different values of $k_{\text{virt}}$ and $b_{\text{virt}}$ to achieve underdamped behavior which has at least a few oscillations before the motion settles at the set-point. Control the Paddle’s position so that it moves from a position of 1.5cm to −1.5cm, and then back to 1.5cm. You may observe different behavior when the Paddle moves left-to-right as to when it moves right-to-left. Once you have achieved adequate underdamped behavior, adjust $b_{\text{virt}}$ to achieve critically and then overdamped motion. For each type of response, note your values of $k_{\text{virt}}$ and $b_{\text{virt}}$ as you discover them. **Do not attempt undamped motion!**

n) Now you will record underdamped motion. Enter the values you noted for $k_{\text{virt}}$ and $b_{\text{virt}}$ and send the paddle to a position of 1.5cm. Enter in the name of your team in the “Team” control and the values of $k_{\text{virt}}$ and $b_{\text{virt}}$ for the test in the “Test” control (e.g. “k20b20”).

o) Record the value shown for the “Data Sampling Period (s)”. Your data file will have only position information per loop iteration; you will need this sampling period to determine the time at each loop iteration.

p) Hit the “Record Data” button. Send the paddle to a position of −1.5cm. Once motion has stopped send it back to a position of 1.5cm. Hit the “Write Data to File” button.

q) Repeat steps n) through p) in order to record critically and overdamped responses.

r) You are done recording data. Retrieve your data files by opening My Computer and entering the following address into the URL field: “ftp://IP address of client machine\Mech 343 Labs\”. Cut your files from this folder and paste them to your flash drive.

s) Explore the other haptic environments. The controls for each environment are listed in the VI.

t) When you are done exploring the environments, if you are at the teleoperation station then you must wait for the other team; otherwise, disconnect your paddle from the SCC and Amplifier and go join the team at the teleoperation station.

**Part II: Teleoperation**

a) The Haptic Paddle of the team at the teleoperation station will be the Paddle A. The setup for this Haptic Paddle does not need to change.

b) From the Paddle B SCC, connect the 3-wire SIP terminal to the pins on the slave Haptic Paddle. Ensure that the “Up” label on the connector is up. Also connect the following wires to the Paddle A connector block: flag “Pos” to channel 65, flag “Vel” to channel 30, flag “GND” to channel 64.

c) From the Paddle B Amplifier, connect the following wires to the Paddle A connector block: flag “Vc” to channel 21, flag “GND” to channel 54. Also connect the red and black banana plugs to their corresponding banana plugs on the Paddle B. Have the TA check your setup. Turn on the power to the Paddle B power supply.

d) In the project viewer, open the file “Teleoperation Lab” for the appropriate remote system. The client machine is labeled with its IP address.
e) Enter the previously determined calibration constants for each Paddle.

f) Enter the values for $b_{eq}$ and $k_{eq}$ for each Paddle, as well as the value for the torque constant. Turn on the “Force-feedback” button.

g) Enter values for $k_{virt}$ and $b_{virt}$ and explore teleoperation of the Haptic Paddle. 100 N/m and 5Ns/m are good initial values. Turning on the “Paddle A Master” button with the “Paddle B Master” button off will make Paddle A the master and Paddle B the slave. The opposite is true for the button positions reversed. Turning on both master buttons enables Haptic teleoperation.

**RESULTS TO REPORT**

- Produce graphs for each type of system response including the values of $m_{eq}$, $k_{virt}$, and $b_{virt}$ that were used to produce each response. Include both the left-to-right and right-to-left motions with a time shift so that $t_0=0$ for both motions. Remove the extraneous data points from before the motion was initiated and after the motion settled.
- For the under-damped system, calculate $\zeta$ and $\omega_n$ from the graph using the log-decrement method. Also calculate the theoretical values of $\zeta$ and $\omega_n$ expected for the chosen $m_{eq}$, $k_{virt}$, and $b_{virt}$.
- Calculate the theoretical values for $\zeta$ for the other two cases.

**ADDITIONAL ITEMS TO ADDRESS IN THE DISCUSSION SECTION**

- Your discussions of the theoretical expectations for $\zeta$ and $\omega_n$ and how they compare to the experimental results are sufficient for discussing the time responses of the PD controlled virtual system.
- Consider the values you determined for $b_{eq}$ and $k_{eq}$ and the values you entered for $b_{virt}$ and $k_{virt}$. What does this imply about the significance of the equivalent damping and spring parameters of the Haptic Paddle system?
- Briefly discuss haptics and teleoperation and aspects of each that you encountered in this exercise.

**REFERENCES:**

1. http://whatis.techtarget.com/definition/0,,sid9_gci212226,00.html
C.6. Lab #6 – Virtual and Teleoperation Systems solutions

Total: ___/33

___ Meets Honest Effort Attempt Completes all sections. Makes valid attempt at addressing prompted results and discussion items.

Table of Contents is up-to-date: ___/1 TOC is to have Lab Title, Abstract, Results, Discussion, and Conclusion

___ (-1 per) Fails to follow general guidelines: missing title page for lab, abstract not on its own page, use of pencil, loose or folded paper, use of staples or other bulky means of affixing loose paper, sloppily affixed paper, uses both sides of notebook, messy work, sections out of order, other sloppy work

Specify which guidelines are not followed

Abstract: ___/2.5

(.5) Identifies experimental system
Virtual and teleoperation systems displayed on the Haptic Paddle System

(.5) Conveys experiment’s purpose
Use the logarithmic decrement method to characterize parameters of a second order underdamped system. Also to experience virtual and teleoperation systems.

(.5) Summarizes equipment, setup, and procedure
A PXI running LabVIEW for windows communicated with a PXI running LabVIEW RTOS. The RTOS machine ran a VI that communicated with the Haptic Paddle system to effect virtual and teleoperation systems.

(.5) Includes important results
Students experimentally determined damping ratio and natural frequency by use of the log decrement method for comparison with expected values from the EOM.

(.5) Includes important conclusions
The important conclusions stated here should be consistent with those presented in the conclusion section.
Pre-Lab Assignment: ____/9

(1) Derives relationship for $\theta_p$

Consider the figure

$\theta_p = \frac{x}{l_x}$

By SAA, $\sin \theta_p = \theta_p$

(1) Derives relationship for $\theta_m$

Recall the gear ratio from Lab #4 and use it to relate $\theta_m$ to $\theta_p$

$\theta_m = \frac{r_{sp} \theta_p}{r_{CS}}$

$\theta_m = \frac{r_{sp} \theta_p}{r_{CS} l_x}$

(1) Derives relationship for $m_{eq}$

Use kinetic energy

$\frac{1}{2} m_{eq} \dot{x}^2 = \frac{1}{2} J_p \dot{\theta}_p^2 + \frac{1}{2} J_{rotor} \dot{\theta}_m^2$

$m_{eq} \dot{x}^2 = J_p \left( \frac{\dot{x}}{l_x} \right)^2 + J_{rotor} \left( \frac{r_{sp} \dot{x}}{r_{CS} l_x} \right)^2$

$m_{eq} = J_p l_x^2 + J_m \left( \frac{r_{sp}}{r_{CS} l_x} \right)^2$

(1) Derives relationship for $b_{eq}$

Use instantaneous energy dissipated

$-b_{eq} \dot{x} dx = -B_m \dot{\theta}_m d\theta_m$

$b_{eq} \dot{x} dx = B_m \left( \frac{r_{sp} \ddot{x}}{r_{CS} l_x} \right) \left( \frac{r_{sp} \dot{x}}{r_{CS} l_x} \right)$

$b_{eq} = B_m \left( \frac{r_{sp}}{r_{CS} l_x} \right)^2$
(1) Derives relationship for \( k_{eq} \)

Consider the figure

![Diagram](image)

Use potential energy

\[
\frac{1}{2} k_{eq} x^2 = m_p g h
\]

\[
\frac{1}{2} k_{eq} x^2 = m_p g r_{cm} (1 - \cos \theta_p)
\]

By SAA, \( \cos \theta_p = 1 - \frac{\theta_p^2}{2} \)

\[
\frac{1}{2} k_{eq} x^2 = m_p g r_{cm} \left( 1 - 1 + \frac{\theta_p^2}{2} \right)
\]

\[
\frac{1}{2} k_{eq} x^2 = m_p g r_{cm} \frac{x^2}{2l_s^2}
\]

\[
k_{eq} = \frac{m_p g r_{cm}}{l_s^2}
\]

(1) Derives relationship for \( f_m \)

This result is from the expression of \( T_m \) in Lab #4. Replace \( F_w \) with \( f_m \)

\[
T_m = \frac{f_m l_s r_{cs}}{r_{sp}}
\]

\[
f_m = T_m \frac{r_{sp}}{l_s r_{cs}}
\]

(1) Provides numerical value for \( m_{eq} \)

\[
m_{eq} = J_p \frac{r_{sp}}{l_s^2} + J_m \left( \frac{r_{sp}}{r_{CS} l_s^2} \right)^2
\]

\[
m_{eq} = \frac{1.8 \times 10^{-4} \text{ kg} \cdot m^2}{(0.0635 m)^2} + 4.16 \times 10^{-6} \text{ kg} \cdot m^2 \left( \frac{0.0762 m}{0.0043 m \cdot 0.0635 m} \right)^2
\]

\[
m_{eq} = 0.339 \text{ kg}
\]
(1) Provides numerical value for $b_{eq}$

$$b_{eq} = B_m \left( \frac{r_{sp}}{r_{cs} I_x} \right)^2$$

$$b_{eq} = 4.02 \times 10^{-6} \text{Nm/s} \times \left( \frac{0.0762 \text{m}}{0.0043 \text{m} \times 0.0635 \text{m}} \right)^2$$

$$b_{eq} = 0.313 \text{N/s/m}$$

(1) Provides numerical value for $k_{eq}$

$$k_{eq} = \frac{m_p g r_{cm}}{l_x^2}$$

$$k_{eq} = \frac{0.0572 \text{kg} \times 9.81 \text{m/s}^2 \times 0.023 \text{m}}{(0.0635 \text{m})^2}$$

$$k_{eq} = 3.2 \text{N/m}$$

(+8) Points recovered for corrected Pre-Lab Assignment Does not apply to bonus Students can receive up to half credit of missed points for correcting any incorrect answers in their Pre-Lab Assignment. The problem must have been attempted on the initial submission in order for the student to receive credit.

(+1) Derives expression for controlled $f_m$

Manipulate equation (1) such that you have a relationship equal to zero

$$m_{eq} \ddot{x} + b_{eq} \dot{x} + k_{eq} x = f_m$$

$$m_{eq} \ddot{x} + b_{eq} \dot{x} + k_{eq} x - f_m = 0$$

Equation (2) is already presented as a relationship equal to zero, thus

$$m_{eq} \ddot{x} + b_{eq} \dot{x} + k_{eq} x - f_m = m_{eq} \ddot{x} + b_{virt} \dot{x} + k_{virt} (x - x_{sp})$$

$$f_m = (b_{eq} - b_{virt}) \dot{x} + k_{virt} (x_{sp} - x) + k_{eq} x$$

(+2) Derives relationship for $V_c$

$$f_m = (b_{eq} - b_{virt}) \dot{x} + k_{virt} (x_{sp} - x) + k_{eq} x$$

$$T_m = \frac{r_{sp}}{l_x r_{cs}} = (b_{eq} - b_{virt}) \dot{x} + k_{virt} (x_{sp} - x) + k_{eq} x$$

$$K_t i_{arm} = \left[(b_{eq} - b_{virt}) \dot{x} + k_{virt} (x_{sp} - x) + k_{eq} x\right] \frac{l_x r_{cs}}{r_{sp}}$$

Recall the dynamic braking figure from Lab #4. The electric circuit for the setup in this exercise is the same as the dynamic braking circuit with the switch in the spin-up position. Also recall that $K_v = K_t$. 
\[ i_{arm} = \frac{V_c - V_{enf}}{R_a} \]
\[ \frac{V_c - V_{enf}}{R_a} = \left[ (b_{eq} - b_{virt}) \dot{x} + k_{virt} (x_{sp} - x) + k_{eq} x \right] \cdot \frac{I_x r_{cs}}{K_r r_{sp}} + K_v \dot{\theta}_m \]
\[ V_c = \left[ (b_{eq} - b_{virt}) \dot{x} + k_{virt} (x_{sp} - x) + k_{eq} x \right] \cdot \frac{R_a l_x r_{cs}}{K_i r_{sp}} + K_i \frac{r_{sp}}{r_{cs} l_x} \dot{x} \]
\[ V_c = \left[ (b_{eq} - b_{virt}) \frac{R_a l_x r_{cs}}{K_i r_{sp}} + K_i \frac{r_{sp}}{r_{cs} l_x} \right] \dot{x} + \left[ (k_{eq} - k_{virt}) \frac{R_a l_x r_{cs}}{K_i r_{sp}} \right] x + k_{virt} \frac{R_a l_x r_{cs}}{K_i r_{sp}} \quad x_{sp} \]

System, equipment, setup, and procedure:

(.5) Lists Experimental System and Equipment

System:
Virtual systems displayed on the Haptic Paddle (x2 for Part II)

Equipment:
PXI industrial computer running Windows
PXI industrial computer running LabVIEW RTOS with 6070E data acquisition (DAQ) card and connector block
Haptic Paddle Power Supply and Amplifier (x2 for Part II)
Signal conditioning circuit (SCC) (x2 for Part II)
Kill switch

Experimental setup
(1) Correctly describes setup
A PXI computer running LabVIEW for Windows communicated with a PXI computer running LabVIEW RTOS. A LabVIEW VI running on the RTOS machine communicated with a 6070E DAQ card to effect virtual systems on the Haptic Paddle System. Students input virtual parameters into the VI, as well as physically controlling the position of the Paddle. Based on this position control, the virtual system output a force displayed by the Haptic Paddle.
(1) Schematic correctly depicts setup

(5) Procedure

Results: __/7

(1) Provides proper chart for underdamped case

*Values for m\textsubscript{eq}, k\textsubscript{virt}, and b\textsubscript{virt} should be noted.*
(1) Uses log decrement method to calculate damping ratio and natural frequency

*The student should present the average values of those determined from the left-to-right and the right-to-left motions.*

*The value n is the number of cycles observed. The values for x are the amplitudes of the peaks, not the position of the peaks. The value p is the period of motion observed. The delta and the damping ratio has no unit, the natural and damped natural frequencies have units of rad/s.*

\[
\delta = \frac{1}{n} \ln \left( \frac{x_i}{x_{i+n}} \right)
\]

\[
\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}}
\]

\[
\omega_d = \frac{2\pi}{p}
\]

\[
\omega_n = \frac{\omega_d}{\sqrt{1 - \zeta^2}}
\]

(1) Calculates expected damping ratio and natural frequency from EOM for UD case

\[
\zeta = \frac{b_{virt}}{2\sqrt{k_{virt}m_{eq}}}, \quad \omega_n = \sqrt{\frac{k_{virt}}{m_{eq}}}
\]

(1) Provides proper chart for critically damped case

*Values for m_{eq}, k_{virt}, and b_{virt} should be noted. Some responses will be slightly underdamped. This is acceptable because the students determined when they achieved critical damping by watching the response and the human eye is not so keen. However, the student should note if they are underdamped.*
(1) Calculates expected damping ratio from EOM for CD case
(1) Provides proper chart for overdamped case

*Values for \( m_{eq} \), \( k_{virt} \), and \( b_{virt} \) should be noted.*

(1) Calculates expected damping ratio from EOM for OD case

**Discussion:**

(1) Provides EOM for PD case

\[
m_{eq} \ddot{x} + b_{virt} \dot{x} + k_{virt} (x - x_{ss}) = 0
\]

(1) Compares expected parameters to experimental parameters

*It is possible for the students to get values that are significantly different from expected. They should discuss what data matched and what did not match expectation.*

(1) Notes difference in motion for different directions

(1) Provides explanation for differences in theory and experiment

*Justifications for why data did not match include coulombic friction of the motor, nonlinearity of the amplifier and system, unaccounted damping in ball bearings at the pivot point.*

(1) Comments on significance of \( b_{eq} \) and \( k_{eq} \)

*The value of \( k_{virt} \) is orders of magnitude greater than \( k_{eq} \), indicating that the effects of \( k_{eq} \) are negligible. The values used for \( b_{virt} \) are also greater in magnitude than \( b_{eq} \), but not so great as to say that the effect of \( b_{eq} \) is negligible.*

(1) Discusses haptic systems

*Users are able to interact with virtual environments through the use of a force-feedback manipulators. The user inputs the motion of the manipulator which the virtual environment responds to by displaying a force.*

(1) Comments on the variety of haptic environments that can be displayed

*Virtual environments can display the effects of interacting with elements such as a wall, viscous fluid, bump, divot, etc.*

(1) Discusses master-slave interaction of teleoperation
The teleoperation scheme implemented in this exercise used one Haptic Paddle as a master robot and another Haptic Paddle as a slave robot. The motion of the slave could be controlled by manipulating the master. This communication was one way from the master to the slave.

(1) Discusses haptic teleoperation
This form of teleoperation allows for communication to go both ways between the teleoperated Haptic Paddles. Each Haptic Paddle in effect became both a master and a slave. This allows a user to explore a remote environment.

Conclusion: __/1.5
(1) States a correct conclusion derived from Results and Discussion
(1) States bulk of important conclusions
The logarithmic decrement method is useful in determining the damping ratio and natural frequency of an underdamped second order system.
The use of force-feedback manipulators enables users to haptically interact with virtual and remote environments.
Appendix D
LabVIEW front panels and block diagrams

D.1. Actuator Characteristics Laboratory VI

Figure D.1. Actuator Characteristics VI Front Panel.

Figure D.2. Actuator Characteristics VI Block Diagram.
D.2. Sensor Calibration Laboratory VI

**Hall Effect Calibration Lab**

Conditioned Hall Sensor (volts)

\[ 0.000 \]

Position = \( A \times x + B \), Position in degrees, \( x \) in Volts

\[
\begin{array}{c|c}
A & B \\ \\
0 & 0 \\
\end{array}
\]

Position (deg)

\[ 0 \]

Figure D.1. Actuator Characteristics VI Front Panel.

Figure D.2. Actuator Characteristics VI Block Diagram.
D.3. Virtual Systems Laboratory VI

**Conditioned Hall Sensor (volts)**
0.000

**Environment**
0

**Th_p (deg) = Ax + B**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**x_sp (cm)**
0

**Th_p (deg) x (cm) x_dot (cm/s)**
0 0 0

**Haptics**
Off

**K_virt (Nm/A)**
0

**K_eq (N/m)**
0

**B_virt (N*s/m)**
0

**B_eq (N*s/m)**
0

**Coulombic Friction (N)**
0

**System Dynamics Cancelation**

**Environment Types:**
0 - PD control
1 - Free space to the left with wall to the right
2 - Breakthrough wall at zero location with viscous space on right
3 - Divert at zero location
4 - Bump at zero location

**Inputs:**
0 - K_sp, K_virt, B_virt
1 - K_sp, K_virt, B_virt
2 - K_virt, B_virt, Break Threshold
3 - K_virt
4 - K_virt

**Figure D.5. Virtual Systems VI Front Panel.**

**Figure D.6. Virtual Systems VI Block Diagram.**
D.4. Teleoperation Systems Laboratory VI

Figure D.7. Teleoperation Systems VI Front Panel.

Figure D.8. Teleoperation Systems VI Block Diagram.