Haptic Museum Display

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ABSTRACT

We present an adaptation of an existing haptic device developed into a freestanding display intended for a science and technology museum. Through haptic interaction with the device and accompanying virtual environment, users will gain a more intuitive understanding of certain underlying physical concepts. The display simulates using a paddle to bounce three different masses in three different gravitational fields. Users can explore the concepts of mass, weight, and inertia in an entertaining and engaging environment. We believe that the use of force feedback will provide museum visitors, especially children, with a more interactive platform for education, and raise their interest in science and engineering. The device design and virtual environment are presented, and ideas for implementation into a museum exhibit are discussed.

1 INTRODUCTION

Science and technology museums typically have “hands-off” policies that do not allow physical interaction between museum visitors and exhibits. It has been shown that hands-on interaction enhances the visitor experience and can greatly improve the understanding of an exhibit [1] [5]. If visitors are permitted to have physical interaction with exhibit displays in a science and technology museum, they can gain a more intuitive understanding of underlying physical concepts. As one Johns Hopkins University study suggests, hands-on interaction makes the process of learning more compelling for people of all ages, and allows them to make connections between theory and reality [4]. A group from Ohio University has developed multiple educational haptics packages by integrating a commercially available haptic interface with several virtual environments. The packages are intended for K-12 education and simulate different physical systems, such as simple machines and high-school physics tutorials [10] [9]. Although their system proved to be effective in helping students learn, the interface was very delicate and complicated, thus not optimal for a freestanding museum exhibit [10]. The device must be robust and require minimal instruction if it is to be implemented as a freestanding museum exhibit. [6].

The haptic device presented here is adapted from a low-cost, single-axis force-feedback device known as the “Haptic Paddle.” The Haptic Paddle project was first developed at Stanford University [8], and further developed at Johns Hopkins University [7]. This device can effectively emulate the interaction forces that occur when humans come into contact with physical systems. By limiting the motion to a single degree of freedom and producing significantly less power than high-end commercial haptic interfaces, the Haptic Paddle can be manufactured and assembled at very little cost. The Haptic Paddle and other similar devices, such as the iTouch motor at the University of Michigan [2], have been successfully implemented into university-level courses on dynamic systems. The novelty and effectiveness of such devices has been acknowledged, however, due to various drawbacks, there exists no optimal platform to incorporate into a freestanding museum display. This project introduces a few design features aimed at increasing the robustness of the Haptic Paddle design, while preserving the functionality, without significantly increasing the cost.

The virtual environment presented here is aimed to explore the relationships between mass, gravity and inertia through bouncing a ball on a virtual paddle. The user can modify parameters and observe the changes in force and visual feedback from the environment. This interaction will aid comprehension of the underlying physical principles [3]. The user can change the mass of the bouncing ball and the gravitational acceleration of the environment. The important insight to be gained is the difference between weight and mass/inertia. The user senses that the inertia of the ball, felt on the paddle, remains constant when the gravity property is changed; however, the motion of the ball in free space, seen on the screen, is significantly affected. Although intended for the K-12 audience, many adults also find the demonstration surprisingly useful for solidifying the concepts of mass and weight.

2 DISPLAY SETUP

As shown in Figure 1, the overall setup consists of three major components: the haptic interface, the laptop/virtual environment, and the power supply/circuitry. Each component is described in detail in the following sections.

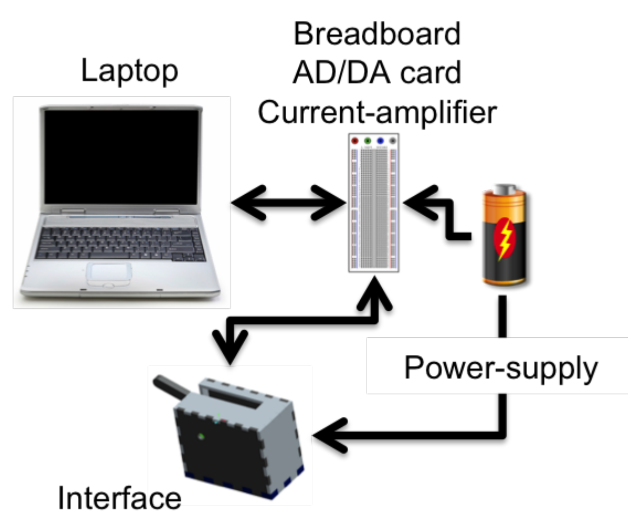

Figure 1: Schematic of the overall setup of the haptic museum display.

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Figure 2: Original Haptic Paddle.

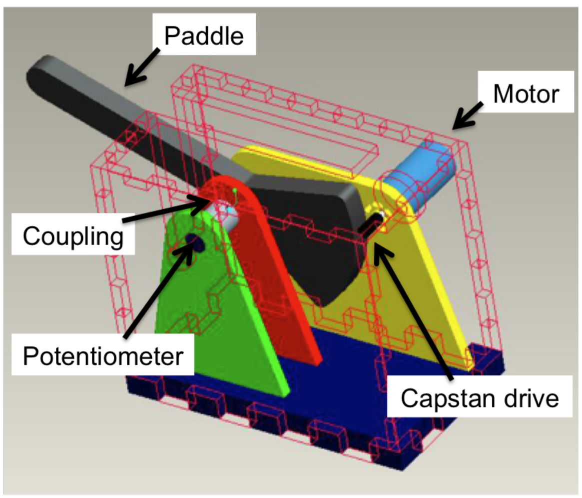


Figure 3: CAD rendering of the haptic interface used for this project.

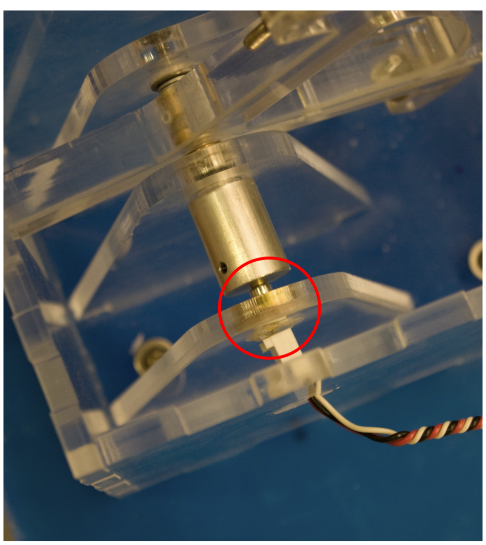


Figure 4: Close-up of the potentiometer (circled) attached to the paddle's center shaft via a coupling.

2.1 Haptic Interface

As previously stated, the design for the haptic device used for this project was based on the Haptic Paddle, shown in Figure 2. All the information needed to create an original haptic paddle kit is available from the Web site `https://haptics.lcsr.jhu.edu/Making_and_Using_a_Haptic_Paddle`, including links to .dwg files for the laser-cut parts, Microsoft Visual C++ source code for the control software, and detailed assembly instructions with pictures.

The first design modification was to invert the paddle orientation so the handle extended opposite the sector pulley. Also, in order to facilitate the vertical displacement of the paddle when bouncing the ball, the mounting was rotated 90° such that the handle of the paddle was approximately horizontal to the ground. A labeled CAD rendering of the modified design is shown in Figure 3.

Another modified design component was the Maxon DC motor #118743 used to power the device. This motor was more powerful, and more expensive, than the surplus Maxon motors used in the original design. The new motor was capable of providing a higher torque output, increasing the capabilities of the device, and was provided at the beginning of the project. Also, it came equipped with a HEDS 5540 digital encoder. The original intention was to use the encoder signal to track the position of the paddle, however no quadrature decoder boards were available at the time of the project.

Instead, a potentiometer, shown in Figure 4, was attached to the paddle's center shaft via a coupling to sense the position of the paddle. The potentiometer provided accurate position values and was easy to integrate into the available analog-to-digital card, described in Section 2.2. Eliminating the need for a quadrature decoder card in a desktop computer preserved the relative portability of the display. The potentiometer was also a significant improvement over the Hall-effect sensor, used to detect position in the original design. The signals from the Hall-effect sensor were noisy, inaccurate, and required complicated calibration.

A design component modified to significantly increase the robustness of the device was the motor pulley, which served as the capstan drive and is shown in Figure 5. The original design used a worm gear and wrapped the cable around the grooves. This design worked very well, as long as the motor never slipped relative to the cable. If the motor slipped, the gear spun while the cable remained stationary, driving the cable off the end of the capstan drive and effecting a catastrophic failure of the device. The frequency of this occurrence was a major barrier preventing the original design from being implemented into a freestanding museum display, due to the maintenance that would be required. Many efforts were made to increase the friction between the motor pulley and the cable in order to eliminate all slipping, including increasing the cable tension and coating the motor pulley. It was found that slipping was inevitable when the drive system experienced very high torques, so the capstan drive was redesigned. A new, aluminum motor pulley was machined with no grooves. This new design was a significant improvement over the original design because if the motor briefly slipped relative to the cable, the cable remained attached and the device remained functional.

It was noted that using the potentiometer to sense the position of the paddle had a distinct advantage over using an encoder. An encoder would require re-calibration after the occurrence of any slippage, which was determined to be unavoidable. Since the potentiometer was attached to the paddle's center shaft and not the drive system, it could be permanently calibrated upon assembly of the device.

The paddle itself was cut from $\frac{1}{2} in$ thick impact resistant clear extruded acrylic sheet using a precision laser cutter. A set screw was added to the side of the gap intended to provide tension to the cable. Inserting the set screw increased the width of the gap and increased the tension on the cable. This helped reduce the slippage of the capstan drive system.

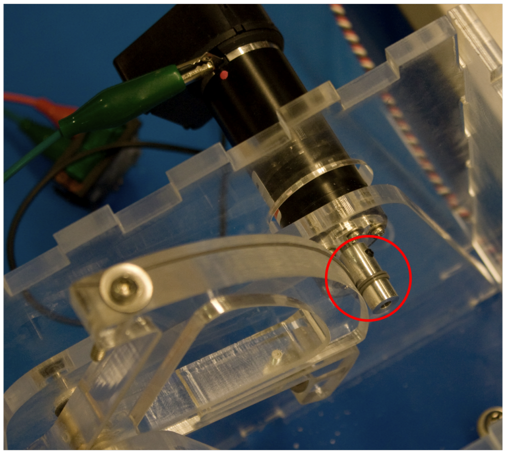


Figure 5: Close-up of the motor pulley (circled). The motor pulley was machined with a smooth surface to ensure the cable remained attached to the capstan drive system.

The supports for the paddle were similar to the original design, however slightly modified to account for the rotated orientation. These were cut from $\frac{1}{4}in$ thick clear cast acrylic sheet using a precision laser cutter. Finally, an acrylic enclosure was constructed to protect the moving parts of the device. The sides of the enclosure were cut from $\frac{1}{4}in$ acrylic and the base was cut from $\frac{1}{2}in$ acrylic.

2.2 Virtual Environment

A Sony Vaio laptop (VGN-S480) was provided at the beginning of the project to host the virtual environment and graphical user interface (GUI). The laptop was equipped with a PC-CARD-DAS16/16AO from Measurement Computing™ to function as the digital-to-analog (D/A) and analog-to-digital (A/D) interface. The program that ran the simulation was implemented in Microsoft Visual C++ and integrated into the Windows API (win32). An overall signal flow diagram is shown in Figure 6.

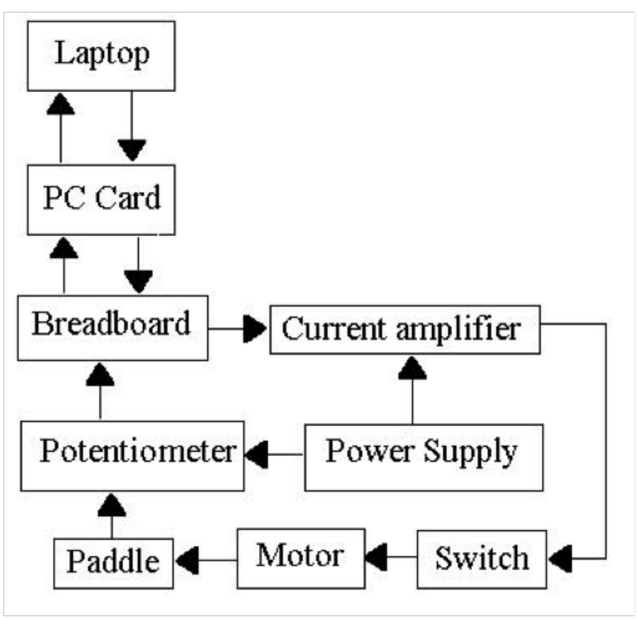


Figure 6: Overall signal flow diagram of the haptic museum display.

The potentiometer was supplied with a fixed $5V$, and the position of the paddle was read from the resulting output voltage. The signal was then filtered to eliminate some of the noise. A conversion was applied to the filtered voltage to obtain an appropriate position value in mm. This conversion factor was determined by finding the range of the potentiometer voltage output that corresponded to the full vertical displacement of the device. Once the position was determined in mm, the dynamic equations were solved for the system. The paddle was modeled as a simple massless spring-damper system. If the position of the ball was below the interaction point of the paddle, appropriate linear spring and viscous damping forces were applied to the ball, according to Equation 1.

$$F_B = -k\,(x_B - x_P) - b\,(v_B) \tag{1}$$

for force on the ball $F_B\,[N]$, stiffness coefficient $k = 0.3\,\left[\frac{N}{mm}\right]$, position of the ball $x_B\,[mm]$, position of the paddle $x_P\,[mm]$, damping coefficient $b = 0.0006\,\left[\frac{Ns}{mm}\right]$, and velocity of the ball $v_B\,\left[\frac{mm}{s}\right]$. The constants k and b were chosen to keep the system stable, eliminate chatter, and provide realistic feedback. The values were determined through trial and error.

The force applied to the paddle from the ball was set to be equal and opposite to the force applied to the ball from the paddle. The force due to gravity was always applied to the ball. The new acceleration of the ball was found by summing the forces applied to the ball and dividing by the mass. From there, the ball's new velocity and position were calculated using the trapezoid method of integration. The calculated force on the paddle was converted to the corresponding voltage and sent to the current amplifier circuit, described in Section 2.3. This voltage was determined using Equation 2.

$$V_{out} = \frac{GF \times l \times N \times F_P}{k_\tau} \tag{2}$$

for output voltage $V_{out}\,[V]$, gain factor $GF = 2.0\,\left[\frac{V}{A}\right]$, paddle length $l = 125\,[mm]$, gear ratio $N = 0.052$, force on the paddle $F_P\,[N]$, and torque constant $k_\tau = 23.5\,\left[\frac{mNm}{A}\right]$.

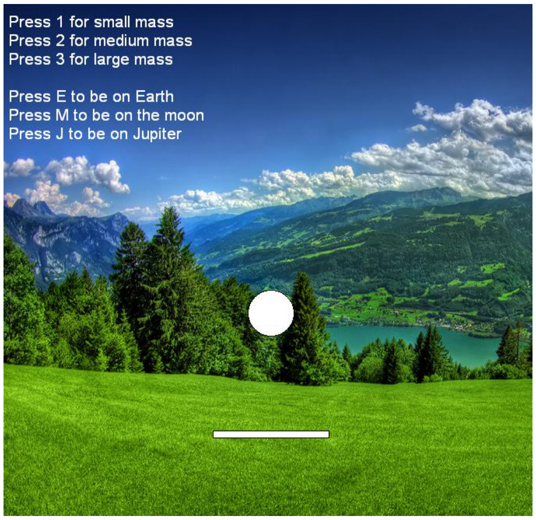
The update interval for the haptic function was $1ms$, or a frequency of $1kHz$. The update interval for the graphic function was $33ms$, or a frequency of $30Hz$.

As previously stated, the user could modify the mass property of the ball and the gravity property of the environment. The user could choose from mass values of $m = 0.01$, 0.02, and $0.03\,[kg]$, corresponding to "small," "medium," and "large" masses. These values were chosen to optimize the response of the system, given certain limitations. The lower limit for the mass was determined by the smallest value that could reliably be perceived in the lowest gravitational field, and the upper limit for the mass was determined by the largest current that could be sourced by the power supply in response to forces experienced in the highest gravitational field.

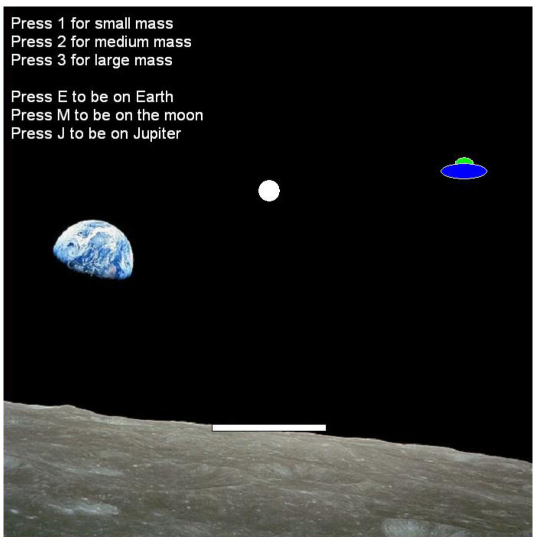
The gravity properties of three astronomical objects were simulated: Earth, the Moon, and Jupiter. These gravitational fields were chosen to provide a range of environments to which users could easily relate. Each environment also had a unique background complete with a representative image. The familiarity of the environments added to the engaging educational experience. The screen refreshed only the parts that changed between each time the graphics function was called in order to minimize the computational burden. Examples of each environment are shown in Figure 7.

2.3 Circuitry

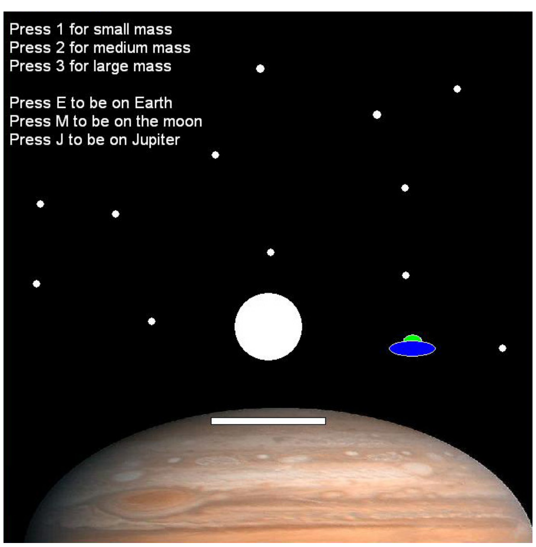
The D/A card could not source the substantial amount of current necessary to drive the motor at a desired torque, therefore the output voltage was applied to a linear current amplifier circuit. This simple circuit was developed for the Robot Sensors and Actuators course at Johns Hopkins University and incorporated an OPA544 power



(a) Bouncing the medium mass on Earth



(b) Bouncing the small mass on the Moon



(c) Bouncing the large mass on Jupiter

Figure 7: Examples of the three environments.

op-amp. The gain factor of the circuit was $\frac{1}{2}\frac{A}{V}$. The power supply had a current limit of $2A$, therefore the voltage output of the D/A card was capped at $4V$.

The final component of the circuitry was a switch. This was inserted between the current amplifier and the motor so that the display could easily function with or without force feedback.

3 Operation

The operation of the display was deliberately designed to be very simple. Since the intention was a freestanding museum exhibit, the exhibit was self-explanatory, easy to use, and appropriate for a wide range of ages. The device was designed such that a user could sit down in front of the device and immediately begin to interact with it. The directions were clearly displayed on the screen as part of the background image to improve the aesthetics. The user could switch between the three different masses by pressing on different keys on the keyboard: "1" for the small mass, "2" for the medium mass, and "3" for the large mass. The user could switch between the three different gravitational fields in a similar manner: "E" for Earth, "M" for the Moon, and "J" for Jupiter. The entire display changed each time a new mass or gravity value was selected. Also, each time either property was changed, the forces acting on the ball and the paddle were zeroed and the ball position was reset to just above the maximum paddle position. Each user was free to use the paddle to explore the virtual environment in any manner he or she deemed appropriate. Force feedback was felt by the user through the paddle; the magnitude of the force feedback was dependent on the mass and acceleration of the ball. The display gave additional visual aid to the user by showing the deflection of the paddle. Figure 8 shows the full display setup with a user interacting with the display.

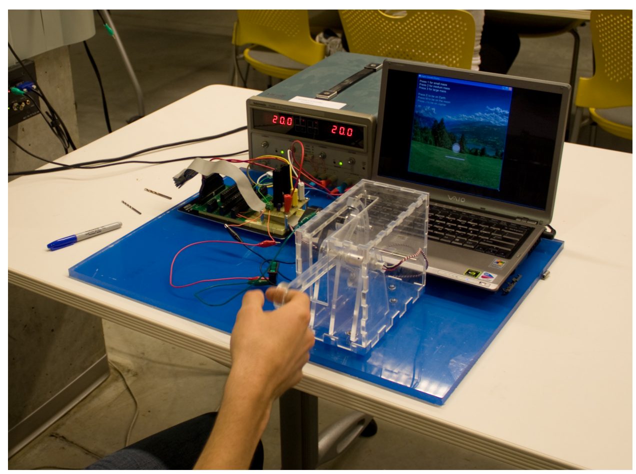


Figure 8: Full display setup with a user interacting with the display. The user was free to find a comfortable grip on the handle and interact with the virtual environment in any manner.

4 Discussion

Overall, users during the poster session had very positive feedback for the haptic museum display. Although no statistical data was obtained to assess the effectiveness of the device, most users thought the force feedback experienced through the haptic interface was quite compelling. The device provided interesting observations on human-in-the-loop dynamic systems. Some users immediately interacted with the device very naturally and responded with considerable enthusiasm. Other users took more time to develop a natural "feel" for the system. Most users took about 10 or 15s to become accustomed to interacting with the device. The more aggressive users seemed to become engaged with the environment quickly, while the more gentle users took more time to produce sensations compelling enough to engage them in the activity. It was very clear that the most compelling feedback was experienced when the ball dropped from some height onto the paddle. This usually required the user to input some forcing frequency, which was challenging for certain values of the parameters.

It was interesting to observe the position most users assumed when interacting with the device. Since the device was sitting on a table, users found it most comfortable to sit in a chair facing the device. This allowed easy interaction with the device, which was slightly lower than chest height for most users, and easy viewing of the display. Also, the most common hand posture when interacting with the device was sliding the index finger through the large hole at the end of the handle and very lightly grasping the acrylic as the paddle was moved up and down. These factors have to be taken into account before the installation concept is finalized. Ideally the visual display for the exhibit would be significantly larger than the existing laptop screen. Also, the device must be mounted at an appropriate height for the majority of users, most likely children and young adolescents. It would be easier for adults to crouch down to use the device than for short children to grow a few inches to reach a device that is mounted too high.

Some users noted that they were unable to feel any force feedback when they began to interact with the device, especially if their first experience was with the small mass on Earth or the Moon. After some minor coaching and switching back and forth between the different parameters, they were able to feel even the smallest force feedback. It was possible that the users did not feel the smallest feedback at first because they needed some time to adjust to the device. It is also possible that they were expecting greater force feedback to be felt at the beginning, thus were simply not paying close enough attention. Some users had difficulty bouncing the ball on Jupiter. Again, these users needed some time to familiarize themselves with the device and to "feel out" the natural frequency of the dynamic system. Since most users were willing to continue to use the device until they mastered the "game" of bouncing the ball, this was an unexpected feature of the device.

Numerous users stated that the graphic display enhanced the experience by providing another sensory input. The background picture provided the users with a familiar association with the relative gravitational constants. The size of the mass on the screen indicated which mass the user was bouncing: small, medium or large. The deflection of the paddle was a visual indication of the force applied to the ball by the paddle, which was directly related to the amount of force felt by the user. The rate at which the mass moved up and down the screen gave the users a sense of how different gravitational constants affected the motion of the ball through free space, and illuminated the difference between weight and mass.

One suggestion made by several users was to output the maximum height reached by the ball to the screen. This would make the display into more of a game, making the environment more entertaining and engaging. This would be very simple to implement using the existing code. Slightly more sophisticated code could probably incorporate entering the user's name into a record board or high score list. This would most likely increase the amount of time spent per user.

Judging by user response during the poster session, this haptic display is almost completely ready to be implemented into a museum exhibit. The robustness of the design was more impressive than anticipated, since the device survived several hours of rough usage from the authors and other users. This usage was certainly comparable to the abuse expected as a freestanding museum display. Of course, a more presentable package for the electronics would be necessary for incorporation into a museum. Suggestions for future work before the full implementation of the mechanical device include having a new motor pulley precision machined, drilled, and tapped. The current pulley was machined to the best of the abilities of the authors using the available equipment, however, an experienced machinist would be able to eliminate the slight imperfections present in the current part. The motor pulley could also be made slightly longer. This, along with mounting the paddle farther away from the support wall shared with the motor, would eliminate interference between the sector pulley and the set screws on the motor pulley, which was experienced near the extremes of the paddle's range of motion. The potentiometer support wall and the entire enclosure should also be glued into place using acrylic glue to ensure stability and robustness. This is a very easy procedure omitted during the poster session in case an emergency repair became necessary.

Finally, thought has been given to the use of an encoder to sense the position of the paddle. This would increase the accuracy and reduced the friction associated with using a potentiometer. The authors feel that using an encoder would introduce more problems than it would solve, mainly because each time the device was turned on, it would require a calibration sequence. Also, if the motor pulley were to ever slip in relation to the cable, which still happened occasionally, the system would have to be re-calibrated. Attaching the potentiometer to the center shaft eliminated this trouble, significantly reducing the required maintenance. Also, the accuracy and response time of the potentiometer was acceptable for this application. The component did introduce some friction; however, the friction could be reduced through a higher precision coupling and mounting method. Even with the existing friction, the device performed its specific purpose well.

Ultimately, a curator should be consulted to develop a final installation concept. A method can then be developed to assess the effectiveness of the display. Suggested metrics include number of uses, time spent per user, and questions posed after the demonstration [4]. Contacts have already been made at the Maryland Science Center in Baltimore, MD; the Carnegie Science Center in Pittsburgh, PA; the Science Museum of Virginia in Richmond, VA; the Chesapeake Children Museum in Annapolis, MD; and the Franklin Institute in Philadelphia, PA.

Other ideas include expanding the applications of the haptic device to explore other physical concepts, such as projectile motion, in a fun and interactive way. The new applications could utilize the same robust haptic device design and develop new virtual environments to explore.

5 Conclusion

We developed and implemented a robust haptic device to explore bouncing a ball in different gravitational fields. We hope that our device will be fully incorporated into a science and technology museum to encourage excitement about math, science, and engineering in K-12 students. This "hands-on" connection between theory and reality will provide an interactive and engaging environment through which children can develop intuition about basic physical principles.

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