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A BALL AND BEAM MODULE FOR A HAPTIC PADDLE EDUCATION PLATFORM

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ABSTRACT

Single degree of freedom force-feedback mechatronic devices, often called haptic paddles, are used in university curriculum as well as massive open online courses (MOOCs). While devices differ based on the goals of a given course, broadly speaking they provide hands-on learning for students studying mechatronics and dynamics. We introduce the third iteration of the Haptic Paddle at Rice University, which has been modified to improve haptic performance and robustness. The modifications to the design increased device up time as well as the devices Z-width. The performance improvement enables the addition of experimental plants to the haptic paddle base, which can be directed at advanced dynamics and controls courses, or special topics in mechatronics and haptics. The first module, a Haptic Ball and Beam, adds an underactuated plant for teleoperation or more complex control structures, and a testbed for haptic motor learning experiments in undergraduate coursework.

INTRODUCTION

Both intuitive and formalized in pedagogical circles [1, 2], hands-on experiences are important for learning, and even more so for haptics, with its focus on kinesthetic information transfer and interactions between users and hardware. Similarly intuitive is the need for the laboratory equipment to balance performance with low cost and ease of operation, maintenance, and implementation. To address this need in haptics and general mechatronics education, several universities and groups have adopted and developed devices broadly categorized as haptic paddles [3].

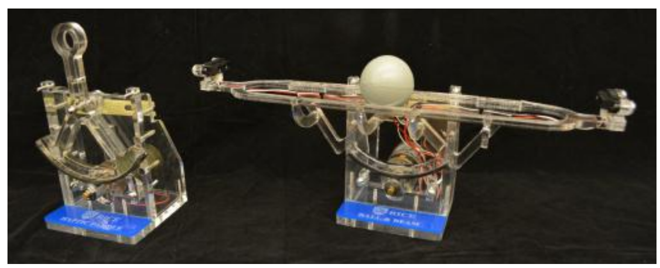

Figure 1. The "V3" Haptic Paddle and the Ball and Beam module at Rice University enable implementation in multiple courses and student experimentation in human visuo-motor learning experiments.

Generally speaking, a haptic paddle, shown in the left of Fig. 1, is a low-cost (as compared to commercial educational products) single degree of freedom (DOF) device, designed to render haptic environments and illustrate mechatronic concepts. Inherent to the paddle design are nonlinear, multi-domain dynamics, which serves well as an introduction to basic control theory, mechatronic implementation hardware, and suite of possible sensors.

Haptic Paddle Designs and Role In Pedagogy

In most paddle designs, a DC motor is connected to the end effector via a torque amplifying transmission, usually a capstan design, that is also the end effector of the device. Angular position is often sensed with low-cost options such as magnetic Hall effect sensors, and haptic environments are can be programmed as a function of position, rendering virtual bumps, notches, and walls with control strategies approachable to undergraduates. Modifications to this general design vary as a function of curricular goals. For example, the Haptic Paddle at Rice curriculum includes basics of electrical circuit materials, and the previous versions of the paddle, V1 [4] and V2 [5], integrated analog filtering of the Hall effect sensor to complement the passive and active circuit experiments. Paddles like the Hapkit [6] are designed to be gateway mechanisms into mechatronics and haptics or implemented in MOOCs, with broader STEM outreach as a goal, so cost and ease of operation drive the design process. Other devices have more specific uses, and their design leverages knowledge of the intended user to improve performance. The FireFader [7] is a one DOF slider used to introduce haptics to virtual instruments, and borrows design elements from the motorized fader, a familiar mechanism to musicians.

In some paddles implementations, considerations are made for corporate sponsorship and resources that can be economically or locally sourced, such as the use of laser cutters and discontinued (and therefore at the time discounted) Pittman motors available during the original implementation of the Haptic Paddle at Rice. To avoid needing luck or local infrastructure, devices such as the Haplet [8] and WoodenHaptics [9] have been propsed to address the need for low-cost, open-source haptic devices.

Haptic paddles have been implemented in multiple senior/graduate level courses, with devices like The Box [10] acting as a plant for embedded controls curriculum. Other paddles adopt a modular approach, either by increasing the degrees of freedom like the Snaptic paddle [11], adding additional sensing such as force sensing or electromyography [12], or altering the haptic paddle plant, such as the series-elastic implementation of the HandsOn-SEA [13] for higher level course objectives.

Organization and Contribution

In this vein of modularity, we propose to use the haptic paddle as an educational platform with modules for advanced haptic and mechatronic curriculum. First, we present the latest improvements to the paddle design, quantified by Z-width, which enable the haptic paddle to serve as a base for a variety of plants. Next, we present the first such plant, a Haptic Ball and Beam. This module improves the current teleoperation curriculum by providing students with a dynamic system which differs from the master. Additionally, the design of the module supports implementation in controls curriculum as a dynamic plant providing complexities beyond the haptic paddle base or to replicate haptic motor learning experiments in undergraduate curriculum. One potential experiment is the replication of visuo-motor coordination tasks [14]. Next, we provide details of the steps taken to validate this module for replicating this study. Enabling students to lead experiment design, instead of performing guided tasks has the potential to increase student reflection and improve learning outcomes, as suggested by recent pedagogy in STEM fields [15]. For reference, the bill of materials and requisite files for the haptic paddle base and module are available at `http://mahilab.rice.edu/content/hands-haptics-haptic-paddle`.

HAPTIC PADDLE DESIGN MODIFICATIONS

The Haptic Paddle at Rice University was designed for a junior-level system dynamics course and is intended to provide students with hands-on experiences with the following course ourcomes: identifying different types of dynamic systems and classify them by their governing equations, developing models of translational and rotational mechanical systems using free body diagrams, developing dynamic equations governing mechanical and electrical systems, identifying and tuning design parameters of under-, over-, and critically-damped systems, and linearizing nonlinear dynamic systems.

Design Revisions

To better meet these course goals, address feedback from the last presentation of the device [5], and create opportunites to implement the haptic paddles in other courses, the haptic paddle design has been modified, as shown in Fig. 2. First, the design of the paddle was modified with cutouts and threaded fasteners to replace press-fits to allow students to assemble paddles each year. While the benefits of this change are minimal for most of the paddle curriculum, the more rigid construction results in improved performance during motor system identification experiments that require spinning large rotational inertias, better meeting the system identification aspects of the course.

The neoprene previously used in the friction transmission exhibited poor creep qualities, and would create 'notches' about the selected equilibrium, resulting in poor performance over extended periods of time, shown on the left of Fig. 2. By replacing this soft neoprene tape (rated to 25% compression at 7 psi) was replaced with a neoprene with a 50A durometer that greatly reduced the effects of creep while still preventing slipping. The solid, $1\frac{1}{4}$" friction drive of the previous design was replaced with a $\frac{5}{8}$" spool held in place by a trantorque, which operates like collet. This increases the continuous force output of the paddle from 3.4 N to 6.1 N and adds functionality to quickly and easily add inertias for system identification experiments.

When fabricating the paddle handle, the pivot point holes of the paddle handle were drilled to dimension, and fixed with a set screw, instead of relying on a split-ring lock washer and an eccentric laser cut hole. This modification improves Z-width and reduces wobble in the transmission. Other changes included replacing the analog differentiation and filtering circuit with digital filter implemented in LabVIEW and the myRIO, which was reduced both time spent on debugging and maintenance.

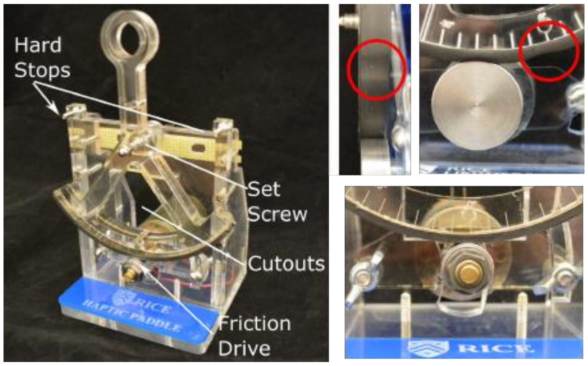

Figure 2. Haptic paddle design changes made to improve maintenance, assembly, and transmission performance (left). Specific changes to the friction drive including stiffer neoprene to reduce creep (circled in red) and higher speed reduction were made to improve haptic performance.

Haptic Performance: Z-Width

While traditional Z-width definitions rely on observing non-passive behavior or 'apparent visual oscillations' [16], low-cost haptic devices like the haptic paddle possess high intrinsic damping and friction in the friction drive transmission that are inherently stabilizing [17] and obfuscate non-passive behavior caused by other nonlinearities like quantization. Further obfuscating these results are the signal noise from the hall effect position sensing and digital differentiation. Therefore, in order to make qualitative comparisons of virtual wall performance, the Z-width presented here attempts to reflect both the stability as well as quality of the rendered wall (signal noise, transmission slippage, or other perturbations reducing quality below a reasonable point). Unsatisfactory passive oscillations were defined as having a variance exceeding 0.008° as measured by the hall effect sensor. While this method posesses limitations for comparison outside of low-cost haptic devices like the haptic paddle, it is sufficient for comparisons between these devices.

In the most recent Rice University Haptic paddle publication [5], an incorrect amplifier gain ($3.18\ \frac{A}{V}$ instead of $1.4\ \frac{A}{V}$) was used to calculate the Z-widths of the two different designs, and so the Z-width experiments were recreated for these paddles, shown in Fig. 3. While the problems associated with the first experiment (slipping between the motor output and the paddle handle mainly in the friction drive, but also present in the capstan transmission, uneven normal forces between the paddle handle and motor output in V2 design due to eccentricities caused by the laser cutter, and in general, high damping caused by friction transmission) are still present, recreating the experiment will reduce inconsistencies in these non-ideal experimental conditions. Each paddle was tested sequentially using the same hall-effect sensor, and the same subject completed all trials. Any further discrepancies between the Z-widths are the result of the variable nature of the transmission designs, and user subjectivity. While friction between cable and motor spool, which is a function of spool and cable surface finish and cable tension, effects the capstan transmission performance, the variations in performance caused by normal force in the friction drive transmissions play a larger role in defining their Z-width. Sensor noise can also be problematic, and was largely held constant for these trials. Furthermore, the subjective nature of this measure of Z-width is highly dependent on grasp pose and user joint stiffness, which are not as repeatable as other implementations of Z-width [18]. Therefore, these results are likely best interpreted in a more qualitative way, to demonstrate that while the capstan transmission offers higher performance, the redesigned friction drive offers performance that is more than sufficient for pedagogic aims. That is to say, by increasing the amount of 'up time' a device has (friction drive does not have to be rewrapped like V1 capstan-cable), and decreasing the perceived/real costs of 'breaking' the haptic paddle, students are more likely to engage with the device and curriculum, instead of spending time resetting laboratory equipment. This extra time spent interacting would hopefully allow more time for reflection and improve learning outcomes [2, 19].

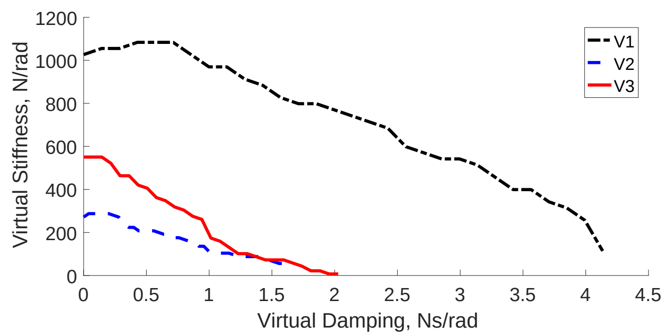

Figure 3. Z-width of the three versions of Haptic Paddles, "V1" [4], "V2" [5] and the new "V3" . While V1 possesses the largest Z-width, the friction drives of V2/V3 greatly increase device 'up time', with the improvement in V3 as a result of the friction transmission modifications.

HAPTIC BALL AND BEAM MODULE

The Haptic Ball and Beam module, shown in Fig, 4, was designed to introduce students to the control and teleoperation of higher order haptic systems and conducting visuo-motor coordination task experiments. A good target experiment to replicate is a visuo-motor training experiment on a similar plant [14]. In this experiment, Huang et al. tested the impact of virtual interaction forces on training for manually controlling a ball and beam. Additionally, students can investigate the effects of haptic guidance, error augmentation, and other methods for encouraging motor learning and skill retention [20].

(a) (b)

Figure 4. As shown in (a), students can teleoperate the ball and beam module, which provides a less abstract way to demonstrate principles of teleoperation. As shown in (b), students can also use the ball and beam module to render torques caused by a virtual ball in order to learn how haptic feedback can influence the learning of visuo-motor tasks by replicating experiments [14] or conducting new ones.

Module Design

With the goal of replicating visuo-motor experiments in a mixed graduate/undergraduate course on mechatronics, cost, availability of parts, and ease of maintenance were high priorities for the module. Thus, the Haptic Ball and Beam module, shown in Fig. 5, was designed such that it could be laser cut out of acrylic and assembled with standard fasteners and adhesive. The estimated cost of a single module given current material prices is \$25.65, with \$16.58 going to the IR distance sensors, and the rest for acrylic and fasteners/adhesives. While the per unit cost of the module is not negligible, especially for a course that would require a large number of plants, it is still orders of magnitude less than commercial plants.

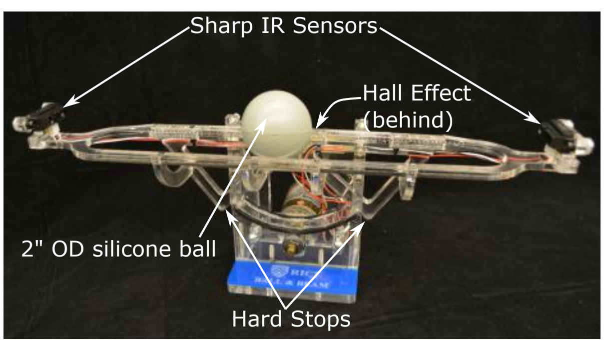

Figure 5. The Haptic Ball and Beam module, a low cost plant designed for bilateral teleoperation and visuo-motor human learning experiments. The ball position and beam angle is measured via two Sharp infrared (IR) sensors and a linear Hall-effect sensor, respectively.

Although the Sharp Microelectronics infrared distance sensors (model GP2Y0A41SK0F) are rated to read distances between 4 cm and 30 cm, they produce increasingly noisy signals as the distance from the detector increases. Thus, to mitigate the loss in accuracy as the distance from the sensor increases, two infrared sensors were placed at either end of the beam. In order to obtain an estimate of the position of the ball, a weighted average of the position reading from each sensor is used, where the relative weights given to each sensor reading are chosen based on the estimated position of the ball at the previous time-step. When used with a low-pass filter, this method allows for the sensing of the position of the ball to within approximately 1 mm.

Interference between the two infrared sensors was an early issue due to the material of the ball and the reflectance of acrylic in the infrared spectrum. Preliminary beam designs placed the infrared sensors in a positions such that the infrared signals could reflect off of the haptic paddle base, causing inaccurate distance measurements. By moving the pivot point of the beam to a location higher on the haptic paddle base, the reflectance of the acrylic became a non-issue. However, interference between the two infrared distance sensors still caused problems when a silicon ball was used due to its apparent translucence in the infrared spectrum. Painting the ball eliminated this issue, although a ball of a different material could also be used.

The final mechanical issue was resonance of the beam during a high frequency motor input, in both on- and off-axis oscillations. These oscillations introduced noise into the angular measurement by the hall effect sensor, greatly limiting the range of stable gains. A combination of a tighter tolerance hole for the beam pivot and Belleville washers on the shaft in order to seat the radial ball bearings greatly reduced the play in the system.

Virtual Model Development

The equations of motion of the ball and beam system are given in Eq. 1 and 2, where m_b is the mass of the ball, m_B is the mass of the beam, J_B is the moment of inertia of the beam, J_m is the moment of inertia of the motor rotor, and τ_m is the torque exerted by the motor on the beam. The total inertia, I, is defined in Eq. 3. Other parameters are defined as shown in Figure 6.

$$\left(m_b\left(1+\frac{2}{5}\left(\frac{R_b}{r_b}\right)^2\right)\right)\ddot{x} = m_b x\dot{\theta}^2 - m_b g sin(\theta) \qquad (1)$$

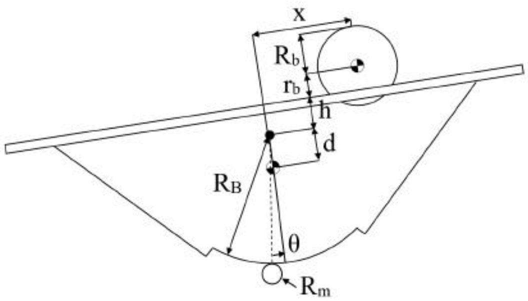

Figure 6. Simplified Haptic Ball and Beam schematic with parameters used to develop the virtual ball model.

$$I\ddot{\theta} = \left(\frac{R_B}{R_m}\right)\tau_m - 2m_b x\dot{x}\dot{\theta} - m_B g d sin(\theta) + \ldots \\ m_b g(h sin(\theta) - x sin(\theta)) \quad (2)$$

$$I = \left(m_b\left(\frac{2}{5}R_b^2 + h^2 + x^2\right) + J_B + J_m\left(\frac{R_B}{R_m}\right)^2\right) \quad (3)$$

Equation 1 can be used to estimate the position of a virtual ball based on the angular position and velocity of the beam. Using the estimated position of the virtual ball, the theoretical torque exerted by the virtual ball can be calculated using the terms including m_b from Eq. 2. Thus, the motor torque required to render the virtual ball is given in Eq. 4.

$$\tau_m = \frac{R_m}{R_B}(-2m_b x\dot{x}\dot{\theta} + m_b g(h sin(\theta) - x sin(\theta))) \quad (4)$$

In evaluating τ_m the effect of the ball on the moment of inertia of the beam (i.e. the m_b term in Eq. 3) is neglected due to the difficulty of evaluating $\ddot{\theta}$ in real time.

The accuracy of the estimation of the ball position using the equations of motion given in Eqs. 1 and 2 was validated anecdotally by comparing the sensed position of a real ball to the estimated position of a virtual ball. In performing the experiment, a physical ball was rolled from one end of the beam to the opposite end and back while its position was sensed using the infrared distance sensors and its position was estimated using Eq. 1. The results of this experiment are shown in Figure 7. The performance limitations of this model are well within requirements for virtual training portions of experiments, or for rendering a virtual ball during bilateral teleoperation.

The motor used with the Haptic Ball and Beam module is the same motor used with the Haptic Paddle, and is able to produce a maximum continuous torque of 0.389 Nm with R_B and R_m taken into account. The maximum torque exerted by the ball in

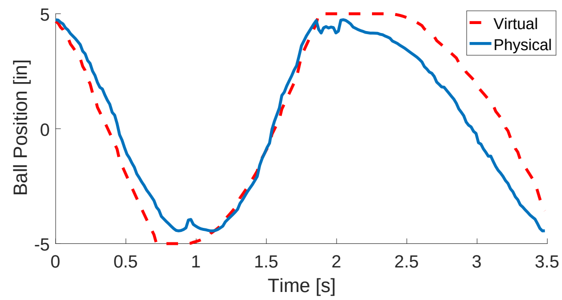

Figure 7. Ball position vs a real-time estimate of a virtual ball position on the beam. Limitations to the accuracy of the model include neglecting the nonlinear sensor response observed at the edges of the workspace, as well as the ball rebounding on the ends of the beam.

the static condition is 9.79 mNm, meaning that the motor is able produce sufficient torque to control the ball and render torques produced by a virtual ball. The module's ability to render a reasonable virtual ball and measure task performance shows that this low-cost Haptic Ball and Beam module could be used to replicate and perform visuo-motor human learning experiments in senior and graduate curriculum.

FUTURE WORK

Further development on the design of the haptic paddle and the ball and beam module will be focused on reducing the cost of materials used without significantly impacting performance. Additionally, we plan to pursue further modules to add to the haptic paddle platform. Continuing pedagogic studies on the effectiveness of physical plants such as the haptic paddle in laboratory curriculum, or the effects of using the same hardware across multiple courses is also a good avenue for developing effective pedagogic tools [21]. Further studies into the best practices in the design and implementation of educational haptic devices is warranted, to explain the limited positive or even negative effects on learning outcomes these devices have had [6]. Without understating the importance of design in the development of successful laboratory equipment, collaboration between experts in the fields of education and mechatronics would likely boost the efficacy of the devices and the accompanying curriculum.

CONCLUSIONS

The Ball and Beam module and redesigned Haptic Paddle at Rice University offer improved performance, as measured by the Z-width and increased 'up time' of the device due to improvements in fasteners and materials. This modular platform that be implemented across multiple courses, spreading equipment costs and creating opportunities for different haptics, mechatronics, and dynamics pedagogic goals. In particular, this ball and beam module has the performance required to replicate and conduct visuo-motor experiments in laboratory exercises in senior/graduate level coursework.

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