Educational Haptics

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Abstract

A major benefit of educational robotics is its hands-on nature. This makes the learning process more compelling for most students, and underscores the connection between science, technology, engineering, and math (STEM) theory and physical reality. Educational haptics takes this premise a step further: haptic devices that provide force and tactile feedback to the student are programmed to generate physical interactions that improve student intuition for STEM subjects. Haptic devices also emphasize the need for interdisciplinary robotics education, and can inspire even very young students to enter STEM fields. In this paper, a variety of methods used by Johns Hopkins University researchers to incorporate haptic devices and simulations into undergraduate, graduate, and grade school curricula are reported.

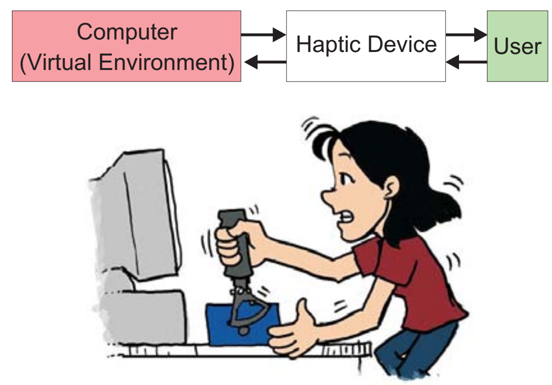

Figure 1: Components of a haptic system.

Introduction

An intuitive understanding of physical systems is key to the success of science and engineering students. Electrical, mechanical, fluidic, and thermal systems each have components that affect system dynamics by storing or dissipating energy in characteristic ways. All too often, students learn how these parameters enter the dynamic equations without fully understanding the role each component plays. Ideally, physical systems would be constructed that allow arbitrary alteration of components and their configuration. By comparing dynamic response, the role of each in the aggregate system could be better understood. Unfortunately, such a system is not practically realizable for use in lecture or laboratory settings. To satisfy the demand for a transformable system, a variety of pedagogical, computer–based simulations have been proposed, e.g. (Bonert 1989; Conley & Kokjer 1989; Lee, Daley, & McKlin 1998).

With most physical systems, our understanding of them comes from some combination of visual, aural, and tactual information. The tacit knowledge gained through such physical interactions is not easily shared between individuals, but thought to be valuable for the process of engineering innovation (Mascitelli 2000). Most computers are equipped to display visual and aural information through a monitor and speakers, respectively. However, for mechanical and thermal systems, our experience and intuition are based on tactual interaction. For example, students know what an underdamped oscillation "feels" like, though a time series of the same motion may appear foreign. Thus, it seems that the lack of tactual feedback from computer simulations limits their pedagogical efficacy. Psychologists have demonstrated the need for different modes of interaction to improve student learning (Bird & Gill 1987; Lowenfeld 1945; Winn 1982). Haptic interfaces are capable of conveying tactual information to augment or replace the visual and aural feedback common to computer simulations (Fig. 1).

The term *haptic* comes from the Greek *haptesthai*, meaning "to touch". Over the last decade, researchers in the haptics community have been developing low-cost haptic devices and corresponding curricula to help undergraduate students connect science, technology, engineering, and math (STEM) theory with physical reality (Richard, Okamura, & Cutkosky 1997; Okamura, Richard, & Cutkosky 2002; Gillespie, Hoffinan, & Freudenberg 2003; Bowen & OMalley 2006). Haptic display technology existed long before that, but most commercial systems are not well suited for educational purposes. Most commercially available high-fidelity devices are too costly and do not provide a transparent view of the device mechanisms. An example of a high-fidelity, multi-degree-of-freedom haptic interface used often in research studies is SensAble Technologies' PHANTOM

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(Massie & Salisbury 1994), which costs approximately US $30,000. The most recent version of this device, the PHANTOM Omni, has lowered the cost of 3-degree-of-freedom haptics to approximately US $2,400. In contrast, there exist less expensive haptic displays for gaming, such as the Logitech Force 3D Pro, which retails for approximately US $70. Although they have been used to provide physical intuition in some undergraduate tutorials (Williams *et al.* 2004), these systems do not have the fidelity or low-level control access needed for many educational simulations. In this paper, we describe our solution for low-cost, high-fidelity educational haptics, discuss the pedagogical efficacy of classroom haptics, and illustrate a variety of educational applications.

Haptics in an Undergraduate Curriculum[1]

This section presents the application of haptics in an undergraduate dynamic systems course. To make haptic interfaces accessible to small groups of students in a large undergraduate course, the device must be low cost and relatively small. A rugged, single-axis force-feedback joystick called the haptic paddle (Fig. 2) can be assembled for less than US $30 (assuming some surplus components) and is controllable by a standard PC. The original design for this interface at Stanford University involved third author Okamura, Mark Cutkosky, Jesse Dorogusker, Christopher Richard, Bart Nielson, David Hsu, and Brad Levin (Richard, Okamura, & Cutkosky 1997). The primary differences between the haptic paddle and high-end haptic devices are degrees of freedom and power.

The operation of the device is simple. As a user takes the handle of the haptic paddle and moves it from side to side, the position of the handle is sensed. Based upon the position and velocity of the handle, various amounts of force are reflected back to the user. The motor interfaces with the handle through a capstan (cable) drive. Device design and parts information, as well as control code and curricula, are available to the public at http://www.haptics.me.jhu.edu/research/paddle/. Haptic paddle kits have been provided to over a dozen robotics educators and researchers internationally. A future improvement to the haptic paddle is to provide a USB and/or Firewire interface, in lieu of the parallel port and PCI cards used previously.

To explore methods for integrating haptic education at the undergraduate level, the curricula of junior-level dynamics systems courses at Stanford University and Johns Hopkins University were designed to make heavy use of the haptic paddle. Because of the paddle's low cost, students were are able to assemble, model, identify, calibrate, and program the device in small groups. Lab sessions held throughout the semester revolve around the exploration of dynamic mechanical systems (Okamura, Richard, & Cutkosky 2002).

[1] This concept was first proposed in (Richard, Okamura, & Cutkosky 1997), and much of the text in this section is taken from (Okamura, Richard, & Cutkosky 2002). The pedagogical efficacy data is new.

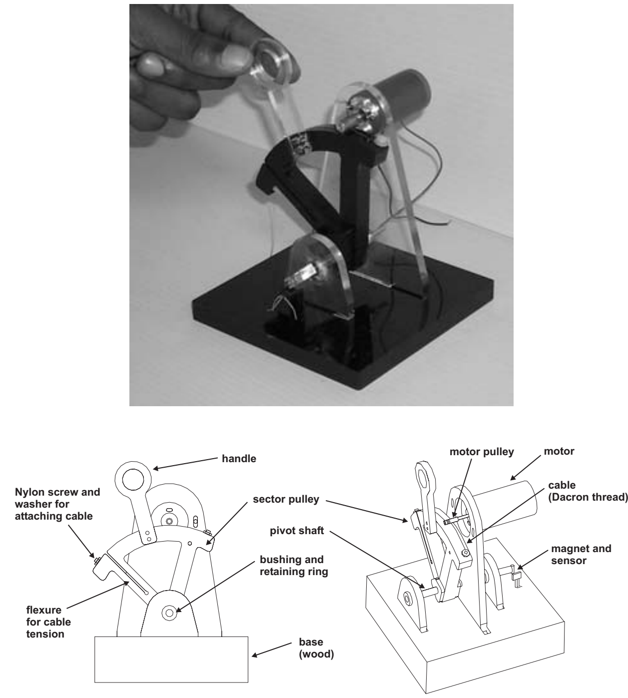

Figure 2: The haptic paddle.

System modeling, identification, and calibration

In all dynamic systems courses, students learn to generate the equations of motion governing first- and second-order mechanical systems. As a laboratory tool, the haptic paddle provides a nice example of a typical second-order mechanical system upon which students can experiment. To calibrate the system, a system model must first be obtained. Next, the numerical values of parameters in the model are identified.

The dynamic model of the haptic paddle is similar to that of the classic inverted pendulum. As an early objective of the course, students were asked to derive the equation of motion governing the paddle's position using Newton's law or an equivalent method.

The derived equation includes parameters for equivalent inertia, equivalent damping, and equivalent stiffness that need to be identified. The paddle's equivalent inertia is determined by combining the inertia of the sector pulley, measured using the bifilar pendulum method, and the reflected inertia of the rotor, calculated using manufacturer specifications and the gear ratio. The equivalent damping of the motor is identified through a least-squares fit of motor spindown data to an exponential decay objective-function. Because of the mechanical construction, Coulomb friction is assumed to be negligible. The equivalent stiffness of the system, which arises from its inverted-pendulum configuration, is calculated using the measured pulley center of mass and some trigonometry.

Next, the motor torque output and position sensor must be calibrated. Motor torque and speed constants are measured to estimate the maximum force the paddle can apply (approximately 7.5 N). Assuming a linear motor model, the

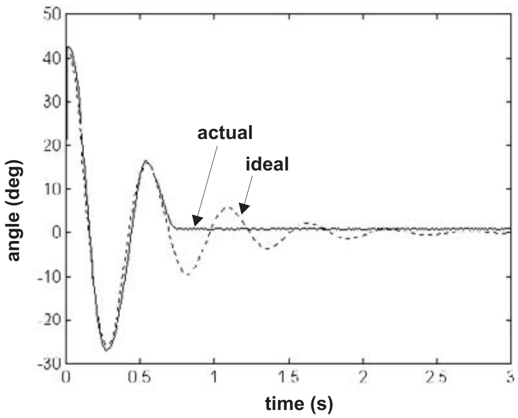

Figure 3: Homogeneous response of the haptic paddle with proportional-derivative feedback control versus an ideal second-order system.

students can then determine the transfer function for applied voltage to force. The Hall-effect position sensor is calibrated by fitting a cubic polynomial to the sigmoidal sensor output.

System response and feedback control

Connecting the device to a computer and using feedback control shows that the haptic paddle is much more than the sum of its parts. By examining the equation of motion, students determined the poles of the system. Since one of the poles had a positive real part, the system was not stable. However, the system can be stabilized through the addition of proportional-derivative feedback control. The students calculated the equivalent poles with feedback control and determined the values of the feedback parameters k_p and k_d needed to satisfy stability requirements. The haptic paddle was then connected to the computer through an amplifier circuit. Control software was designed that allowed students to tune the the control gains while they felt (holding the paddle handle and moving it around), or saw (deflecting the paddle and releasing it, or adding a step input) the effect on system response.

The haptic paddle control software was also configured to take several seconds of position, velocity, and input force data. Students were asked to tune the feedback gains to make the haptic paddle respond to a step input or initial condition (the homogeneous response) like a classic, lightly damped second-order system. From position data taken during the response, students were asked to determine the corresponding dimensionless damping parameter, ζ, and damped natural frequency, w_d. An ideal second-order system response was then plotted over the actual haptic paddle data. The students observed that the plots of actual data did not precisely match those of an ideal second-order system due to Coulomb friction (Fig. 3).

Using the paddle to explore virtual systems

The haptic paddle can also be used to interact with an unlimited number of "virtual systems." During the final stage of the course, students were able to make their haptic paddle behave as if it were a virtual spring, or a virtual dashpot. By adjusting the magnitudes of the virtual spring and damping constants, students could immediately feel the effects of greater stiffness and greater damping. Moreover, by experimenting with negative values for the spring and damping constants, students gained an immediate intuition of how such values make a system unstable. Several more complex virtual environments were also designed and simulated (Fig. 4), which allowed students to excite different modes of multi-degree-of-freedom systems. In summary, the paddles allow students to interact with ideal, changeable physical systems that exist only in the virtual world.

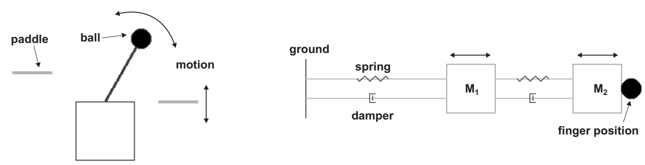

Figure 4: Virtual dynamic systems: (Left) Inverted pendulum with friction that can be manipulated by two cooperating paddles. (Right) Two-degree-of-freedom second order dynamic system whose model frequencies can be excited through paddle motion.

Quantifying pedagogical efficacy

It is expected that hands-on laboratory sessions that incorporate haptic interfaces will improve students' tacit knowledge of dynamic systems. A set of laboratory sessions that feature the haptic paddle were designed and refined during 2002 and 2003 at Johns Hopkins University. To quantify the effectiveness of these labs, a study was performed during the following two years. Each semester the dynamic systems class had two lab sections with roughly 20 students in each. There were five lab sessions during the semester and each included a quiz either before or after the hands-on exercises. One section would take the quiz before the lab and the other section took the quiz after, in alternating order. Pre- and post-lab quiz results were later compared.

The study suggests that the lab exercises significantly improved student understanding of course material. On average, students quizzed after the lab scored 10% higher (M_1 = 0.59, SD_1 = 0.22, M_2 = 0.64, SD_2 = 0.20, $p<0.05$). An even greater increase in performance was observed for quizzes accompanying the third and fifth labs, which focused on tacit knowledge. Fig. 5 provides the distribution of combined scores for these two labs. Quiz scores among the post-lab group were over 20% higher than the control (pre-lab) group (M_1 = 0.49, SD_1 = 0.26, M_2 = 0.59, SD_2 = 0.21, $p<.01$).

Other indications also suggest that haptic education was successful. Students were enthusiastic about having their own high-performance electromechanical systems. Many students personalized their paddles and even made small design modifications to improve performance. Once the kits were assembled and connected to computers, many students

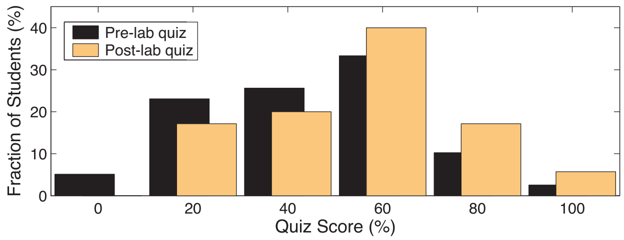

Figure 5: Quiz scores for select laboratory sessions using the haptic paddle at Johns Hopkins University. Higher quiz scores were associate with quizzes taken after performing a haptics-based laboratory.

who had already been taught about resonant frequencies, feedback, stability, etc. in the lectures were clearly surprised at how small changes in feedback gains could have a profound effect on system behavior. As the students compared their actual and ideal step responses and estimated the dimensionless damping and resonant frequency of their haptic paddle, it was evident to the instructors that many of the students were fully understanding these concepts for the first time.

Haptics in a Graduate Curriculum

Robotics is inherently an interdisciplinary research area, yet it is rare to find robotics courses that mix programming, experiments, design, artificial intelligence, and device mechanics/dynamics. The JHU graduate course "Haptic Systems for Teleoperation and Virtual Reality" was developed specifically with an interdisciplinary audience in mind, including students from Biomedical Engineering, Computer Science, Electrical Engineering, and Mechanical Engineering. The course project encourages teams with mixed backgrounds, as each major can impart essential knowledge to the team. Biomedical engineers can provide background information on neuroscience needed for human psychophysical studies and tissue models for surgical simulation. Computer scientists can emphasize real-time programming and haptic rendering (analogous to graphics rendering). Electrical engineers are usually more experienced with control design and systems and signals analysis. Finally, mechanical engineers provide needed expertise in hardware design and dynamic modeling. Over the three years this course has been taught, approximately 50% of course projects have resulted in refereed conference papers.

In September 2006, the IEEE-RAS/IFRR School of Robotics Science on Haptic Interaction was held in Paris, France (http://www.cim.mcgill.ca/ haptic/summerschool/). The robotics "summer school" series intends to provide a high-quality, interdisciplinary, international education in a chosen theme for each year. This occurs through interaction with researchers in an informal classroom setting as well as through joint student exercises and hands-on experiments. At the summer school, students were allowed approximately 8 hours to develop and execute a hands-on haptics project, which were then available for demonstrations at the end of the school (Fig. 6). We brought 9 haptic paddles with as-

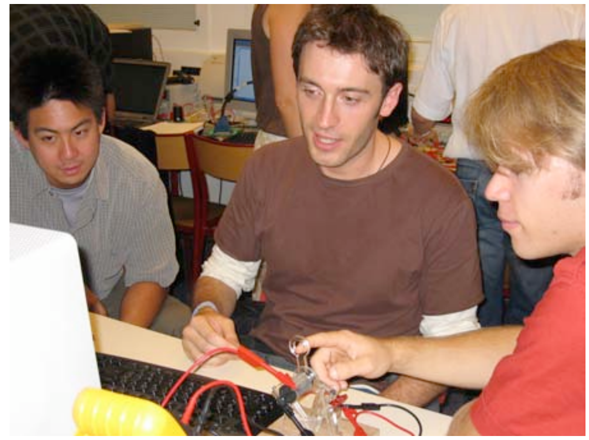

Figure 6: Students at the IEEE-RAS/IFRR School of Robotics Science on Haptic Interaction assembled, programmed, and found creative uses for one-degree-of-freedom haptic paddles.

sociated computer boards and amplifiers, as well as basic control code. Other researchers brought high-end haptic devices, including Force Dimension's Delta, MPB Technologies' Freedom 6S, Sensable's PHANTOM Omni, and Haption's Virtuose 6D. Approximately half the project teams used haptic paddles, and the other half used high-end devices with existing C++ haptics libraries, such as CHAI 3D (http://www.chai3d.org/).

In the first four hours of the project, the haptic paddle teams assembled and calibrated their devices, and demonstrated a basic level of functionality. For teams working on virtual environments and low-level controls, this was a simple virtual wall (a unilateral spring). For teams doing teleoperation, this was a simple position-exchange bilateral controller. In the final four-hour period, each team developed a more complex controller or demonstrated a psychological/psychophysical behavior. Some example controller projects include: (1) friction modeling and compensation to improve device transparency, (2) teleoperation with position and force scaling, and (3) teleoperation with time delay. The psychological/psychophysical projects included: (1) a haptic illusion in which lateral forces convey bump "height", (2) a psychophysical experiment to determine human bump detection thresholds, and (3) a psychological experiment in which users were asked to "shake hands" with an imagined person via the paddle in a manner determined by their emotions toward the imagined person (handshake motions were recorded for later analysis and playback). The breadth and sophistication of the projects was very impressive; this underscores the effectiveness of simple one-degree-of-freedom high-fidelity haptic devices in encouraging interdisciplinary education and innovation.

Haptics in K-12 Outreach

Haptic devices are excellent mechanisms for encouraging excitement about engineering in K-12 students (Williams, Chen, & Seaton 2003). Most children are familiar with hap-

Figure 7: Demonstration of a haptic device and physics-based virtual environment at an elementary school in Maryland, USA.

tics already, in the form of the "rumble pack", which is a hand-held video game controller that vibrates to reflect certain events in the virtual environment. But it is not until they feel high-fidelity force feedback during simulations of dynamic systems and 3-D shapes that they understand the potential of haptics *and* gain knowledge about physical principles. A popular demonstration among elementary school students and teachers alike involves bouncing a virtual ball up and down using a horizontal, soft, virtual paddle under the acceleration of gravity. The student shown in Fig. 7 is using a commercially available 2-degree-of-freedom haptic device, Immersion's IE2000, to bounce a ball. She is able to change the gravitational constant to make it feel as if she is bouncing the ball on earth, the moon, or Jupiter. The key insight to be gained from this demo is that weight is not the same as mass/inertia. The student feels the same inertia of the ball when trying to accelerate it using the paddle on all planets, but the ball's motion in free space is significantly affected by the gravitational constant.

Another way to use haptics in education is to bring the devices into the public arena. An ideal mechanism for this is a museum installation that uses haptics. There could be many purposes for such an installation. In (Lazzari *et al.* 2001), haptic devices allowed patrons to "feel" works of art that typically have a "do not touch" sign. However, the goal of our work is to improve math, science and technology education, so the device to be created will display interesting scientific or mathematical phenomena to the patron. Several museums contain modified scales that are programmed to display the weight of patrons on various planets. It would be much more compelling to allow patrons to *feel* what it would be like to bounce a ball up and down under the effects of gravity on different planets. Other systems could demonstrate electromagnetic systems, forces on a satellite orbiting the moon (with a push button to apply jet forces), and manipulation of nanoparticles (Jones *et al.* 2003). To date, we have redesigned the haptic paddle to create a larger, more robust version. The local museums popular for young children and most likely to host the final display are the Baltimore Museum of Science and Port Discovery. Working with a curator, we plan to develop a final installation concept and find a method to assess the effectiveness of such public haptic displays. Metrics may include number of uses, time spent per user, task execution in the virtual environment, or questions posed after the demonstration.

Conclusion

Methods for integrating haptic technology into various classroom settings have been described. Hopefully, this work will provide a foundation for the proliferation of haptics in a wide variety of undergraduate courses, graduate robotics courses, K-12 demonstrations, and public spaces such as museums.

Acknowledgments

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