Haptic Interaction for Hands-On Learning in System Dynamics and Controls

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Introduction

Every student entering the control engineering classroom brings years of experience in the hands-on practice of controls, earned through the control of the motions and actions of his or her own body and the control of objects in the environment. Much of this control experience has been subjected to conscious observation and experimentation, yet this expertise is very seldom leveraged when teaching control theory in the classroom. Certainly, tying theory to existing practical knowledge is a process containing many potential pitfalls. But if concepts in control theory can be correctly and appropriately tied to personal experience and intuition in human motor control, then our effectiveness as control educators could be significantly increased. By harnessing this intuition, the mathematical symbols manipulated on paper might be integrated with intuitive, long-lasting memory and used to develop good engineering judgement.

Haptics is an emerging technology and field of research that can be brought to the controls classroom and used as a means to connect theory to existing intuition. The word *haptic* is used to describe the tactile and kinesthetic senses, which mediate mechanical interaction between each person and his or her environment. A haptic interface is a motorized linkage or robotic device designed to connect a human user to a virtual environment so that virtual objects can be touched and manipulated. Through a haptic interface, students can go beyond passive observation to actually reach in and interact with controllers and simulated physics. We have been using haptic interfaces to complement existing exercises and teaching tools in system dynamics and controls education and to encourage the development of appropriate relationships between theory and prior experience of motor control.

Interaction with Control Laws and Dynamical Models

Each haptic interface is itself a control system containing a motor and a motion sensor, and it is coupled to a digital or analog computer through an appropriate interface. These aspects are worth study in themselves in the controls classroom and can be used as the basis for numerous control design problems and homework assignments. The exciting opportunity offered by haptic interfaces, however, is to allow students to manipulate virtual objects whose behaviors derive from the control laws that the students program. For example, a haptic interface can be placed in position control using position feedback and proportional control. The student then pushes and pulls on the interface and recognizes a virtual spring: a force proportional to its displacement. The error signal takes on meaning as the relative displacement of the two ends of a spring: one end is tied to the desired position and the other tied to the actual position of a reference tracking controller. Likewise, derivative control feels like a damper. Integral control, which has no simple mechanical analog, will be recognized by feel as a force proportional to accumulating error. A student can clearly feel that integral control is a straightforward means to drive down steady-state error.

Complex dynamical systems can also be modeled and simulated. Through the haptic interfaces, students have the opportunity to manipulate the mathematical models they have built and to observe system response in a direct, dynamical, and physical manner. We have found that for many students, haptic interaction brings to life the static graphs and equations introduced in lecture.

Cost Effectiveness

An important consideration in educational haptics is the development of low-cost laboratory exercises that minimize load on teaching staff and facilities. With creative designs and effective use of resources, costs can be minimized without sacrificing performance. Devices can be fabricated from low-cost materials and components using rapid prototyping tools often found in academic environments. The cost of the single and two-axis devices that we have developed ranges from US$30 to US$600 dollars. We have also found that haptic device design presents an excellent undergraduate research opportunity. Undergraduate students employed during summers at both The University of Michigan and Johns Hopkins University have iterated device designs and continually improved pedagogy.

In this article, we describe our experiences, results, and further plans involving the use of haptic interfaces for teaching systems dynamics and controls in the mechanical engineering and electrical engineering departments at The University of Michigan, Johns Hopkins University, and Stanford University. Our discussion begins with a brief background in the pedagogy of interactive learning that motivates much of our work. We present the electromechanical and software designs of three devices and corresponding projects that we have used in the controls classroom. In continuing work, we are investigating the use of haptic interfaces for mathematical and science education by transferring basic propositional concepts to tacit, physical examples that can be explored by touch within a virtual environment.

Pedagogy of the Haptic Learner

Modern conceptions of learning and classroom pedagogy suggest that students differ in their cognitive style, and therefore in the ways in which they acquire information [1], [2], [3]. Some students are *kinesthetic* or *"haptic"* learners. A haptic learner embodies knowledge in the experience of motion in his or her own body rather than in verbal or visual abstractions used by the visual or verbal learners. By addressing the sense of touch, haptic interfaces are promising tools for helping students with haptic cognitive styles understand abstract concepts. Research has also demonstrated the need for using different modes of interaction to improve student learning in general [4]. Further, cognitive psychologists have viewed the learning process as a situated act, where the perceived environment plays a strong role [5], [6], [7]. Thus, perception and embodied experience become tools for reasoning that are just as important as strict logical inference processes such as identifying variables, collecting data, constructing formal mathematical models, and drawing conclusions. As Reiner [6] points out, a novice tennis player can hit the ball without knowing anything about the mathematically formulated laws of projectile motion. Instead, there is implicit knowledge about how to move the body in order to obtain an appropriate response. In educational settings, examples such as playing tennis or kicking a football are often verbally described to help students obtain a physical intuition for mathematical and scientific concepts.

Simply watching a tennis player hit a ball will indeed provide an experience beneficial to learning, as does listening to an instructor explain how to hit a ball. However, nothing can replace the act of going through the motions of hitting the ball, feeling the forces between the ball and racket, and observing the response. A key notion here is that feeling the contact forces is essential to learning the task. Previous work in cognitive psychology underscores the importance of motion and interaction; Johnson [8] and Lakoff [9] suggest that the understanding of a new situation is profoundly impacted by bodily experience and object manipulation. There is also preliminary evidence [10] that haptic learning can assist in cross-modal retention, i.e. words “felt” can be recognized later when displayed visually or aurally.

Virtual environments that aid comprehension of a basic concept or principle must allow students to modify parameters and then observe what properties of the environment change, and which remain constant. Consider the example of a haptic simulation that allows a student to bounce a ball on his or her virtual “hand,” as shown in Figure 1. The student can then change the mass property of the ball or the gravity property of the virtual environment. By entering in the gravitational constant for the moon, we can demonstrate what it would be like to manipulate an object in lower gravity. Anecdotal evidence from using this simulation has shown that even adults are surprised by how something can still feel massive due to inertia, despite low gravity.

In previous work, the use of haptics in education has primarily focused on training, where specific tasks, such as surgery [11], [12] or flying an airplane [13], are practiced in a virtual environment. The aim in these applications is generally to teach manual skill or task execution rather than teach concepts. A specialized form of educational haptics is in the area of scientific visualization. For example, project GROPE at the University of North Carolina [14] allowed research chemists to feel the forces of molecular docking through a large, six degree-of-freedom robot. Some haptic interfaces are also used in graduate-level engineering and computer science courses, but primarily as part of robotics or virtual reality courses, where the haptics is the

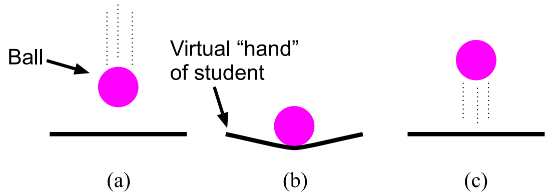


Fig. 1. The “Bouncing Ball” virtual environment. In this example of an educational virtual environment, the student observes a resilient paddle (at the position of the operational point of the haptic device) and a ball on the computer screen. The student can bounce the ball up and down, and also modify the mass of the ball and the gravity present in the virtual environment. The sequence of events in a typical bounce are: (a) the ball falls down towards the paddle, (b) the student feels the force of the ball against the paddle while manipulating the paddle to throw the ball, and (c) the ball loses contact with the paddle. Such an environment can be used to teach students about the difference between mass and weight, the effectiveness of human muscle control in system stabilization, and the design of controllers that catch a ball in minimum time.

topic rather than a tool to illustrate other concepts. Two examples of research in haptics for education include a web-based touch display for accessible science education [15] and a virtual environment that allows students to easily construct and understand vector fields [6].

The Haptic Interface: Coupling Two Control Systems

A haptic interface can be considered a *plant* and the computer a *controller* just as the human body is a kind of plant under the control of the central nervous system (CNS). When a user grasps the haptic interface, another feedback loop is closed: the neuro-mechanically coupled CNS and body are mechanically coupled to the electro-mechanically coupled haptic interface and computer, as shown in Figure 2. The objective of the computer controller is to cause the haptic interface to display the behavior of a virtual object, so that is takes on dynamics other than its own inherent dynamics. The performance of a haptic device and control system is typically judged on the extent to which it can render stiffness, damping, or inertia effects in its powered state that are significantly different than those inherent to its un-powered state. With discontinuous or switching control laws, the haptic interface can display the effects of changing contact conditions and arbitrary dynamical behavior. The controller is often formed from a numerical differential equation solver, so that the dynamical behavior embodied in the equations of motion of the target virtual object becomes the basis for the force/motion relationship imposed through the haptic interface on the user.

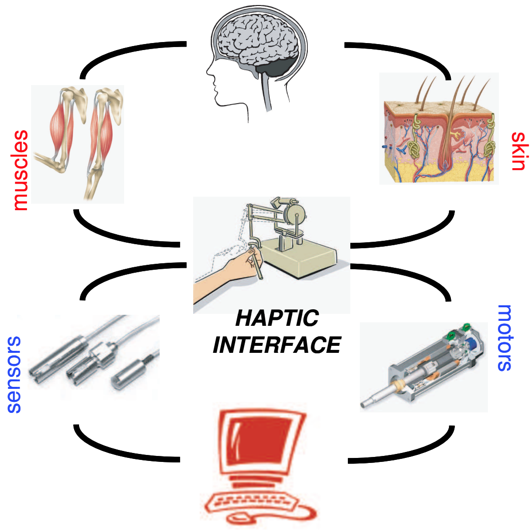


Fig. 2. Components of a haptic control loop. The haptic device serves as a physical link between the human operator and a representation of a virtual environment. Ideally, a virtual environment model that is programmed into the computer and rendered through the haptic interface produces an appropriate and corresponding internal model in the mind of the human operator.

Although Figure 2 might be interpreted as a block diagram, the arrowheads on the connecting lines were left off intentionally since causality is not necessarily restricted in the force/motion relationship imposed by a virtual object (or for that matter, physical object) on a user's hand. Causality, or the specification of whether force is imposed and motion a response or motion imposed and force a response, is specified by the physical system modeler. The design of the haptic interface, however, is usually based on the motor acting either as a force source or motion source. When the motor acts as a force source, the haptic interface is called an "impedance display" and the sensors are usually motion sensors. When the motor acts as a motion source (possibly under the control of an inner feedback loop,) it is called an "admittance display" and a force sensor is usually included in the design.

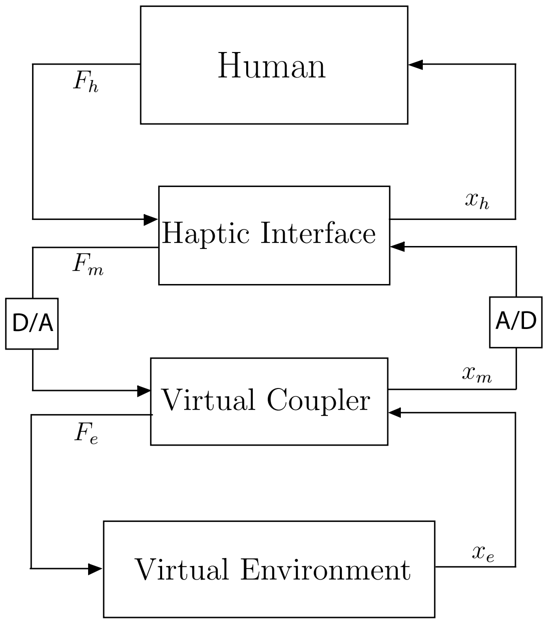


Fig. 3. Block diagram for haptic rendering. A coupled dynamic system is formed by the combination of transfer functions representing the human user, the haptic interface, and computer-generated force/motion relationships (consisting of a virtual environment and a virtual coupler designed to maintain system stability).

As mentioned above, the various components in Figure 2 form a coupled dynamical system whose behavior depends on the force/motion relationship imposed by each component. Figure 3 shows these components interconnected in a block diagram, where the additional indication of causality has been made. This is an impedance display device, where the human operates on the velocity v_h (common to the finger or hand and device end-effector) to produce the force F_h imposed on the haptic device. The haptic device is a two-port that operates on the force F_h imposed by the human and the force F_m produced by its motors to produce the velocities v_h and v_m. Usually, by careful transmission design, v_h and v_m are the same, and measured with a single encoder. Intervening between the human and haptic device, which exist in the continuous, physical world, and the virtual coupler and virtual environment, which exist in the discrete, computed world, are a sampling operator and zero-order hold. The virtual coupler, a common tool for rendering dynamical virtual environments through an "impedance display" interface, is shown as a two-port that operates on velocities v_m and v_e to produce the motor command force F_m and force F_e imposed on the virtual environment. Forces F_m and F_e are usually equal and opposite. Finally, the virtual environment is shown in the forward dynamics form, operating on applied forces F_e to produce response motion v_e. The virtual environment is realized using real-time numerical solution of a set of differential equations. For example, the virtual environment model might be written in state-space form using state x, state transition function f, and output function g as

$$\dot{x} = f(x, F_e) v_e = g(x, F_e). \tag{1}$$

Naturally, the haptic device may use motors on its joints, so the task-space command forces F_m are first transformed into joint-space motor commands through the manipulator Jacobian.

When we use haptic interfaces for teaching system dynamics or controls, we generously use these block diagrams and their variants in lecture. We find that the generalization of the prototypical reference tracking controller with disturbance rejection to haptic rendering with the goal of imposing desired force/motion relationships is a very valuable objective that can be taken up toward the end of the course. We also find that the concepts of physical equivalents like the proportional controller/virtual spring are encapsulated very conveniently in the haptic interface problem. Generalization from proportional control to differential equation solver nicely ties together concepts in controller design and dynamical system modeling. Whereas control engineering is essentially a design activity, it is always important for the student to remember that the dynamical model of the plant is not set in stone. It is subject to assumptions and its referent may be amenable to design modifications.

Device Designs

A haptic interface may be thought of as a computer peripheral, but unlike a mouse, keyboard, or computer monitor, a haptic interface functions simultaneously as an input and output device. By creating certain force-motion relationships, a haptic interface supports a type of human-computer interaction that may be used to supplement or even replace traditional forms of human-computer interaction based on the graphical user interface. In our work, we use force-feedback haptic interfaces rather than tactile array or vibrotactile haptic interfaces. Tactile interfaces pose a significantly greater design and fabrication challenge since they require a distribution of forces on the skin. Also, vibration feedback (used, for example, in Logitech/Immersion's iFeel™Mouse) is simple in that it does not require forces to be "grounded," but it limits the vocabulary of interaction. To date, a variety of force feedback interfaces have been developed by various researchers and a few have been commercialized for the academic, medical/surgical training, and gaming/arcade markets [16]. The device most often encountered in academic haptics or robotics laboratories is a three-axis device from SenseAble Corporation called the PHANToM™[17].

Haptic interfaces were first implemented as a vehicle for teaching system dynamics and control in 1998 by Mark Cutkosky and his former students Allison Okamura and Chris Richard at Stanford University [18]. Their device, called the "Haptic Paddle," is a single-axis motorized joystick with a workspace of 70 degrees. Students would move the handle back and forth within the 14 cm arc-shaped workspace and feel reaction forces up to 7.5 N in either direction.

Okamura has further developed the Haptic Paddle and used it in courses in system dynamics and robotics at Johns Hopkins University. A recent extension of the original design, called the "Snaptic Paddle," allows multiple devices to be snapped together to form more complicated mechanical linkages. Gillespie and his students have designed two single-axis and various versions of a two-axis device for instructional purposes at The University of Michigan. These devices supply several options within the cost versus strength and cost versus workspace size trade-offs.

Single-Axis Devices

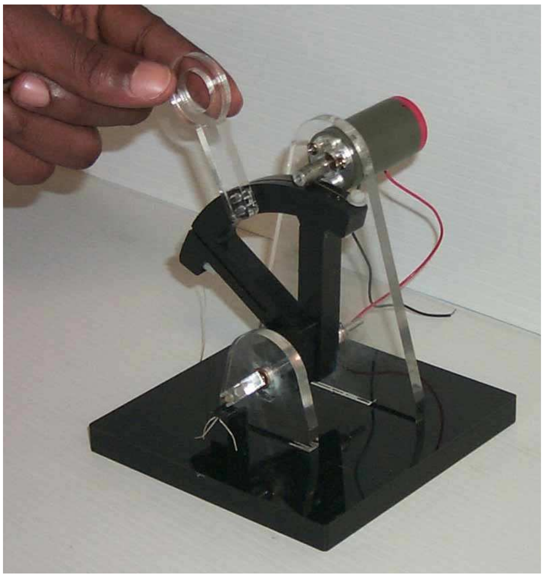


Fig. 4. The Haptic Paddle. This one-degree-of-freedom device was the first haptic interface developed specifically for the purpose of teaching dynamic systems and controls. Students in courses at Stanford University and the Johns Hopkins University have modeled the dynamic parameters of the device components, assembled and developed linearized models of the complete device, and then applied feedback control to modify closed-loop system behavior.

The Haptic Paddle, shown in Figure 4, is based on a precision brushed DC motor acting through a capstan transmission (a pair of pulleys that roll without slip by virtue of a cable wound several times around one pulley and anchored to the other). A calibrated Hall effect sensor and rare-earth permanent magnet provide angular position feedback. The structural components are laser-cut acrylic, and the pivot uses a steel shaft and brass bushing. The motor is driven by a linear amplifier based on a LM675 power op-amp. The total cost for each Haptic Paddle is approximately US$30.

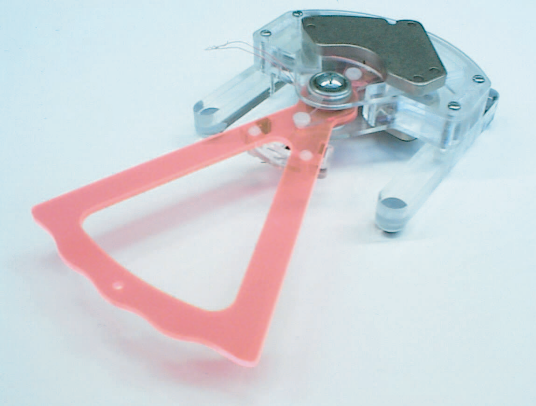


Fig. 5. The iTouch device. This one-degree-of-freedom haptic interface was inspired by the Haptic Paddle, but uses a voice-coil type actuator built by hand and an analog computer for feedback control. This device has been used at The University of Michigan in both undergraduate and graduate dynamic systems and controls courses.

Figure 5 shows a single-axis device, called the "iTouch" developed at The University of Michigan. The iTouch was inspired by the Haptic Paddle, but rather than employing an off-the-shelf DC motor to produce the force, the iTouch employs a voice-coil motor built from scratch. The armature is wound by hand with magnet wire and the magnetic field is set up using surplus magnets normally used in disk-drive manufacture. The hand-wound armature resolves the uncertain availability at surplus-supplier prices of the high-performance DC motor required to construct the Haptic Paddle. In contrast, the disk drive magnets (while also surplus), are generally widely obtainable, and the iTouch design can be easily modified to incorporate whatever magnets are on hand. Otherwise, the iTouch design is much like the Haptic Paddle: it is fabricated from laser-cut acrylic and features a hall-effect sensor for position feedback (two neodymium magnets are arranged in a push-pull fashion to double the signal and increase linearity).

For the motor, the iTouch uses four neodymium magnets arranged to create two adjacent magnetic fields oriented in opposite directions. The armature containing the magnet-wire coil is sandwiched between two flanged roller bearings, providing 30° of rotation. By winding our own motor and configuring it as a limited angle torquer, we have eliminated the capstan-drive transmission upon which the Haptic Paddle is based. The hand-wound armature is barely viewable behind the magnets in Figure 5. The elimination of the transmission adds a great deal of reliability to the iTouch motor.

The fact that assembly requires the winding of the armature is actually a feature as far as the pedagogical aims of our course are concerned. Our system dynamics course includes most students' first introduction to motors. We hand out the unassembled iTouch kits along with a 30 m length of magnet wire and ask each student team to build up their motor according to printed instructions (a process which takes about 2 person-hours). We have found that this exercise significantly enhances the lecture that covers the physics of the motor and generator. The iTouch interface has a peak torque of 0.2 Nm which produces 2.5 N at the handle. It has a motor constant of 0.126 N/Amp and its cost is US$20 per unit.

In a system dynamics course, building a mathematical model of the Haptic Paddle or iTouch device from first principles can be easily integrated into lecture and homework assignments. Referring to the electromechanical schematic shown in Figure 6, the laws of Farraday and Lorentz are used to introduce the relationship between winding current i and torque τ_m acting on the armature and the relationship between armature angular velocity ω and back-emf voltage V_{emf}.

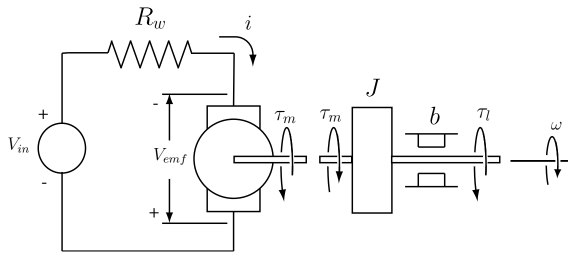


Fig. 6. The electromechanical schematic used to develop a model of the iTouch motor. The internal torque τ_m is shown acting on the ideal motor element and the rotor inertia J and viscous shaft damping b. The load torque applied to the motor is τ_l.

Kirchoff's Voltage law is used to relate the input voltage V_{in}, the current i and the winding resistance R_w, and the back-emf voltage V_{emf} (winding inductance has been neglected in this schematic). Newton's law is invoked to relate τ_m, the load torque τ_l, the bearing viscous load of damping coefficient b and the rotor inertia J. Equations are combined to produce two transfer functions relating the Laplace transforms of V_{in} and i to the Laplace transforms of τ_l and ω. A model of the Haptic Paddle also includes the capstan drive transmission. That model can then be used to show that the inertia presented by the device to the user includes that of the motor multiplied by the mechanical advantage squared.

To serve as the prototype "product" in which to embed a controller, and to provide the context for realizing and testing product function within a course on embedded control, we designed "The Haptic Box", shown in Figure 7. The cost and function limitations are rather different from those that governed the development of the iTouch and Haptic Paddle. Each box is US$600, and only 15 units have been built in contrast to the approximately 100 Haptic Paddles and iTouch devices in existence today. The Haptic Box features commercial linear amplifiers with PWM input and 6 Amps of peak current drive. For feedback, The Box features a 1024 count per revolution encoder. A switching power supply is also incorporated into the

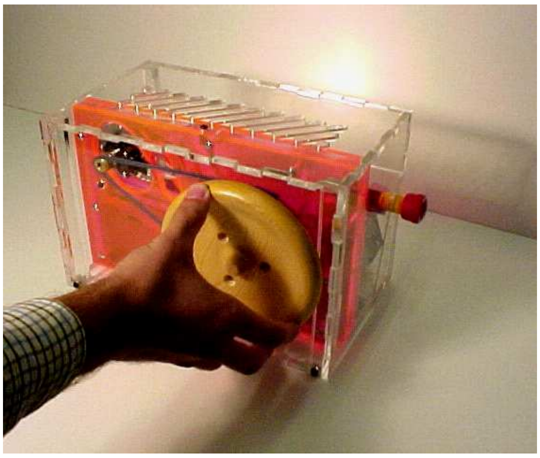
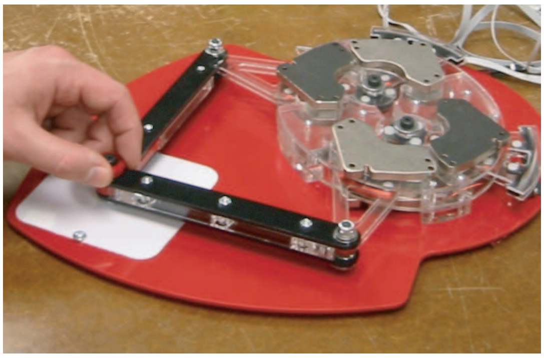


Fig. 7. The Haptic Box. This single-axis device was created for an embedded controls laboratory at The University of Michigan, so the design goals were quite different from the Haptic Paddle or iTouch devices. The Box has infinite workspace and higher torque output than previous devices, and it serves as a prototype product in which the students can embed a controller to create certain virtual environments. Popular projects pursued at the culmination of the embedded controls course have been driving simulators and "Pong" games with force-feedback.

package so that the box plugs directly into the wall. A single ribbon cable connects the Box to the embedded controller evaluation and interface boards. The drive for the Box is a RE35 35mm diameter brushed Maxon motor rated at 90 Watts. A 10 cm diameter wooden wheel is provided for the users to grasp. The wheel is driven from the motor with a 7.1:1 transmission in the form of a pair of Berg sprocket gears and a cable-chain.

Two-axis Devices

The photograph on the left in Figure 8 shows the first version of a two-axis device, called the "uTouch" developed at The University of Michigan. It is a 5-bar linkage based on four iTouch motors with bearings at the joints. (Two iTouch motors are arranged to work in tandem on either base link to double the force capability.) Rather than hall-effect sensors, the uTouch has two linear encoders arranged with the codestrip flexed in an arc that is centered at the pivot.



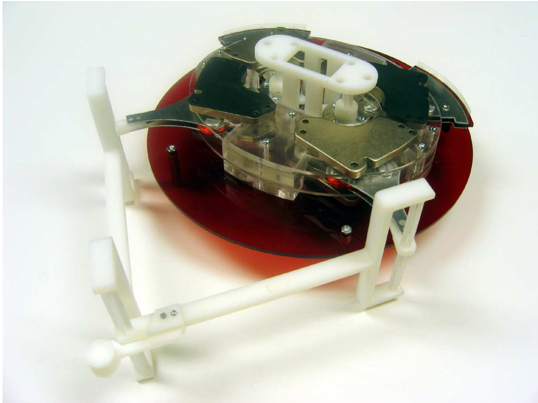


Fig. 8. The uTouch (left) and cTouch (right) devices. The additional degree of freedom allows for more sophisticated modeling and control exercises in comparison to the single-axis devices. The uTouch connects two iTouch devices to create a kinematic five-bar. The cTouch device replaces all the bearings of the uTouch with compliant joints, creating a device that is simpler to manufacture and provides additional control challenges for the students.

The linear encoder is arranged with a horizontal optical path to read the flexed codestrip. To drive the uTouch, we built amplifiers based on the LMD18245 digital input H-Bridge chip, wiring the digital inputs all high and using the analog reference as input. The uTouch has a 6x6 cm workspace and a peak force of 4.4 N at the end-effector.

The photograph on the right in Figure 8 is the latest two-axis design, called the “cTouch”. To eliminate the expensive bearings, it features a compliant mechanism that replaces all bearings at the joints with compliant joints. The compliant mechanism is fabricated in ABS in a Stratasys^{TM}fused deposition rapid prototyping machine. The compliant mechanism has the effect of always driving the end-effector to a home position in the center of its workspace. This effect can be eliminated, however, by feedback compensation, which consumes about 20% of the available power at the edges of the workspace. This is, in fact, one valuable exercise posed for student users of the device.

The armature is fabricated out of 0.635 mm thick sheets of aluminum using a water-jet cutter. The metallic armature remedies the insufficient heat dissipation which had proven a problem in the the iTouch and uTouch designs. The aluminum armature, however, adds another property to the device: an eddy-current damper. However, the damping effect may be recognized as a feature rather than a bug, based on a theoretical recommendation for stability by Colgate [19]. The physically mediated damping serves to stabilize the energy-instilling effects of the zero-order hold that accompanies sampled-data control using a digital computer. Finally, to drive the cTouch, we built a souped-up amplifier based on two LM12 op-amps per axis that can drive up to 6 amps through the coils. The cTouch also has a 6x6 cm workspace but a peak force capability of 15 N.

An Analog Computer

As an alternative to a digital computer and control interface card, we have constructed a small analog computer to control the single-axis devices. It is a single printed circuit board stuffed with operational amplifiers configured as integrators, summers, and multipliers. There are four operators of each type, with header pins and crimp connects functioning as input and output ports (low-cost cabling proved important for keeping down costs). A package of home-built 6-in wires with crimp connectors on either end may be used to connect the integrators, summers, and multipliers into a network that implements the dynamics in question (the virtual environment to be felt). As in the era of early computing, programming the analog computer is accomplished by connecting patch cords, and the connections are guided by the very same differential equation or block diagram that embodies the system model to be simulated. Students enjoy programming by wiring and find satisfaction in the close connection between analog computer circuit dynamics and differential equations. Incidentally, at The University of Michigan, the system dynamics course is the students' first introduction to the operational amplifier, and its configuration as an integrator and multiplier is a regular part of the syllabus.

Instructional Implementation and Results

An undergraduate mechanical engineering curriculum invariably includes a course in system dynamics through which students learn to reduce physical systems to mathematical models and apply various analytical techniques to extract information from such models. Electrical, mechanical, and electromechanical systems (including motors) are modeled and analytical tools from the time, Laplace, and frequency domains are introduced and exercised. In addition, engineering judgment and skills that one might call intuition are usually addressed at some level, as these proficiencies are required for effective modeling and relevant analysis. However, to encourage the development of a honed intuition is quite difficult in a lecture-style course. The rather abstract nature of the mathematical tools introduced during the course tends to further discourage the linking of topics and concepts covered in class to the students' experience of movement and dynamics in the physical world. Hoping that students will better grasp the course topics, we have led them first to grasp a haptic interface. In so doing, we aim to provide tools that encourage each student to make the connection: that the behavior we describe using mathematics in class is the same behavior to which they have access with their haptic senses, their sense of touch and motion. Haptic interaction with virtual environments provides an ideal means to accomplish this goal. We effectively bring the mathematical models produced in class into the physical world where they can be touched and manipulated by the students.

For example, if proportional control $F_m = k(x_e - x_m)$ is implemented in the "Virtual Coupler" block of Figure **??**, and the "Virtual Environment" simply produces a constant position x_e, the device end-effector will be attracted to x_e by a virtual spring of spring constant k. The user recognizes spring action by feel—a restoring force proportional to the displacement away from a reference position. A negative proportional gain produces the feel of an unstable negative virtual spring, something rarely felt in the physical environment. The virtual damper $F_m = b\frac{\mathrm{dx}}{\mathrm{dt}}$ motivates a discussion of numerical differentiation. Also, a digital filter can be used to remedy the amplification of high frequency noise or quantization error brought about by differentiation. To introduce the family of virtual environments based on potential functions, we first define the potential function for the spring $U_k = \int_0^x k(x_e - x_m)dx_m$ and then generalize. The sinusoidal grating, which we call "virtual corduory" is simple but very useful: $U_s = \int_0^x A\sin(\frac{2\pi}{\lambda}dx$, where A is a scale factor and λ a spatial wavelength. On the two-axis devices, we implement the virtual corduroy both axes, creating the "virtual egg crate".

To introduce dynamic virtual environments, or those with states extrinsic to the user's body and physical interface device, we finally demonstrate the basis for the name "virtual coupler". The virtual spring control law $F_e = F_m = k(x_e - x_m)$ is used, but now the formerly fixed end of the spring x_e becomes dynamic, or moves in response to F_e, and in general according to a function with memory or *state*. For example, if $X_e = \frac{1}{ms^2}F_e$, where capitalization indicates Laplace transforms, then the virtual coupler and virtual environment become a virtual spring-mass of stiffness k and mass m attached to the haptic device. The transfer function $\frac{X_e}{F_e} = \frac{1}{ms^2+bs}$ is also very instructive and as it turns out easier to implement because of the suppression of initial condition response provided by the virtual damper b. Implementation of the dynamic virtual environment motivates a discussion of numerical integration of differential equations. Conversion to state-space form and discretization and solution according to Euler's method has proven itself an efficient means of covering large classes of virtual environments. In all of the above virtual environments, the physical equivalents are developed and presented schematically.

At The University of Michigan, haptic interface has been integrated into three courses: an undergraduate course in systems dynamics and control and the senior undergraduate laboratory in the mechanical engineering curriculum, and a senior-level elective course in embedded controls in the electrical engineering curriculum. Both courses capitalize on the multidisciplinary nature and multi-domain (electrical/mechanical) nature of haptic interface to meet instructional objectives. But according to differences in the course objectives, various parts of the haptic interface and virtual environment programming problem have been hidden from the students. Accordingly, the design of the haptic interface devices themselves is distinct.

Undergraduate students implemented virtual springs and dampers and graduate students have implemented virtual spring-masses on the analog computer. A very effective laboratory exercise based on the iTouch motor involves an experimental determination of a system frequency response. Since frequency response is often a difficult concept for junior mechanical engineering students to grasp, a quick and simple open-loop experiment has proven very valuable. Prior to the laboratory session, students assemble the haptic interface from kits, derive the linearized equations of motion for the iTouch system, and predict its resonant frequency. Theoretical predictions are then verified during the first half of a two-hour lab where students use a function generator to analyze the response of the system when driven sinusoidally between 0.5 and 20 Hz. The second portion of the same lab requires students to implement a virtual spring using the analog computer circuit board.

The course in embedded control systems was developed at The University of Michigan by

Jim Freudenberg. Having completed a course in microprocessors at the junior level, senior students in electrical engineering or computer engineering now have an opportunity to expand their knowledge and experience into the highly relevant area of embedded control. Students learn about the sensors and actuators and auxiliary interfacing hardware that connect a microprocessor to the physical world and qualify that microprocessor to be called an embedded controller. Given the ever increasing number of devices and processes in our world that function using embedded real-time control, there is a critical need for engineers and computer scientists who understand the concepts and tools required to develop these systems. Students seem to be aware of this need, as the course is heavily over-subscribed. Industry is intimately familiar with this need; they provided much of the original impetus and continue to closely monitor the course and aggressively recruit its alumni for employment. The embedded control systems course at The University of Michigan is based on the 40 MHz Motorola MPC555 featuring a 32 bit Power PC core with a floating point unit, Control Area Networking (CAN) modules, and Time Processing Units (TPUs).

During the first several weeks of the semester, students in the embedded control course complete a sequence of laboratory exercises. At the end of this sequence they have implemented an embedded control system for the Haptic Box. In so doing, they learn (i) generic concepts from microprocessor interfacing, such as quadrature decoding and pulse width modulation, (ii) specific features of the MPC555 microcontroller for doing such interfacing, (iii) generic concepts from signals and systems, such as sampling and frequency response, and (iv) had a lot of fun programming and experimenting with interesting virtual environments. Use of the haptic interface is thus both interesting as a task in itself as well as in teaching concepts common to many embedded control applications. An additional advantage is that students learn that engineering problem solving and design is inherently interdisciplinary.

To illustrate, we consider the second lab exercise, in which students learn about quadrature decoding. The MPC555 has a special module, the TPU, which is used to perform I/O intensive operations that would otherwise require CPU interrupt service, or an auxiliary chip. Students learn how to use the TPU module to read the position of the wheel on the Box. To emphasize the multidisciplinary nature of embedded systems development, they are required to compute the maximum rate at which the wheel may be turned before the MPC555 loses track of position. This calculation involves (i) the gear ratio between the drive wheel, where the encoder is mounted, and the haptic wheel students hold, (ii) the size of the counter register the TPU writes into, and (iii) the rate at which the CPU reads the counter. Hence to work properly, the mechanical hardware, computer hardware, and computer software must all function together. A change in the mechanical design for example, may require changes to the software. Other interesting tradeoffs emerge when trying to implement a stiff, chatter free, virtual wall. To do so requires that sample rate, encoder resolution, and spring constant all have compatible values. After the students have implemented a virtual wall, and a virtual spring mass system, they then explore advanced concepts. The MPC555 has a Control Area Networking (CAN) submodule, and they implement a virtual wall over a simple CAN network. For appropriate parameter values, they find that a chatter free wall implemented locally will exhibit chatter due to networking delay when implemented on a remote processor. Other advanced concepts include the use of rapid prototyping software. A major industry thrust in embedded software development is the use of high level tools such as Matlab/Simulink/Stateflow to model the behavior of the software, and the use of auto-code generation to produce executable software. This process allows the engineer to rapidly prototype and test the embedded control software. Students experience this process themselves in class, by developing a Simulink model of a virtual world, such as a spring/mass/damper system, with specified properties such as natural frequency and damping. They then generate executable C-code automatically from the Simulink model, which is subsequently compiled, and the resulting executable image is downloaded to the MPC555. Having produced similar code the hard way (by hand), they greatly appreciate the value of model based software design.

In the final weeks of the semester, students complete a short project wherein they implement a driving simulator with both haptic and visual feedback to the driver. The haptic feedback is provided to the wheel of the Haptic Box, which serves as a steering wheel for the simulator. The visual feedback is provided by a PC-based OpenGL display. To complete the project, they will utilize all the concepts of the course, including networking, modeling, and code generation. This demonstration of humans interacting with one another and a computer over a network with both haptic and visual feedback yields a strong sense of accomplishment to the students.

Summary

Control engineering education is an area where haptic interfaces can serve a particularly useful purpose: to represent complex and abstract ideas by leveraging years of control intuition developed through the manipulation of real objects. By manipulating and modifying dynamical system models, students develop physical intuition related to the mathematical representations of force and motion interaction presented in traditional lecture. In addition, control laws can be directly felt and compared to physical analogs such as springs and dampers. Haptic laboratory exercises have been successfully developed and implemented in courses at The University of Michigan, Johns Hopkins University, and Stanford University to explain a number of topics in dynamical systems, introductory controls, and embedded controls.

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