Haptic Interface for Hands-On Instruction in System Dynamics and Embedded Control

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Abstract

Haptic interface serves as an ideal context and platform for teaching both system dynamics and embedded control. At The University of Michigan, a traditional undergraduate mechanical engineering course in systems dynamics and a new undergraduate electrical engineering course in embedded control systems have been equipped with instructional modules based on two new single-axis haptic interface devices. The iTouch motor is a low-budget, single axis, voice-coil based haptic device intended for teaching system dynamics fundamentals. Students gain hands-on experience by assembling these motors from scratch, performing experiments, and comparing actual to theoretically predicted dynamic response. A second device called "The Box" features higher torque output and robustness for the embedded control systems course. Both device designs are presented and contrasted and results following from their introduction into the curriculum are discussed. The uses of these devices to rapidly prototype various research projects and integrate undergraduate students into a research program are also briefly discussed.

1. Introduction

Many modern engineered artifacts employ sensors and actuators to combine mechanisms that live in and interact with the physical world with controllers that live in the digital world. Increasingly, the design of such artifacts must consider tradeoffs that cross the traditional functional and curricular boundaries. Engineering professionals trained in more than one discipline are becoming very valuable to industry and even academia. Witness the rapid deployment and immense popularity of Mechatronics courses in Mechanical Engineering Departments and Embedded Control courses in Electrical and Computer Engineering Departments.

Controls as a discipline, but also robotics and more recently haptic interface have taken up positions that span the boundaries between disciplines. Projects in these areas serve as excellent vehicles for developing and delivering interdisciplinary courses. Recently, haptic interface has been proposed as an ideal vehicle for teaching systems dynamics to mechanical engineering undergraduate students [1] [2]. This paper expands on the use of haptic interface for teaching system dynamics by adding a few hardware features that enable more flexible uses. A new device design is presented that we expect will encourage broader distribution among teaching and research institutions. This paper also extends the use of haptic interface to the teaching of embedded control systems within the electrical and computer engineering curriculum.

At The University of Michigan, haptic interface has been integrated into two courses, one in the mechanical engineering and the other in the electrical engineering departments. Two new devices have been developed to support these courses, according to their rather distinct course objectives. Certainly 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. But the overall aim remains the same: to present multidisciplinary, complete, yet accessible challenges to the students that are also rewarding.

The paper is organized around the sequential presentation of each new haptic interface device in section 2, and section 3. Since both devices were envisioned to serve not only curriculum development, but also research startup needs, the role of each device in a research program is also described. In the following sections, the objectives of each course are outlined and the device designs are presented with highlights of the means by which haptic interface is used to meet those course objectives. Finally, research applications are highlighted before concluding.

2. System Dynamics Instructional Objectives

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 interface to 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.

2.1. The iTouch Motor Design

We enthusiastically acknowledge the Haptic Paddle project first developed at Stanford University [1], and now under further development at Johns Hopkins University [2] whose aims are likewise to provide a vehicle for teaching system dynamics to mechanical engineering students. The Haptic Paddle enjoyed significant success with students at Stanford and a warm reception from the Haptics community. Our project has added several major and a few minor features that we hope will extend this success and encourage wider distribution.

First of all, the iTouch motor includes no traditional store-bought or surplus motor. We build our motor from scratch, winding the armature with magnet wire and setting up the magnetic field using permanent magnets. Thus we resolve the primary criticism of the Haptic Paddle: that the low-friction ironless core basket-wound motor is not widely or regularly available at low surplus prices. We do, however, buy our magnets from a surplus magnet supply house: they are surplus hard-drive magnets. Though it is not guaranteed that the particular motor magnets used in the iTouch will be available in the future, crescent shaped magnets are generally widely obtainable, and the iTouch design can be easily modified to incorporate whatever magnets are on hand.

The core mechanics of the iTouch lie in its home-built voice-coil actuator. Similar to a hard disk reader, the iTouch has four high strength Neodymium crescent shaped magnets arranged such that there are two equal-strength magnetic fields created in opposite directions. A rotor containing a magnet-wire coil is sandwiched between two flanged roller bearings, allowing the rotor 30° of rotation. Rotor position detection is handled through a Hall Effect sensor and two small, commercially available neodymium magnets. Note that flat coil actuators have been implemented previously in haptic interface. See, for example, [4], [5] and [6].

Like the Haptic Paddle, we laser-cut the structural components from Plexiglas to keep costs low. 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. Figure 1 shows the fully assembled iTouch motor. The hand-wound armature is barely viewable behind the magnets. Figure 2 shows a line-drawing of the iTouch design.

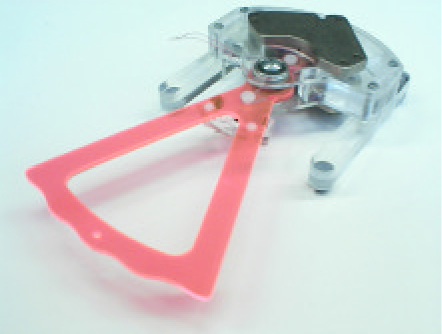

Figure 1. The iTouch motor. A user generally rests his or her wrist on the housing/magnet assembly and extends their fingers to rest on the end of the crescent-shaped handle.

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. At The University of Michigan, our systems dynamics course includes most students' first introduction to motors. We hand out the unassembled iTouch kits along with a 100 ft 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 process significantly enhances the lecture that covers the physics of the motor and generator.

Table 1 presents the specifications of the iTouch motor.

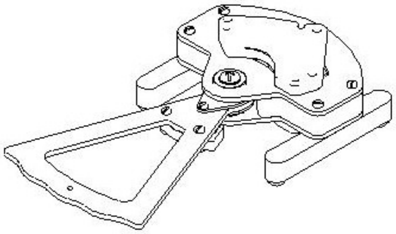

Figure 2. iTouch motor line drawing

Table 1. iTouch motor specifications

Max Torque	0.202 Nm
Workspace	30°
Motor Constant	0.126 ± 0.011 N/amp
Max Current	1.6 amps
Time @ Max current before failure	About 3 minutes
Cost/Unit	$19.22

2.2. Analog Computer and Amp

Rather than interface the iTouch motor through a motor- control interface card to a digital computer for the purpose of implementing control, we have constructed a small analog computer. Our analog computer 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 functioning as input and output connectors. 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). Figure 3 shows the analog computer and amp beside an iTouch motor. As in the era of early computing, programming the analog computer is accomplished by connecting wires, and the connections are guided by the very same differential equation that embodies the system model to be simulated. Students get a real kick out of 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 systems dynamics course is the students' first introduction to the operational amplifier, and its configuration as integrator and multiplier is a regular part of the syllabus.

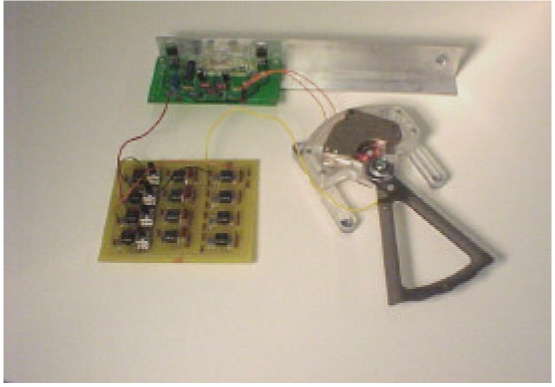

Figure 3. The analog computer (front left) and amplifier with aluminum heatsink (back) are shown with an iTouch motor.

To complete the control loop, we have fabricated a linear amplifier based on power operational amplifiers. It is a Howland current pump-type amp [3, p. 182] using two power op amps. Figure 3 shows our amp mounted to a piece of aluminum angle iron as a heatsink. Together, the iTouch motor, the analog computer, and amp can all be run off of batteries or a simple power supply, making the complete system portable, or at least not subject to the availability of a computer lab. This is an important feature for courses in system dynamics at many Universities.

2.3. Instructional Implementation and Results

We have used the iTouch motor for teaching undergraduate system dynamics on two occasions and on one occasion at the graduate level. Undergraduate students implemented virtual springs and dampers and graduate students have implemented virtual sprung 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 their motor 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 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.

Our basic teaching approach is to create an environment in which students teach students. To support these aims, the haptic interface kits are simple, portable, and easy to program. Students tend to share their encounters with virtual objects, with each other and even with persons outside of class. Also notable are the modeling and analysis of the haptic interface that form the basis for homework assignments. Finally, the students will gain some very valuable hands-on experience with electromechanical hardware.

3. Embedded Control Instructional Objectives

A course in embedded control systems has recently been developed at The University of Michigan. 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 they are flocking to this course. Industry is intimately familiar with this need; they provided much of the original impetus and continue to closely monitor the course and snap up its alumni for employment.

Industry has been faced with the problem of putting together disparate teams of engineers and computer scientists who are unfamiliar with the big picture and lack experience with the emerging tools for design, analysis, simulation and implementation. Although students graduating with degrees in electrical and computer engineering, mechanical engineering, or computer science have some of the background needed to develop these systems, these various students lack the multidisciplinary background that is essential to design and implement sophisticated embedded control systems. The embedded controls course aims to create a cadre of engineers who can make decisions across the boundaries that divide the microprocessor and the physical environment. Thus this course covers a broad range of disciplines: from algorithms and real-time operating systems to signal processing and system dynamics.

The embedded control systems course uses a set of innovative instructional modules and laboratory exercises featuring a haptic interface. Students are introduced to concepts and tools that are emerging from the recent research in modeling, simulation, analysis, and implementation of virtual environments that interact with humans (the students themselves) living in the physical world. The research area of hybrid system dynamics also plays a role in the design of this course.

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 floating point, Control Area Networking (CAN) modules, and Time Processing Units (TPUs).

3.1. The Box Design

To serve as the prototype "product" in which to embed a controller, and to provide the context for realizing and testing product function, a new haptic interface device that we affectionately call "The Box" has been designed and fabricated. The cost and function limitations are rather different from those that governed the development of the iTouch motor. We built six Boxes for $600 each. They feature commercial linear amplifiers with PWM input and 6 amperes of output current drive. For feedback, The Box features a 1024 count per revolution encoder. A switching power supply is also incorporated into the package so that the box plugs into the wall. It connects to the embedded controller evaluation and interface boards via a single ribbon cable.

The drive for the box is a RE35 35mm diameter brushed Maxon motor rated at 90 Watts. A 4 inch diameter wooden wheel with an inner half-inch diameter knob 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. Figure 4 shows a picture of The Box and Figure 5 a CAD rendering. Not quite visible in either picture or rendering is the sandwich-plate design which allows the motor to be re-positioned on an arc for the purposes of tensioning the cable. The Plexiglas housing neatly packages all components yet makes them visible so they can be appreciated by electrical and computer engineering students. All components are in fact mounted on a central Plexiglas plate and stand so that the cover can be easily removed without losing function.

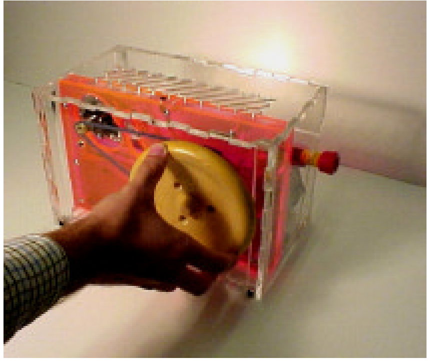

Figure 4. The finished Plexiglas Box. The emergency stop button is visible on the right and the cable drive is visible inside the clear housing.

Table 2. Specifications for The Box

Continuous stall Torque	5.4 Nm
Effective Encoder Resolution	7270 counts/revolution
Cost/Unit	$600

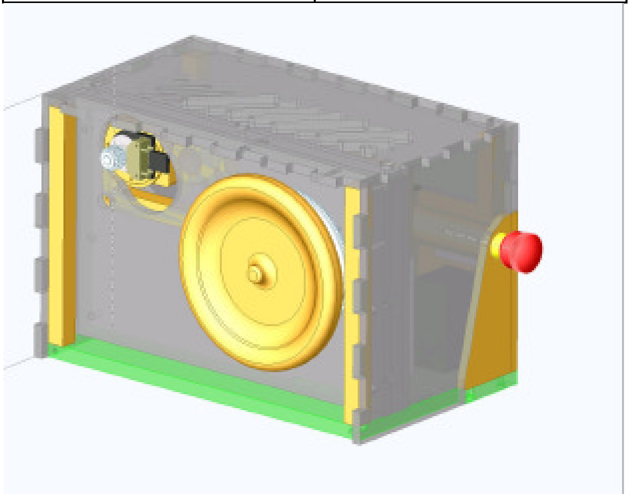

Figure 5. CAD rendering of The Box design.

3.2. Laboratory implementation and results

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 will have implemented an embedded control system for the haptic "Box". In doing so, 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 worlds. 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 intensive I/O 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 sprung 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 will 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 will then directly generate executable C-code from this diagram that will download to the MPC555. Having just done all this the hard way, they greatly appreciate the value of model based software design. The specific code generation tools used in the lab produce C code written in the form of task states in OSEKWorks, a real time operating system intended for automotive applications. This fact allows the students to appreciate such additional concepts as multi-tasking.

In the final weeks of the semester, students complete a short project wherein they implement a virtual “Pong” game, allowing them to bounce a virtual ball back and forth between virtual paddles attached to two haptic boxes. To do so, they will utilize all the concepts of the course, including networking, modeling, and code generation, as well as build an accompanying graphical display using OpenGL, or the virtual reality toolbox of Matlab. 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.

4. Research Uses of the iTouch and Box.

Both the iTouch motor and The Box have been used in the research laboratory in addition to the teaching laboratory to “prototype” certain research projects. Having these devices readily available in the lab has enabled various demonstrations to be quickly assembled. Two iTouch motors were used to realize a force-reflecting teleoperator called the juggler. Both the master and slave are single axis devices as shown in Figure 6. With this device, we have demonstrated the value of haptic feedback versus visual feedback for maintaining a stable juggle. The iTouch motors have also been configured side-by-side to realize a force-reflecting synthesizer keyboard as shown in Figure 7. The relative ease with which the iTouch motor housing may be re-used and quickly interfaced has been very valuable.

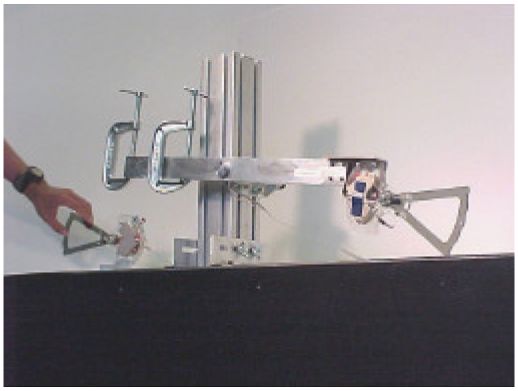

Figure 6. The force-reflecting teleoperated juggler using two iTouch motors.

Also, The Box has been used to render a virtual sprung inertia, which we are proposing to use in human subject studies to test the value of haptic feedback in developing a rehabilitation therapy. The availability of the Box meant that we could easily demonstrate the sprung inertia to the clinicians and occupational therapists with whom we are collaborating on this project.

5. References

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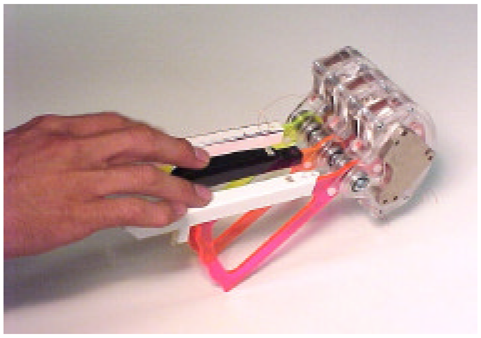

Figure 7. A force-reflecting synthesizer keyboard using stacked iTouch motors.