Haptic Interfaces for a LabVIEW-based System Dynamics Course

Abstract

Too often in undergraduate mechanical engineering courses, the content of laboratory exercises is not well coordinated with course content, and the exercises are unrelated to each other. As a result, students have a difficult time grasping the "big picture" themes. This project at Rice University seeks to improve the effectiveness of laboratory exercises in a required undergraduate mechanical engineering system dynamics course via student-centered learning and laboratory topics featuring haptic paddles, devices that allow users to interact via the sense of touch with virtual environments. One outcome of these improvements is a cohesive set of laboratory experiments using the haptic paddles as a single experimental test bed for multiple experiments. The Haptic Paddle exercises are unique because they allow the students to analyze and build their own haptic interface, or force-reflecting system. The students are able to see many subsets of mechanical engineering come together in a series of exercises, including assembly, system analysis, calibration, system modeling, and dynamics. Finally, a key advantage to the haptic paddle labs is that they tie closely with the course material.

This paper describes the development of haptic paddle laboratory kits and associated National Instruments LabVIEW virtual instrumentation to support the adaptation of laboratory experiments for a required undergraduate system dynamics course at Rice University. The laboratory experiments use simple haptic interfaces, devices that allow the students to interact via the sense of touch with virtual environments. A clear benefit of this laboratory series is that students study the haptic paddle as a real electromechanical system in addition to using the haptic paddle as a tool to interact with virtual mechanical systems. The haptic paddle hardware has been modified to improve robustness, and the LabVIEW graphical programming language is used for data acquisition and control throughout the laboratory series. The paper will present some details of the laboratory components, and preliminary assessment of learning outcomes using this laboratory series compared to more traditional modular labs used in prior years.

1. Introduction

This paper describes the adaptation of the haptic paddle laboratory series to a dynamic systems course at Rice University. The primary changes include revised hardware to improve robustness, and the use of National Instruments hardware and software for computer control of the electromechanical devices. Slight revisions to the laboratory exercise content have also been made to match the content of this particular course.

Integrated systems, such as the haptic paddle, introduce students to more realistic multi-domain systems, rather than addressing each domain (mechanical, electrical, fluid) separately. These multi-sensory (visual, haptic) labs are closely tied to course concepts and feature embedded assessment. This is a unique aspect of Rice's course, MECH 343 (Modeling Dynamic Systems), compared to similar courses, both within Rice's curriculum and at other institutions.

The primary goal of the haptic paddle laboratory experiment adaptation is to improve the effectiveness of laboratory exercises in a required undergraduate mechanical engineering course via student-centered learning and laboratory topics featuring integrated systems.

The specific objectives of the effort are:

- Improve the cohesiveness of course and lab content and consequently, deepen student conceptual understanding
- Demonstrate that haptic virtual learning increases student ability to apply conceptual knowledge to real-world systems
- Improve understanding of critical system dynamics topics in multiple domains in a cost-effective way

To reach these objectives, Rice University has adopted laboratory exercises based around haptic interfaces, devices that allow users to interact via the sense of touch with virtual environments. Specifically, the successful Haptic Paddle Laboratory series[1], developed at Stanford University and currently used in undergraduate courses at Johns Hopkins University, was selected for the *MECH 343: Modeling Dynamic Systems* course.

This section will present pedagogical information for the haptic paddle laboratory series. Section 2 will describe details of the hardware redesign, both mechanical and electrical. Section 3 describes the National Instruments control software for the haptic paddle laboratories.

1.1. The Haptic Paddle

The Haptic Paddle exercises are unique because they allow the students to analyze and build their own haptic interface, or force-reflecting system as seen in Figure 1. The students are able to see many subsets of mechanical engineering come together in a series of exercises, including assembly, system analysis, calibration, system modeling, and dynamics. Students are engaged in the laboratory exercises and see the project develop throughout the semester, rather than following a recipe or list of instructions in order to elicit a desired outcome. The laboratory exercises encourage students to move beyond the reiteration of detailed steps, using the results of early laboratory exercises to improve the performance of their haptic paddle system, and ideally gaining a better understanding of dynamic systems, thus establishing a student-centered laboratory environment. As stated by Bransford et al.[2], learner-centered environments are one key to optimizing learning.

A key advantage to the haptic paddle labs is that they tie closely with the course material. In Okamura et al.[1], a student was quoted as saying, “One of the better labs I’ve done… each built on the previous one and supported the course material well. Very helpful.” The authors also state, “Haptic interfaces, which allow a user to feel a virtual environment, are promising tools for helping students obtain an understanding of these physical phenomena,” in reference to topics such as instability and time constants of dynamic systems[1]. It is expected, based on these findings and first-hand experiences of the presenters, that haptic interfaces will be more effective at teaching the concepts of dynamic systems than other computer-based dynamic simulations that have been used in pedagogical settings[3-5].

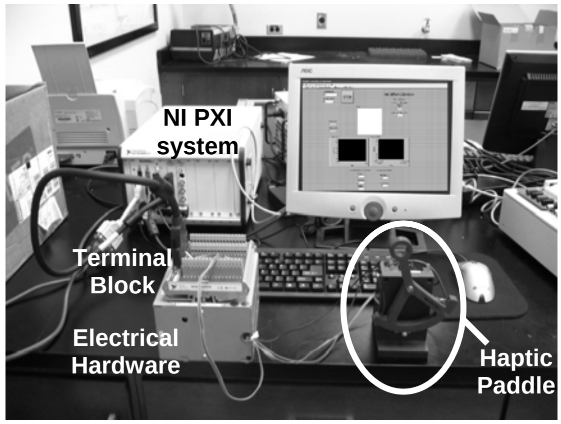


Figure 1. The complete Haptic Paddle laboratory hardware system.

A clear benefit of this laboratory series is that students study the haptic paddle as a real electromechanical system in addition to using the haptic paddle as a tool to interact with virtual mechanical systems. Because the haptic paddle is a multi-domain system, it is representative of real-world systems with which the students will interact, rather than typical laboratory exercises that focus on single domain behavior. The advantages of using a haptic device to interact with virtual mechanical systems are that parameters (e.g. spring stiffness and damping of a mass-spring-damper system) can be changed easily, and students can interact with systems that are more difficult to implement in wet labs due to various reasons (e.g. required hardware, nonlinearities in real systems). The haptic paddle is a sophisticated device for teaching mechanical engineering concepts because it is an integrated system. Students interact with a real mechanical system, and then use that system in a lab setting to touch the concepts that are conveyed in lectures and homework.

There are alternate hardware choices for this series of laboratory experiments. Commercial hardware such as force feedback gaming joysticks, Sensable's Phantom Omni haptic device, and Immersion's Impulse Engine 2000 provide platforms that can be used off-the-shelf for conveying system dynamics concepts via a haptic device. However, these systems are cost prohibitive compared to the haptic paddle kits, and do not allow students to study the hardware on a component-by-component basis prior to working with the assembled system. The authors are aware of only one other low-cost haptic interface kit, developed at the University of Michigan[8]. This hardware platform should work equally as well as the haptic paddle hardware, but would require additional revisions to the laboratory exercises as students fabricate voice coil actuators rather than using DC motors. Therefore, the haptic paddles were chosen due to the availability of sample kits from the developers and documentation on the laboratory exercises.

1.2. Curriculum needs

In the fall of 2001, the Mechanical Engineering and Materials Science Department at Rice University revised the curriculum in response to student requests for more flexibility. Five area specialization clusters, biomechanics, computational engineering, fluid mechanics and thermal science, solid mechanics and materials, and system dynamics and control, were added to the program, along with a general mechanical engineering option. In the new curriculum, all students take basic courses in areas such as thermodynamics, engineering mechanics, system dynamics, fluid mechanics, machine design, vibrations, feedback control, and heat transfer. In addition, students take laboratory courses in mechanics, thermo/fluids, industrial processes, and heat transfer. In the fifth semester of study, students declare a specialization area and take four additional courses (one per term) in their chosen area.

While this revised curriculum allows the students more flexibility when choosing courses, several courses, required on the old plan, were dropped and replaced with new required courses. The most notable change was the exclusion of an introductory electrical engineering course from the required core curriculum. This course was replaced with MECH 343 (Modeling Dynamic Systems). This new four-credit course, which includes a laboratory component, includes topics such as Laplace transforms, Newtonian dynamics, Lagrangian dynamics, lumped-parameter modeling, derivation of equations of motion, and introductory system theory. At the same time, the students are exposed to systems in several domains (mechanical, electrical, thermal, and fluid). The lectures and laboratory exercises have attempted to introduce all of this material to the students in a clear and understandable format, but the approach has been only marginally successful to date. The most likely reason for the lack of success is the disjointed nature of the lectures and laboratory exercises, attributable to the wide range of topics that must be covered in order to prepare students for their upper-division courses. What is needed is a set of laboratory exercises that tie closely with the lecture content and reinforce the material, while still exposing the students to basic electronics, mechanical systems, and modeling techniques.

The second item lacking from the new curriculum is a focus on dynamic systems and control (DSC) topics in laboratory exercises. Three required laboratory courses focus on mechanics of materials, thermo-fluid systems, and heat transfer topics. In order to expose students to hands-on activities in DSC, instructors must lump laboratory exercises into lecture-based courses. The result is insufficient exposure to dynamic systems and controls in the laboratory setting, as there are typically only a few short laboratory exercises in these courses. Students who select capstone projects in the DSC area have extremely limited experience with electromechanical systems and likely have never even hooked up a DC motor to a power supply!

1.3. Adapting the Haptic Paddle

As an initial step to including more interactive, exciting laboratory experiments into the required undergraduate mechanical engineering curriculum, the Haptic Paddle laboratory series[1], developed at Stanford and currently implemented at Johns Hopkins University, is adapted to fit Rice's curriculum. This series of five laboratory exercises was developed for use in an undergraduate course on dynamics and controls, and is fully explained in the literature and on several websites[1,6,7]. A low-cost, single-axis force-reflecting joystick was used to teach students about electromechanical systems, dynamics, and controls. Figure 2 clearly illustrates the topics from the lecture portion of the Hopkins course and the related topics in the Haptic Paddle Labs. It should be noted that other researchers have adopted haptic devices to undergraduate courses with much success[8].

While most of these labs fit right in to the syllabus for Rice's Modeling Dynamic Systems course, several topics such as vibration modes and closed loop control are not covered.

Therefore, the labs in their current form have been modified to apply more directly to the Modeling Dynamic Systems syllabus. The following section describes the five laboratory experiments as proposed by Okamura, *et al*[1].

1. **Motor spin-down test:** Explore a simple first order dynamic system: a spinning motor. Record position information as a motor spins down, and extract system information such as damping and time constant.
2. **System Components:** Students measure basic system properties of the haptic paddle, such as the speed and torque constants of the motor and the inertia of the sector pulley.
3. **Equivalent Systems:** Students assemble the components of the Haptic Paddle into a single dynamic system and calibrate the position sensor. Students will develop the equations describing the equivalent system in terms of the properties of the system components and analyze the response of this system without any control feedback.
4. **Second Order Systems and Step Response:** Students provide a step input to the electromechanical system (the haptic paddle) and view the response via an oscilloscope. Features of the step response are studied and compared to the parameters gathered in prior experiments, and to the model that has been derived.
5. **Feedback Control:** Students hook up the Haptic Paddle to a computer and program that provides feedback control. By changing the parameters of the feedback, they are able to influence the dynamic response of the device. Because this paddle is designed as a haptic interface, students are able to *feel* the changes in system parameters.

Dynamic Systems Course		Haptic Paddle Labs
Viscous Damping and Dissipative forces	►	Motor spin-down test
Equations of motion Inertia	►	Bifular Pendulum Paddle's equivalent inertia
Electromechanical systems	►	Motor constants Sensor calibration
Second order systems Step response	►	Computer control of paddle
Feedback control	►	Using the paddle to interact with virtual systems

Figure 2. Correspondence between course material and haptic device experiments (adapted from Okamura, *et al*[1])

In order for these laboratory experiments to fit the needs of our Mechanical Engineering undergraduate curriculum, several modifications have been made. First, a set of labs that introduce electrical systems have been created and use National Instruments equipment including LabVIEW and NI ELVIS (Educational Laboratory Virtual Instrumentation Suite). NI ELVIS is a design and prototype environment for university science and engineering laboratories that consists of LabVIEW-based virtual instruments, a multifunction data acquisition (DAQ) device, and a custom-designed bench-top workstation and prototype board. Because it is based on LabVIEW and provides complete data acquisition and prototyping capabilities, the system is ideal for academic coursework that range from lower-division classes to advanced project-based curriculum. These labs will not be discussed within the scope of this paper. Second, the Haptic Paddle hardware was redesigned for improved robustness and to facilitate kit production with resources available to our university. Finally, the NI-based computing platform was developed to support the haptic paddle laboratory experiments so that all experiments for the course used the same computing hardware. These hardware and software revisions will be the focus of the remainder of the paper.

2. Haptic Paddle hardware redesign

The Haptic Paddle hardware is advantageous for a number of reasons mentioned in Section 1. An additional benefit is that the devices are relatively low-cost. The cost per unit for mechanical hardware described in this section is just under $30US. Including the cost to fabricate four power supplies (assumes four groups of students per lab session), the cost per system is still under $48US, not including the cost of computing platforms. The revised hardware systems (mechanical, electrical, and computing platform) are described in the following sections.

2.1. Mechanical hardware

The redesign of the mechanical hardware, as seen in Figure 3, gives particular focus to long-term reusability and robustness of the hardware, since it is intended for use in an undergraduate laboratory course.

2.1.1. Materials. Assembly of the documented hardware required a significant amount of glue, thus new kits were required each year if students were to assemble their own paddles. The new hardware design takes advantage of fasteners to assemble the paddle, providing for disassembly at the end of the semester and reuse in subsequent years. Type 1 PVC has been chosen as the material for the base, support, and sector/end effecter components due to its durability, low cost, and ability to be tapped for fastener threads. Threads that bear significant stresses are reinforced with steel helicoils. The components are fabricated using standard CNC and manual machining techniques.

2.1.2. Sector design. The geometry of the sector/end effecter component has been modified from the original paddle design so that the end effecter and sector are opposite of the point of rotation and can thus be fabricated out of a single piece of Type 1 PVC. An additional benefit of this revision is an increase in the distance between the end effecter and the pinch point of the capstan drive. The previous geometry did not prevent users from resting their fingers on the sector, thus it was possible for the resting finger to come in contact with the capstan drive shaft and get pinched between it and the sector. The redesigned capstan drive now provides a 19:1 transmission ratio, and the workspace of the device is approximately 80 degrees.

2.1.3. Actuation. A surplus 15V DC motor (Pittman Lo-Cog 9434) has been chosen to drive the motor due to its low cost and ability to provide sufficient torque to produce the desired 10N output force at the end effecter. The motor provides a maximum torque output of 41.3oz in and continuous torque of 6.1oz in. The motor torque constant is approximately 2.76 oz-in/A. A precision steel shoulder screw is used for the sector shaft, and steel radial ball bearings are used for sector shaft support and alignment, and to prevent wear due to the rotation of the shaft.

2.1.4. Sensing. As in the original Haptic Paddle design, a Hall-effect sensor is used for position sensing. For the new design, the magnet is inserted into a machined PVC cap which is affixed to the sector shaft using a slight interference fit. Wires crimped at one end with a female quick slide terminal and crimped at the other end with a ring terminal provide connections from the motor to banana plugs, a durable solution that facilitates quick and easy connection and disconnection to the motor amplifier. An eight-pin DIP header is sawed in half and glued to a support member to mount the hall-effect sensor and provide a secure connection for a three-wire ribbon cable. This is the only use of glue in the assembly of the paddle and does not significantly affect its disassembly.

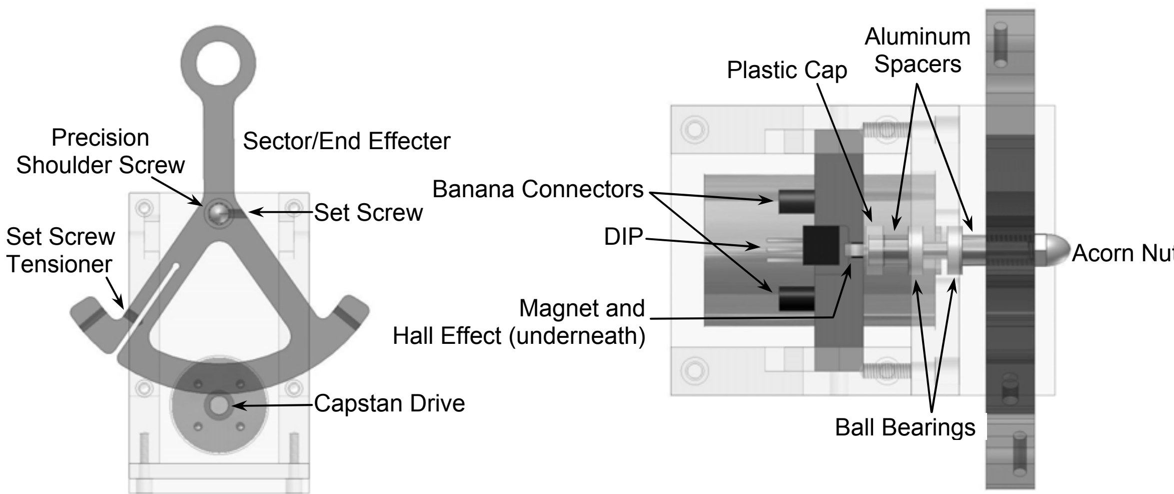


Figure 3. Redesigned mechanical components of the Haptic Paddle

2.2. Electrical hardware

The redesign of the electrical hardware focuses on portability and ease of use with the mechanical system and National Instruments (NI) data acquisition (DAQ) card. The electrical hardware consists of a power supply and power operational amplifier used to drive the paddle motor, as well as a signal conditioning circuit for the hall-effect sensor. The power supply and amplifier are capable of delivering ±12V at 2 amps to the DC motor. The signal conditioning circuit adjusts the Hall-effect sensor's 0-5V output to a ±10V signal in order to take full advantage of the range of the DAQ card's analog to digital conversion capabilities. Two wires with banana plug terminals and a three-wire ribbon cable connect to the mechanical hardware of the paddle to provide power to the motor and read the output of the Hall-effect sensor respectively. A three-wire ribbon cable connects to an NI screw terminal block to provide a connection to the DAQ card.

A computer power supply has been salvaged to enclose the electrical hardware. All internal components have been removed with the exception of the 110V plug connector and 12V DC cooling fan. The new hardware is mounted inside the housing as can be seen in Figure 4. The prototype of the power supply is constructed using standard wire wrapping and soldering techniques. Three more sets of electrical hardware have since been constructed incorporating a printed circuit board for easier construction and greater reliability. The total number of electrical hardware systems allows four lab groups to perform the exercises at a time.

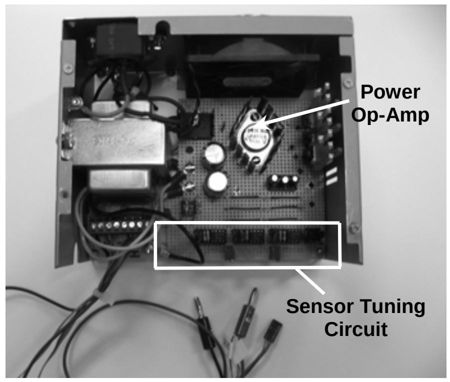


Figure 4. Electrical hardware components including power supply, motor amplifier and signal conditioning circuits.

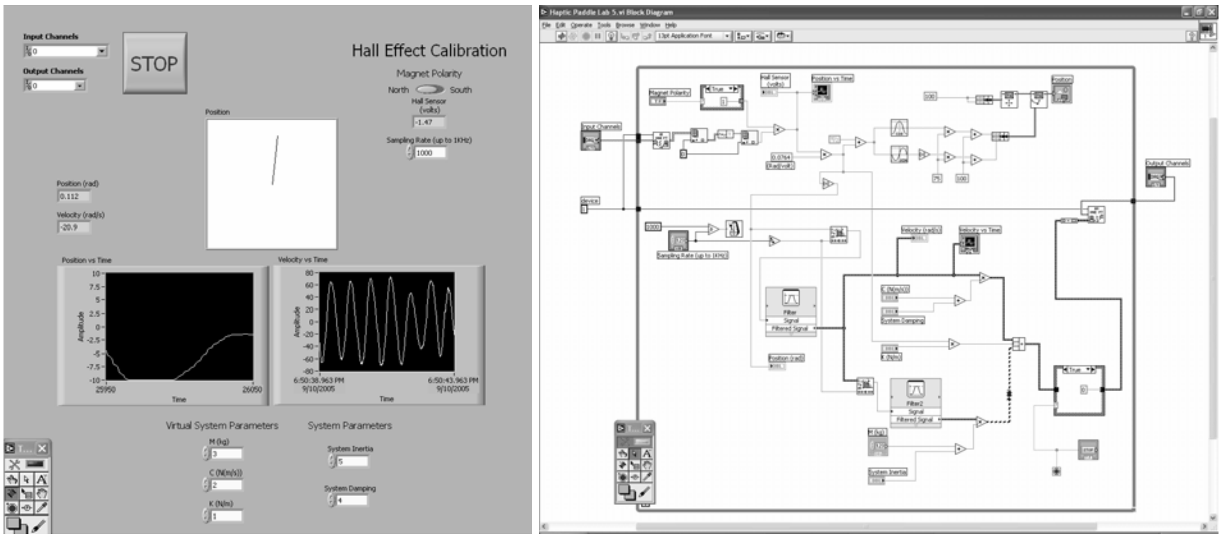
3. Haptic Paddle computing platform

In addition to revising the Haptic Paddle mechanical and electrical hardware, the system also has a revised computer interface. The most notable difference between the documented haptic paddle system and the redesigned system is that the computer interface system at Rice University is based on a National Instruments LabVIEW real-time (RT) system, rather than compiled C code running in DOS to assure real-time operation, as implemented in the original laboratory series.

3.1. Computing hardware

A National Instruments PXI industrial computer with DAQ card 6070E running LabVIEW is used for the revised Haptic Paddle laboratory series. LabVIEW is useful not only for the Haptic Paddle experiments, but also for the electrical systems experiments mentioned earlier. Additionally, it allows for easier expansion of hands-on experiments, both for this course, and for other courses in the system dynamics and control cluster of the mechanical engineering curriculum. LabVIEW is the accepted standard in visual programming environments[9] and is used extensively in undergraduate engineering education[10-13].

Admittedly the cost savings for the haptic paddle laboratory kits does not carry over to the proposed computing interface. The NI PXI system is a significant investment for anyone developing an undergraduate laboratory. The system was selected for use at Rice for a number of reasons that the authors feel justify the cost. First, NI has made a strong commitment to supporting undergraduate engineering education, and often supports universities with gifts of equipment or matching support on grants. Many undergraduate laboratories already use LabVIEW as the computing platform for data acquisition. For the majority of the experiments in the haptic paddle series, real-time computing is not required, and therefore a standard desktop PC with a DAQ card is sufficient. Second, the PXI systems offer a versatile platform for use in other courses, in capstone projects, and in research. Therefore, it is felt that this investment offers additional capabilities to the department beyond education in this single course, and such benefits offset the cost.



(a) **(b)**

Figure 5. LabVIEW graphical programming environment for sensor calibration experiment. (a) Front panel for sensor calibration experiment (b) Wire diagram

3.2. Computing software

An example of a LabVIEW graphical interface and program can be seen in Figure 5. For each laboratory experiment, a Virtual Instrument (vi) was created. The front panel provides the required indicators, dials, and charts for the student to complete the laboratory exercise. The wire diagram, which in effect sits behind the front panel, handles signal flow and interfacing between the hardware and the computer via the data acquisition card. For the first three of the haptic paddle laboratory exercises (motor spin-down test, system components, and equivalent systems), the students rely on the data acquisition capabilities of the NI system. They are able to easily control the command input to the sensors and actuators via the front panel’s virtual knobs and switches, and plots of the recorded data from the sensors are displayed for the student to analyze. Because these experiments do not rely on real-time control, they are built on the standard processing platform within the PXI system. For the laboratory experiments that involve simulation of virtual mechanical systems, real-time control is required to ensure sufficient performance of the system. For these experiments, LabVIEW Real-Time (RT) is used as the processing platform. In this case, the graphical programming interface remains the same, but the file is compiled and run on a target processor that guarantees real-time operation. These distinctions are transparent to the student conducting the experiments.

4.0 Assessment

Grading rubrics were developed to measure conceptual understanding for key concepts in each laboratory experiment. For laboratory experiment seven, students use an IE2000 commercial haptic interface (see Figure 6) to interact with virtual first- and second-order mechanical systems.

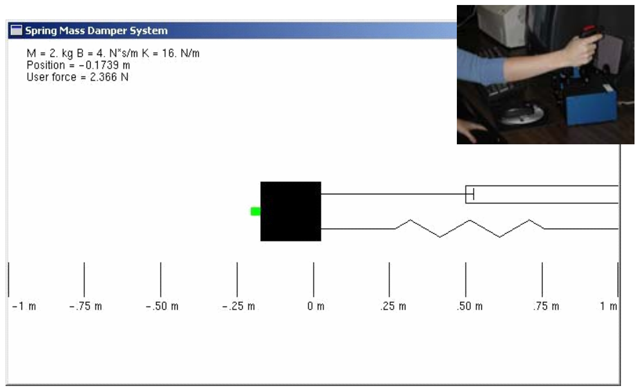


Figure 6. Simulated mechanical system environment (inset) IE2000 joystick

Students see a graphical representation of a mechanical system on the computer screen. By changing the parameters of the system (mass, damping, and stiffness), they are able to influence the dynamic response of the device. Because this paddle is designed as a haptic interface, students are able to *feel* the changes in system parameters. This laboratory experiment will eventually be implemented on the haptic paddle devices, but for initial assessment the IE2000 platform was maintained. Students in Year 1 completed the standard series of laboratory experiments which were disjointed from course material, which each experiment independent of all other experiments. In Year 2, students completed the haptic paddle laboratory series, where the final experiment in Years 1 and 2 were completed with identical hardware (the IE2000).

Students were asked to carry out a number of tasks with the virtual mechanical systems including altering the system parameters and observing the response. They were instructed to prepare a report in the lab notebook that contained the following: an abstract, additional details about the purpose of the lab, background information, equipment used, methods employed, and results. Specifically, the students were told to include:

<u>First-order system</u>

- Appropriately labeled graphs for the mass-damper system for both values of the damping constant that you chose
- Discussion of the effect of B on the time constant and comparison of the values of the time constant obtained from the graphs to the values expected from the definition.

<u>Second-order system</u>

- Appropriately labeled graphs of each type of system response (underdamped, critically damped, and overdamped), including the values of M, K, and B that were required to produce each graph

- For the under-damped system, calculate ζ and ω_n from the graph using the log-decrement method and compare those values to the theoretical values expected from equations (5) and (6). Explain any differences.
- Calculate ζ for the other two cases using equation (6) and check to see if the damping constant is within the expected range for each case.

The reports from Year 1 and Year 2 were then evaluated with the grading rubrics, which evaluated student understanding of engineering concepts and fundamentals. The rubric elements were:

First-order System

1. Student describes concept of mass-damper system
2. Student documents output signal
3. Student recognizes differences between system output for different parameter values
4. Student describes that behavior of mass-damper system follows equation
5. Student identifies the importance of the time constant
6. Student relates the time constant to the damping in the system

Second-order System

7. Student describes concept of mass-spring-damper system
8. Student documents output signal
9. Student understands and computes the system parameters using log-decrement method
10. Student documents system behavior and explains correctly
11. Student relates behavior of second order system to equation (damping coefficient and natural freq)
12. Student describes the change in behavior of the response with varying damping coefficients

General

13. Student identifies the human-supplied input as an impulse
14. Student relates the measured output to impulse response of the system
15. Student describes concepts of haptic system
16. Student correctly uses measurement equipment

For each element, the student response, as determined from the entire content of the report, was graded as 0-not at all, 1-a little, 2-mostly, 3-fully correct. Scores for each rubric element were averaged for students in Year 1 and Year 2 and are presented in Figure 7.

In the figure, Year 1 (traditional labs, disjointed from course material in lecture) results are shown in solid, with Year 2 (haptic paddle series) results shown with diagonal lines. The questions represented in bold are conceptual questions, while those shown in lighter shades are fundamental or procedural questions.

It is the responses conceptual questions which the authors hypothesized would be scored higher after completion of the cohesive haptic paddle laboratory series. This laboratory experiment is the culmination of concepts taught in the MECH 343 Modeling Dynamic Systems course.

Therefore, it was felt that the use of a cohesive set of laboratory exercises would better demonstrate to the stduetns these important concepts, as compared to the disjointed laboratory series used prior.

It should be emphasized that this assemssment was for the same lab experiment, conducted at the end of the course, in each year. The differences in years were the content of the earlier laboratory experiments, and the careful incorporation of course concepts closely tied to lecture material in the haptic paddle laboratory series (Year 2). The authors expected that Year 2 students would have better conceptual understanding because they have seen the concepts repeated in exercises throughout the semester, and have learned the material in an exploratory fashion rather than following strict laboratory guidelines on the procedures.

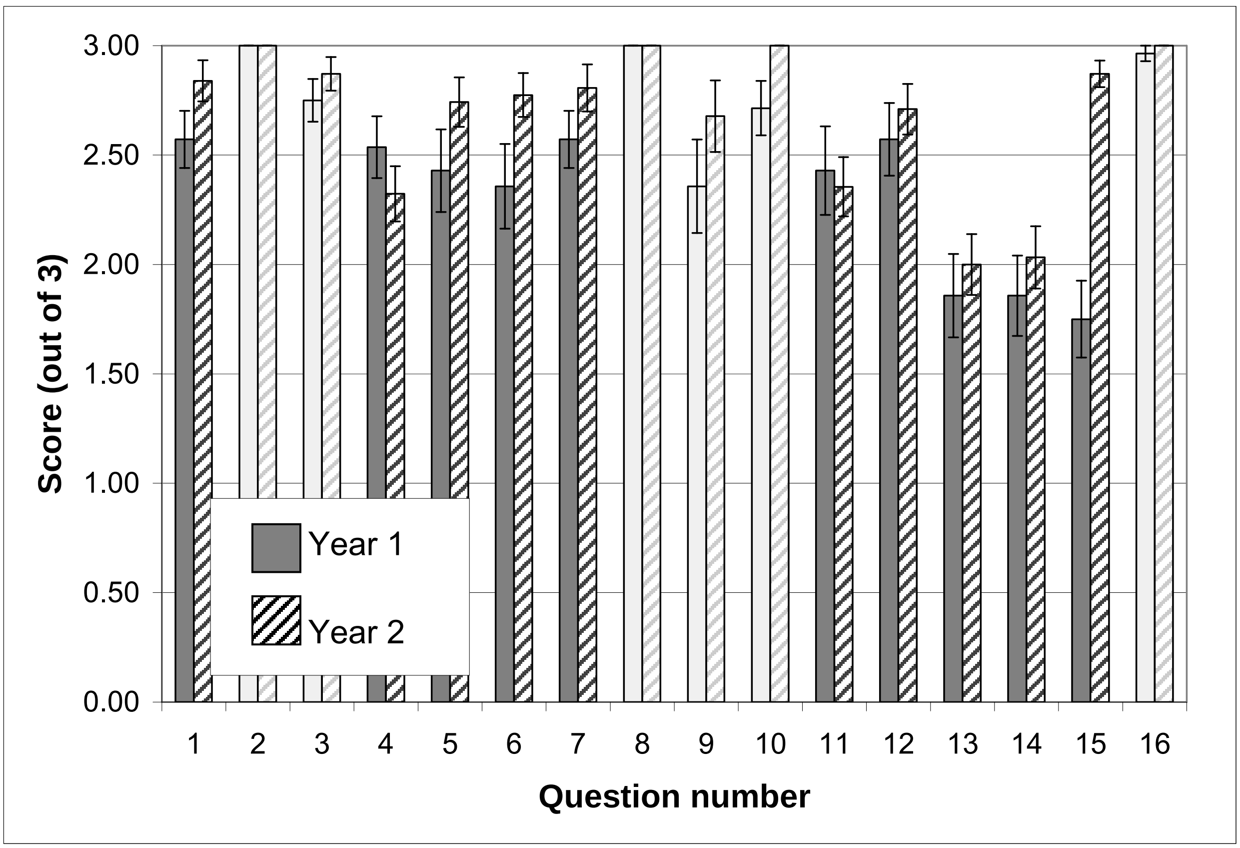


Figure 7. Student performance on laboratory notebook questions. Questions with bold bars indicate assessment of conceptual knowledge rather than factual questions. Significant improvement is seen after the integrated haptic paddle laboratory experiments were implemented.

It is clear from Figure 7 that there are significant gains in student understanding of concepts after completing the haptic paddle laboratory series. Such improvements included conceptual understanding of mass-damper systems, importance of time constant, relation of time constant to the damping in the mechanical system, concept of mass-spring-damper system, and concept of a haptic system (largest gain). Negligible gains/losses (not significant) were seen on the conceptual questions regarding the behavior of the mechanical system following the characteristic equation, that the change in behavior varied with damping, that the input given by the student was an impulse, and that the measured output was the impulse response. In addition, basic questions like correctly using equipment, using log-decrement method, and observing experiment output, all clearly outlined in experimental procedures, did not vary significantly from year to year.

Future work includes completion of assessment for individual laboratory exercises, comparing the traditional labs (Year 1) to the haptic paddle (Year 2) series. This is difficult because the content of the exercises was significantly different, and therefore the authors must look at numerous assessment methods to compare student learning with the two approaches. In addition to more extensive educational assessment, the authors are refining the hardware and software kits and documentation for dissemination.

5. Conclusions

This paper describes modifications to the Haptic Paddle hardware for use in an undergraduate mechanical engineering course in system dynamics. The modifications include revisions to hardware for improved durability and re-use, and a change in computing platform to a National Instruments PXI system running LabVIEW. The laboratory experiments utilize simple haptic interfaces, devices that allow the students to interact via the sense of touch with virtual environments. A clear benefit of this laboratory series is that students study the haptic paddle as a real electromechanical system in addition to using the haptic paddle as a tool to interact with virtual mechanical systems. Preliminary assessment shows that the haptic paddle laboratory series was successful at improving student learning of system dynamics concepts when compared to traditional, disjointed laboratory exercises. Future work includes additional assessment of student learning to determine if the labs are more effective at conveying important engineering concepts than traditional modular laboratory experiments, and dissemination of findings to colleagues in both the haptics and engineering education communities.

6. Acknowledgements

This work is supported in part by grant NSF DUE-0411235 with matching support for equipment provided by National Instruments. Also, thanks to Allison Okamura for providing extensive documentation and starter kits for her Haptic Paddles, and for supporting this adaptation effort.

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