A Low-Cost Dynamic Plant and Data Acquisition System for Laboratory Courses on Control Systems and Mechatronics

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Abstract

Hands-on experiments for upper-level engineering courses greatly enhance student enthusiasm, core-concept comprehension and retention. Given the high cost of commercial instructional control systems lab equipment, we sought to provide an affordable, robust solution to hands-on learning, without compromising technical caliber. To this end, we have developed a low-cost dynamic plant and data acquisition Haptic Paddle system for control systems and mechatronics laboratory courses. A Haptic Paddle is a single degree-of-freedom force-feedback joystick that is well-suited to be used as a test bed for both basic and advanced concepts in system dynamics, control theory, mechatronics, haptics and enables students to physically interact with simulated dynamic systems. Our novel hardware design offers a robust solution to repeated laboratory use at a cost that greatly facilitates the number of lab setups available for student use to significantly enhance the opportunity for hands-on learning.

1. Introduction

It is largely agreed on\(^1\)\(^-\)\(^8\) that engineering education is greatly aided with hands-on demonstrations, lab activities, and design projects, in that these exercises develop students’ intuitive understanding of system behavior. The Haptic Paddle device gets students interactively involved with dynamic systems and has perceivably increased student enthusiasm\(^1\) while providing an enhanced understanding of system dynamics theory\(^8\). Since its first creation at Stanford University\(^1\)\(^-\)\(^2\) in 1997, the Haptic Paddle has been developed and modified by a number of other universities including Rice\(^6\), Johns Hopkins\(^7\), Vanderbilt\(^8\), Michigan\(^3\), and Utah (see\(^9\) for more information).

1.1. Review of Prior Haptic Paddle Designs

The first design at Stanford University (Figure 1a) strived to minimize manufacturing costs and was made from laser cut acrylic, employed a surplus Maxon motor, a capstan pulley transmission, and a Hall effect angular position sensor. A computer and computer interface card comprised the data acquisition system, which added significantly to the total cost of each Haptic Paddle station. Though the Stanford University Paddle produced handle forces up to 7.5N\(^1\) and functioned well as a dynamic plant, it lacked robustness in that the cable in the capstan pulley was prone to slip and often required re-tensioning.

Building upon the original Stanford University design, the Haptic Paddle developed at Rice University (Figure 1b) made a few key improvements. This included relocating the motor to the base of the device, allowing the handle to be fabricated without lamination, unlike the kits at
Stanford University, which relied on gluing in their assembly process. This created the opportunity to reuse kits each semester, as they could be assembled and disassembled each semester. The Rice Haptic Paddle also achieved higher handle forces up to 10N with a 10:1 gear ratio\(^6\).

![Haptic Paddles](a) The Stanford and John’s Hopkins Haptic Paddle. (b) The Rice University Haptic Paddle. (c) The University of Michigan Haptic Paddle. (d) The Vanderbilt University Haptic Paddle. (e) The University of Utah Haptic Paddle.

Michigan University developed their own haptic device called the “iTouch Motor” (Figure 1c) that is rather different from any of the other Haptic Paddles. In place of using a DC motor, they have implemented a voice coil actuator that their students hand-wind themselves each semester. Their system uses no transmission, and the voice coil directly provides a maximum torque of 0.202Nm over a range of motion of 30 degrees\(^3\). Control is provided by an analog computer (hosting analog integrators, summers, and multipliers) that students program by connecting wires to the various sub-circuits available, guided by the differential equation that describes the system they aim to simulate.

Vanderbilt University’s Haptic Paddle (Figure 1d) has uniquely implemented a friction drive transmission, in an effort to avoid the capstan pulley limitations regarding cable fall-off, slip and the need to re-tension the cable, reportedly leading to student frustration and delays in lab instruction\(^8\). They were also the first to implement a low-cost data acquisition system with an Arduino microcontroller. Though the Arduino platform interfaces with the system’s position sensor and motor controller, all control is performed in Matlab’s Simulink (The Mathworks, Inc.) environment.

The University of Utah’s Haptic Paddle (Figure 1e) is very similar in design to the Haptic Paddle developed at Rice University. The system uses a cable drive transmission, and boasts simple assembly and a resilient hardware. They have also bundled all power supply and control electronics into a single box, providing a compact and robust solution. Computer data acquisition was supported through a 3\(^{rd}\) party computer I/O card.

1.2. Prior Design Limitations

While the Haptic Paddle design has undergone a number of key advancements since its first inception at Stanford University, some common limitations are evident in each design cycle. The use of a cable drive transmission does not prove to be a robust enough solution for durable laboratory use and also limits the working range of the device. Friction drive transmissions aim to solve the reliability concerns of a capstan-based transmission, yet still suffer from limited
range of motion. All prior Haptic Paddle designs also lack an inexpensive solution to position measurement over the complete 360 degrees of angular range.

Low-cost data acquisition and control is another feature that most prior Haptic Paddle designs have left unaddressed, often requiring an expensive computer interface card and computer to run the control. As the only exception, Vanderbilt University aimed to lessen this cost with Arduino-based data acquisition. However their system relies on Matlab/Simulink to perform control processes and operate their Haptic Paddle, which reduces the control loop rates that are achievable.

1.3. Addressing Prior Limitations

While our design incorporates the essential Haptic Paddle features, we also aimed to resolve the limitations that prior designs exhibit. Thus, we strived to provide a robust continuous rotation drive and all-quadrant position measurement solution, yielding a system with significantly increased range of motion, thereby providing means to explore additional control scenarios (see Sections 2 and 3 for more detail on our solution).

We have also implemented a low-cost Arduino-based data acquisition and control solution. Unique to our Haptic Paddle, all timing and control are performed on the Arduino, significantly increasing the control loop rates (up to 1kHz) and alleviating the need for a computer if not available. Also, USB connection from our system to a computer running the graphical user interface we have developed in Matlab allows students to view system response in real-time for an enhanced learning experience.

In this paper, we present the design considerations and specifications of our Haptic Paddle plant and data acquisition system and the set of lab experiments being developed to accompany this hardware. In Section 2, we report our hardware design approach and technical performance specifications. In Section 3, we present our sensing solution with associated electronic hardware and sensor calibration performance. Section 4 covers our low-cost solution to data acquisition and control, and introduces the custom graphical user interface we have developed. In Section 5, we address the application of our design in hands-on engineering education, and present a set of lab experiments we are developing for Control Systems and Mechatronics courses. Finally, Section 6 discusses the current limitations of our Haptic Paddle and future work.

2. Mechanical Design

Made almost entirely from durable, laser-cut acrylic, our Haptic Paddle presents a novel modular hardware design that is easily and inexpensively manufactured (see Figure 2). The design incorporates a timing belt-drive transmission between the motor and the handle, offering a significant advantage over prior Haptic Paddle designs in terms of robustness and variety of additional control scenarios. It provides zero slip, continuous rotation and robustness against mechanical failure under routine student use as opposed to earlier designs with cable-drive or friction-drive transmissions with limited angular range of motion and robustness. The paddle handle is clamped to a steel shaft that is supported by Polytetrafluoroethylene (PTFE) plastic bearings.
Figure 2. Our Haptic Paddle demonstrates a modular design using laser-cut acrylic that is easily and inexpensively manufactured. It incorporates a timing belt-drive transmission, and includes an Arduino-based solution to data acquisition and motor drive electronics. It is powered by a standard computer power supply (not shown).

2.1. Actuation

Actuation is provided with a Hansen 116-126123 brushed, permanent magnet DC motor. Rated for 12V, the Hansen motor provides 42 mNm maximum continuous torque at a maximum continuous current of 1.7A. We have purchased each motor for $12, at a surplus rate. Other engineering departments looking to build our or develop similar Haptic Paddle setups may want to make a similar consideration to keep actuation costs down.

2.2. Voltage Amplifier

A low-cost, commercially available voltage amplifier (the “Ardumoto”, SparkFun Electronics) is used to interface the microcontroller and motor. The Ardumoto has two independent channels (for two motors if needed), is rated for a maximum of 18V input, and can drive a maximum of 2A per channel. We use a standard computer power supply to provide 12V input to the Ardumoto driver. The average motor voltage is adjusted via a pulse width modulated (PWM) control signal from our microcontroller board. We have set the frequency of this PWM signal to 31.25 kHz, thereby eliminating any audible “whining” in the motor driver system, while accomplishing reliable voltage control.

2.3. Transmission

The motor and handle shaft are coupled via a timing belt-drive transmission. Toothed pulleys on the motor and handle shafts provide a 4:1 gear ratio for enhanced torque output at the handle. We have incorporated a simple belt tensioning mechanism in the design by making the motor mounting plate adjustable with respect to the paddle base. With this transmission and the current handle length, our Haptic Paddle can provide a maximum force of 2.5N at the handle. The durable timing belt and pulleys provide a zero slip and robust transmission, offering infinite rotation and resilience to failure under heavy laboratory use. The total transmission costs amount to $33.
3. Sensor and Signal Conditioning

Angular displacement measurement of the handle is accomplished with a cylindrical permanent magnet fixed to the handle’s shaft in direct proximity to an inexpensive ($4), dual-axis Hall effect sensor, the EM3242 (AKM Semiconductor, Inc.). This approach avoids rotational friction and wear and enables a measurement solution for the system’s 360 degree angular range, an option that was not possible in earlier Haptic Paddle designs. The EM3242’s analog output can also be fed to an analog differentiator to obtain velocity information.

3.1. Dual-axis Hall Effect Sensor

The EM3242 houses two orthogonal Hall elements, the outputs of which are internally processed to produce a unique analog output voltage over the full angular range. The sensor’s processing decodes sine and cosine magnetic field components, while simultaneously compensating for variations in average net field strength, yielding a highly linear output.

The use of a dual-axis Hall effect sensor offers a few key advantages over prior Haptic Paddle designs. Earlier designs such as Stanford University’s original paddle used a single Hall effect sensor. This approach limits the angular range to two quadrants at best, and yields a noticeably nonlinear (sigmoidal) response over the full range, leading to greater difficulty in alignment of the sensor and magnet. The conditioned linear output of the EM3242 is less sensitive to the exact magnet-sensor alignment, and hence greatly facilitates calibration for students. Lastly, the ability to measure the handle’s position at +/- 180 degrees further enables our system to fully function in any quadrant and explore additional control scenarios such as constant speed control or a self-uprighting pendulum.

The EM3242 is a ratiometric sensor and provides an analog output ranging from 10-90% of its supply voltage. Powered with 5V, and sampled by our data acquisition system with a 10-bit Analog to Digital Converter (ADC), the angular resolution of our system is 0.44 degrees. This configuration also eliminates the need for additional signal conditioning to match the Arduino’s analog input voltage range, which adds practicality and robustness to the base paddle system.

3.2. Sensor Mounting PCB

The EM3242 ships as a surface mount device (SMD) with a rather uncommon footprint. To most efficiently integrate this technology into our system, we have designed and manufactured a custom Printed Circuit Board (PCB) (see Figure 3) to mate the SMD sensor to the Arduino microcontroller board. The sensor’s position on the PCB has also been aligned with the magnet and paddle geometry to facilitate calibration. PCB manufacturing was batch produced for a total cost of $0.63 per board.
3.3. Sensor Performance

Figure 4a shows data collected during sensor calibration. Raw voltage readings taken at 15 degree intervals are shown, in addition to 1st and 3rd order calibration fits on the estimated angle. Figure 4b shows the absolute error between each calibration fit and the target angle. Using the 1st order fit, the maximum sensing error was limited to 5 degrees, while using the 3rd order fit kept the error below 3 degrees. Both error ranges are sufficiently low for educational purposes and are experimentally tested to work satisfactorily under closed loop control.

Figure 4. (a) A plot of the raw voltage readings over the entire angular range in addition to estimated angle with 1st and 3rd order fits. (b) The absolute error from the true angle for 1st and 3rd order fits.
3.2. Velocity Measurement and Signal Conditioning

For many control systems and haptic interaction related experiments, velocity data is needed to accomplish responsive and stable control. While it is possible to estimate velocity information discretely in the digital domain, this method can be prone to noise, especially if the position measurements are not sampled with high resolution.

Another approach is to procure velocity information in the analog domain, thus avoiding resolution errors on position, and obtaining a cleaner velocity signal that can then be sampled by the microcontroller. To this end, one lab exercise we are developing incorporates an analog differentiator coupled with a low-pass filter that students will build on a breadboard using op-amps.

4. Data Acquisition and Control

An Arduino Uno development board is used for data acquisition and control. Integrating this widely known platform will assist novice programmers, yet will also help elevate the Arduino community from the hobbyist realm to more complex control systems applications. Furthermore, at only $30, the Arduino development board is an extremely affordable data acquisition solution, a significant portion of the cost that was left unresolved in earlier Haptic Paddle designs. We have also developed a Graphical User Interface (GUI) in Matlab that communicates with the Arduino for enhanced real-time learning experience.

4.1. Arduino Development Board

The Arduino development board keeps the cost per lab station low, while providing local onboard control and a convenient USB connection to a computer for data acquisition and communication. The Arduino directly samples the paddle’s angular position and interfaces with the motor via the motor driver described in Section 2. All timing and control processes are performed on the Arduino, while simultaneously transmitting dynamic measurements to a host computer.

Another compelling reason we have chosen the Arduino platform is to provide the option to familiarize students with low-level, C-programmed, embedded control techniques. This enables them to learn how digital control systems are realized at the microprocessor and hardware levels. With the Arduino platform and our set of instructional materials (discussed further in section 5), Mechatronics students can gain hands-on experience in this multidisciplinary field, developing the framework for a practical understanding of the integrated hardware and software solutions to common control problems found in industry. To facilitate learning embedded techniques, we have developed a number of support methods (discussed in section 5.2) to assist students with less background in C-programming.

4.2. Graphical User Interface

System response analysis is a main objective for our Haptic Paddle as an educational tool, thus we had a strong incentive to make the paddle’s behavioral data easily viewable in real-time and
Our Haptic Paddle GUI allows students to view oscilloscope-like plots of angular position and velocity data, as well as motor voltage, all plotted against time. Numeric readouts accompany the plotting windows to show a more precise value of each parameter. The plots can be set to autonomously scale vertically, so the response’s most relevant details, such as overshoot, response time, and settling time are emphasized for the student. Using the GUI controls, students may start and stop recording data, change the oscilloscope (viewing) mode, clear the scope screens, and most importantly save collected data to a long-term storage file for analyzing various responses in their lab reports.

While this GUI functions well as a general Haptic Paddle control station, we are using the design as a framework to concurrently develop other GUIs that are specifically tailored to certain experiments done on the Haptic Paddle, the collection of which includes sensor calibration, motor and plant characterization, open and closed-loop step response, position tracking control, constant speed control, and inverted pendulum balancing. Each of these GUIs will have panel controls and plotting windows specific to the laboratory exercise. For courses strictly limited to control theory, where emphasis is placed entirely on system response specifications and controller design and tuning (and not on embedded control specifics), students can test response for different controller structures and gains from directly within the Matlab GUI.

**Figure 5.** Our custom Haptic Paddle GUI runs in Matlab and allows students to view system response in real-time.

### 4.3. Example Step Response Data

Shown in Figure 6 are the step responses of position tracking control for proportional (a) and proportional-derivative (b) control. Both are in response to a step input of +50 degrees-- starting
at -20 degrees, and tracking a +30 degree set point. The control loop was running at 100Hz, and angle estimation was implemented with a 1st order linear fit on the sensor's voltage readings.

**Figure 6.** (a) Step response with proportional (P) control. (b) Step response with proportional-derivative (PD) control.

The step response of the system under proportional-only control depicted in Figure 6a shows that the system has significant inherent damping, due to combined pulley and bearing friction effects. However the friction is dominated by the plastic bearings currently installed on the paddle. The step response of the system under proportional-derivative control in Figure 6b indicates increased damping, reduced overshoot, and a reduced settling time. These plots give an example of what students see in real-time as they interact with the paddle, enhancing the connection between control theory and real world system behavior.

5. Engineering Education

The primary goal of our work is to enhance the educational quality of Mechatronics and Control Systems laboratory courses by developing an easy to manufacture, robust and inexpensive dynamic plant and data acquisition system. To this end, we are designing a set of laboratory experiments in control theory, mechatronics, and haptics to complement our hardware and enhance the intuitive understanding of course topics. These experiments include sensor calibration, motor system identification, open-loop and closed-loop plant response, constant speed control, inverted pendulum control and haptic interaction experiments including virtual springs, virtual walls, viscous friction fields, and teleoperation with two Haptic Paddles. Some of these experiments are similar to ones developed previously at Stanford University and Vanderbilt University, however some are new experiments rendered possible by the unique characteristics of our paddle design.

5.1. Control Systems Laboratory Exercises

Our Control Systems lab exercises (see Table 1) are designed to add a physical intuition to how systems respond naturally and in various control scenarios. Emphasis is placed on relating changes in the control law with observed system behavior, and comparison to theoretical models. To facilitate this, students will tune control law directly through controls (switches and sliders)
on our Matlab GUIs specifically developed to provide a transparent environment, placing the focus on the paddle’s response and its relation to the governing system dynamic equations and control laws, while freeing the students from having to program (or navigate) software code.

Table 1: Control Systems Lab Exercises

<table>
<thead>
<tr>
<th>System Identification: Open-Loop Response</th>
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<tbody>
<tr>
<td>Closed-Loop Response</td>
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<tr>
<td>Position Tracking Control</td>
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<tr>
<td>Constant Speed Control</td>
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<tr>
<td>Disturbance Effects On Position Control</td>
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<tr>
<td>Disturbance Effects On Speed Control</td>
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<tr>
<td>Inverted Pendulum Balancing</td>
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<tr>
<td>Self-uprighting Pendulum</td>
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5.2. Mechatronics Laboratory Exercises

While our Control Systems labs focus exclusively on control law and system behavior, our Mechatronics labs additionally incorporate exercises in embedded control. We feel, as other engineering departments do\(^4,^8\), that embedded control is a critical skill set for Mechatronics students to gain, given the large need for engineers versed in the concepts and tools required to design quality embedded control systems. This involves the integration of such engineering disciplines as digital and analog hardware, microprocessors, sensors, actuators and electromechanical systems, programming, and control system theory. A fundamental understanding of how these various fields integrate is essential to a solid foundation in embedded control.

Toward bringing these various disciplines together, we are compiling a set of lab experiments that aim to introduce the Mechatronics student to embedded control techniques at a hardware and microprocessor level. While control algorithms are covered, more emphasis is placed on embedded hardware specification/configuration and usage, programming techniques, and hardware and software limitations. Table 2 provides a listing of lab exercises we are developing to implement in our Mechatronics Lab course.

Regarding C-programming, we recognize that C is a non-trivial language, and have implemented a few support methods to ensure students are sufficiently prepared. A basic C-programming course is prerequisite to Mechatronics, and we are also offering a hands-on course in C-programming for microcontrollers to further prepare students. Lastly, most of the laboratory exercises we have developed are designed around “skeleton” source code we have pre-written that is mostly functional except for a few segments of the program. Students can then apply their coding solutions to fill in the missing segments, allowing them to focus on the embedded control techniques without the added anxiety of writing an entire program from a blank slate.
Table 2: Mechatronics Lab Exercises

<table>
<thead>
<tr>
<th>Exercise Area</th>
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<tbody>
<tr>
<td>Introduction to Microcontrollers: Arduino, Digital I/O</td>
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<tr>
<td>Serial Communication</td>
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<tr>
<td>Analog to Digital Conversion</td>
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<tr>
<td>Sensors, Sensor Calibration, and Signal Conditioning</td>
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<tr>
<td>Timing and Pulse Width Modulation</td>
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<tr>
<td>Actuators, DC Motor Model, Motor Spin-Down Tests</td>
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<tr>
<td>System Identification:</td>
</tr>
<tr>
<td>Open and Closed-Loop Response, Proportional Derivative Control</td>
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<tr>
<td>Haptic Effects:</td>
</tr>
<tr>
<td>Virtual Spring, Viscous Damping, Virtual Wall, Teleoperation</td>
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6. Discussion

Our new design complements the set of previously designed Haptic Paddles while also offering advancements that further reduce lab setup costs, enhance robustness, and expand the variety of control scenarios possible. Our design implements very low-cost data acquisition and control, an expense that was left unaddressed by prior Haptic Paddle designs, except for Vanderbilt University.

There are a few key revisions we have in process to improve the quality of our Haptic Paddle. Referring to the position step response shown in Fig 6a, there is currently significant friction at the paddle shaft. We are working to reduce this friction by replacing the plastic bearings with steel ball bearings. This crucial revision is important to provide a more realistic plant for control and higher quality haptic interactions.

Lastly, one final limitation is that few of the parts in our design still require machining to produce. Access to a laser cutter is needed to fabricate the majority of the assembly pieces. This does not pose a significant problem, however, since laser cutters have already become a tool that is frequently used at many higher education institutions. We aimed to make as much of the system as possible to be built directly from laser cut pieces, to reduce cost as well as time required to manufacture. We believe that this is a key requirement for wider dissemination and use of haptic paddles or similar instructional setups.

7. Conclusion

We have developed an inexpensive, robust control plant for mechatronics and control systems instructional labs. With Arduino-based data acquisition, a low-cost sensor, and inexpensive hardware manufacturing, the build cost for our plant totals to approximately $150. This serves as an affordable and accessible solution to engineering departments seeking to outfit control...
systems or mechatronics laboratory classrooms with multiple laboratory setups for significantly increased opportunity for hands-on learning experience.

References


