BYOE: Affordable and Portable Laboratory Kit for Controls Courses

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Presenter Information

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Summary

A portable and affordable laboratory kit for an undergraduate control systems course will be demonstrated. The kit includes a Raspberry Pi (a single board computer), DC motor, and other circuits and sensors. The kit's custom components were 3D printed. All other components of the kit can be purchased from online retailers such as Adafruit or Sparkfun for a total cost of about $130. This kit could replace expensive equipment with an affordable alternative that can be easily shipped anywhere in the world and used by students with any computer. The low cost and portability of the kit greatly enhance the accessibility of the laboratory experience to students in budget-strapped campus laboratories and those participating in distance education.

Using a DC motor allows the instructor to assign experiments using a proportional-integral-derivative (PID) to control the motor's position.[1] Additionally, a DC motor setup can be expanded to create more complex setups like the inverted pendulum.[2] Inverted pendulum experiments can illustrate different types of systems and different types of control methods. These methods include bang-bang control, fuzzy logic control, neural network control, PID adaptive control, robust control, hybrid control, predictive control, and feed-forward control.[3] Because of this versatility, both the DC Motor and inverted pendulum systems will be used as the basis for the kit being developed.

Pedagogical Context

A controls laboratory experience should prepare students for a career in control systems[4] by performing the following steps: building the system,[5] modeling and analyzing the system, developing a controller to meet performance requirements, simulating the controller and system, observing the physical system, collecting the data, and using the data to improve the system model or control tuning.[6,7] Experiments based on DC motors[1,2] and inverted pendulums[6,8] have been identified to meet these goals for controls laboratory experiences.

To date, five experiments have been designed for our new kit: introduction to the sensors, introduction to the equipment, first principles system identification, black box system identification, and PID control. These experiments align with the existing experiments in the first control systems course for general engineering students (GE320). The two introductory experiments enable students to get acquainted to the sensors and the equipment that will be used throughout the course. In the first principles system identification experiment, students measure the motor's individual parameters including the armature resistance and inductance to create a mathematical model. In the black box system identification, the students confirm their model from the previous experiment by analyzing the step and frequency response of the motor. In the final experiment, the students design, simulate, and test proportional, proportional + derivative, and proportional + speed controllers for the position of the motor. For all of the experiments the students use MATLAB and Simulink to program the Raspberry Pi and collect data.

Sample Experiments

Detailed instructions for each laboratory experiment can be found at http://coecsl.ece.illinois.edu/ge320/. Each of the laboratory experiments below were designed to be as close as possible to the existing equipment experiments, in order to reduce the risk of interruption to the course.

Laboratory 1: In this experiment, the students become familiar with Simulink and building models to run on the Raspberry Pi. The students build proportional, derivative, and integration models similar to the ones they will create later in the semester. They also build a model with pulse width modulated signals to blink the LEDs on the breadboard.

Laboratory 2: In this experiment, the students become familiar with the sensors that will be used throughout the semester. The deadzone of the motor and H-bridge is also measured in this experiment. The students are provided with a Simulink model that runs the motor and collects the data. The sensor measurements are displayed to the students in real time via a Scope block.

Laboratory 3: In this experiment, students build a system model of the motor through first principles. The time constant of the voltage decay was too fast to accurately capture with Simulink and the Raspberry Pi, so an inductance, capacitance and resistance (LCR) meter was used to measure the armature inductance. If this kit were made portable, an LCR meter would need to be made available to the students or an approximate value for armature inductance

provided. Of the six motors used in the initial test run there was a difference of 0.2 mH, which is less than 10% of the average value.

Laboratory 4: In this experiment, students build a system model of the motor through black box testing. The students look at both step responses and frequency responses of the motor to develop another system transfer function. This transfer function is compared with the first principles transfer function.

Laboratory 5: In this experiment, students design, simulate, and test a proportional, proportional + derivative, and proportional + speed control of the motor's position. In the prelab exercises the students calculate analytical gains for each controller type and then simulate the whole system in Simulink with the model from Laboratory 3. Then students test the design with the real motor and tune the gains as needed.

Kit Design

There are several components to the kit: Raspberry Pi, motor, sensors, 3D printed stand, and the student interface in MATLAB and Simulink. The Raspberry Pi support package from Mathworks was used in all of the experiments.[9] The detailed bill of materials, including supplier, is in listed in Table 1. Most of the components of the kit are off-the-shelf as indicated in Table 1. The complete kit can be found in Figure 1. A 3D model for the 3D printed base is available upon request.

Circuit Board

For the initial trial run the additional circuit interfaces were implemented on a solderless breadboard to allow for easy updates to the prototype. In the future we are going to consider a protoboard or a custom PCB. The diagram of this breadboard is included in Figure 2.

Position Sensor

The final control design uses the position of the motor as a reference input. A rotary position sensor was selected for this purpose. Because the Raspberry Pi does not have analog inputs, an analog to digital convertor (ADC) was used to convert the signal from the rotary position sensor to a digital signal. Both the MCP3002 and the Raspberry Pi use the serial peripheral interface (SPI) protocol, so this functionality was used to read the position values in Simulink. An S-function driver was created in Simulink to implement the SPI interface and display the value on a scope or use in a control design. The code for this driver can be provided upon request.

Tachometer

The system modeling experiments and proportional + speed control design require the speed of the motor. A 3D printed optical encoder wheel and photo interrupter were selected for this

purpose. A 3D model for the encoder wheel is available upon request. The output of the photo interrupter is input directly to the Raspberry Pi. Within the Simulink model the pulses in the signal are counted and converted to an angular velocity. Since direction is not important in this set of experiments only one photo interrupter was used. However, a second photo interrupter could be added if direction is needed in the future.

Motor Driver

Since the voltage and current required for the motor are too high to be directly sourced by the Raspberry Pi, an additional power supply and H-bridge were used to drive the motor. A variable DC power supply that has 1.5V increments from 3V to 12V was selected. However, 4 AA batteries could also be used. The SoftPWM library from the WiringPi libraries was used in another Simulink S-function driver to generate the pulse-width modulated (PWM) signal to drive the H-Bridge.[10] The Raspberry Pi has 17 general purpose input/output (GPIO) pins. To drive the motor clockwise, the output on pin 4 is set to high and to drive the motor counter clockwise set the pin 17 to high. It is important to set the pin 18 output (the input to the H-Bridge enable) to low before the end of the time the Simulink model runs, because otherwise the motor will continue to run.

Limitations

The current design of the kit has a few limitations that were identified during the first run in the 2014-2015 academic year. First, to measure deadzone in the same way as the existing equipment, the students need access to a DC power supply that varies both voltage and current independently. The experiments in the first run were designed to use the DC power supply in the laboratory. In the future the concept of deadzone will be illustrated through the width of the PWM signal. The measurement of the armature resistance also requires a similar power supply. Resistance could also be measured with the LCR meter used in Laboratory 3. There is also a ground loop issue with the two power supplies, which creates noise on the position signal. In the first run the ground loop noise was reduced by connecting the ground on the bread board to the bench ground. Solutions to the noisy position signal will be investigated to make the kit portable again.

Item	Supplier	Cost
Raspberry Pi Model B	Adafruit	$ 39.95
12V DC motor	Sparkfun	$ 12.95
3D printed stand	In house	$ 5.00
Bread board	Adafruit	$ 5.95
H-bridge (L293D)	Adafruit	$ 2.50
ADC (MCP3002)	Sparkfun	$ 2.30
Power supply (for RPi)	Adafruit	$ 9.90
Power supply (for DC Motor)	Adafruit	$ 14.95
Rotary position sensor (3382)	Digikey	$ 2.60
Photo interrupter	Sparkfun	$ 3.45
Pi T-cobbler breakout & cable	Sparkfun	$ 6.95
Wires	Adafruit	$ 1.60
Resistors	ECEStore	$ 0.15
LEDs	Sparkfun	$ 0.59
SD card	Amazon	$ 17.09
Total		$ 125.93

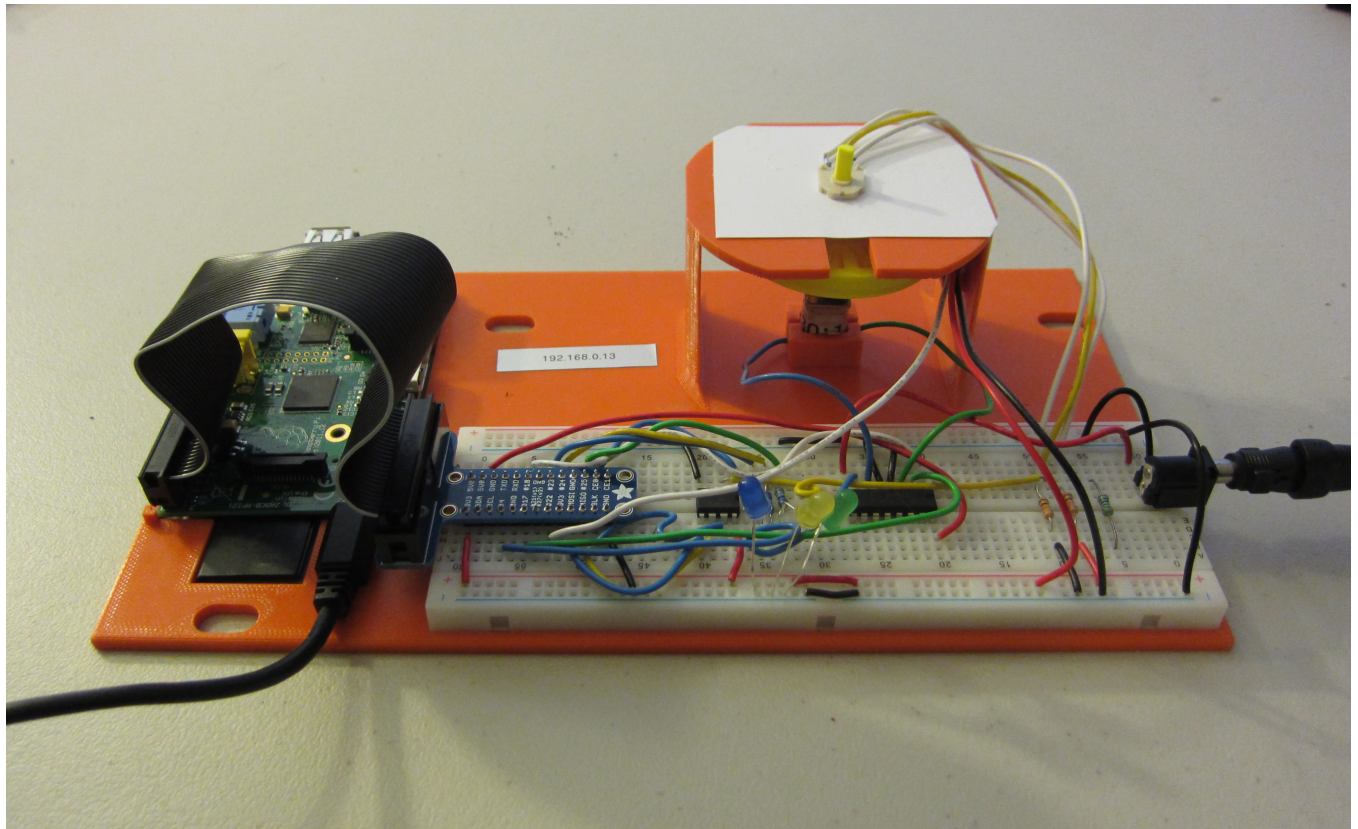Table 1: Bill of Materials

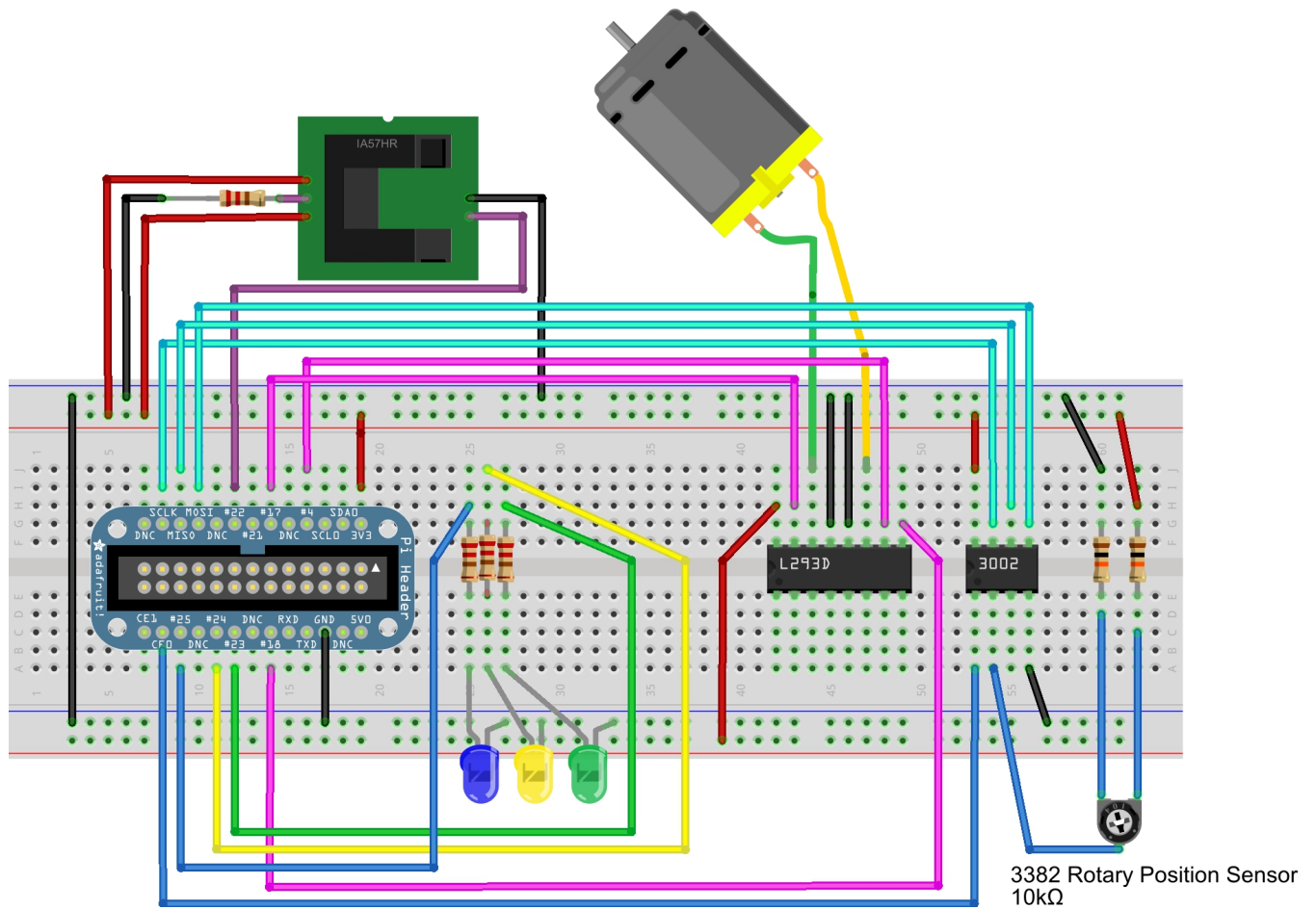Figure 1: Complete Kit for Introduction to Control Systems

Figure 2: Circuit board layout for the kit

Implementation

In each semester of the the 2014-2015 academic year, half of the laboratory sections of GE320 used the existing equipment and the other half of the sections used the new kit. During this first run, the kits were purchased by the department and were used in a traditional laboratory space with limited contact hours to keep the experience as close as possible for each group. There were approximately 75 students enrolled in the course during the first run. One lecture section is offered each semester of the first run. To measure the effectiveness of each type of equipment, both qualitative and quantitative data are being collected from the students. The quantitative data collected included exam scores, laboratory report scores, concept inventory, and satisfaction survey. The concept inventory was based on the test by Bristow et al. [11] The qualitative data includes laboratory observation and student reflections included in their individual laboratory reports. The data between the two groups were analyzed for differences in overall course performance as well as the attainment of the objectives listed in the experiments above.

Conclusions and Future Work

A portable and affordable kit was created for under $130. Based on the fall 2014 semester data, the kit looks to be as effective as the existing equipment for this course. Data collection and further analysis of the data are still on going. Future work includes adding attachments to create a Furuta inverted pendulum for use in more advanced courses. Use of the kit beyond the traditional laboratory space will also be explored including pedagogies that take advantage of the size and cost will be explored, such as studio learning, project based learning, or additions to an online course or MOOC.

Acknowledgments

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