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DEVELOPING AN AFFORDABLE LABORATORY KIT FOR UNDERGRADUATE CONTROLS EDUCATION

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ABSTRACT

The aim of this research is to expand the possibilities of multi-disciplinary controls education at the undergraduate and graduate levels with an affordable laboratory kit. A kit was assembled for around $130 while replicating the educational functionality of a typical laboratory station in a university controls laboratory. This kit could also replace expensive equipment with an affordable alternative that can be easily shipped anywhere in the world and used by students with any computer. This greatly enhances the accessibility of the laboratory experience to students in budget-strapped campus laboratories and those participating in distance education. The kit design consists of a Raspberry Pi, a DC motor, and various components required for the lab exercises. The first two kits allow students to complete labs that include DC motor system identification, DC motor control, inverted pendulum control, and any other project a student might want to create with a Raspberry Pi, DC motor, and a 3-D printer.

INTRODUCTION

This research developed a modular, portable, and affordable laboratory kit to support the accompanying curriculum for two controls courses in the General Engineering program at the University of Illinois at Urbana-Champaign (UIUC). The objective was to design each kit to be assembled for under $100 while replicating the educational functionality of a lab bench in a university controls laboratory. This will also allow older analog computers to be updated with newer technology that is more representative of what is currently used in industry [1]. By replacing expensive equipment with an affordable kit that can be shipped anywhere in the world increases the accessibility of the controls laboratory experience for students on campus and remote locations. Previous research shows that hands-on laboratory experiments help students understand and apply course material [2].

Some affordable and transportable laboratory devices for engineering education have already been developed, such as the Mobile Studio IOBoard, which is centered on a custom-built board that replicates the functionality of an oscilloscope, function generator, multimeter, and power supplies and is primarily used in introductory circuits courses [3].

The target courses for the first kit are GE320 (an introduction to control systems for general engineering students) and GE420 (a digital control course for general engineering students). These courses are representative of the first two courses in controls for many electrical, mechanical, and aerospace engineering departments. The kit design initially consists of a Raspberry Pi (a fully functional ARM-based computer that is the size of a deck of cards), a DC motor, and the various components required for the GE320 lab experiment. Where possible, off-the-shelf components are used to reduce the cost. Initial prototyping of the kit was done with an Erector set, however parts will eventually be 3-D printed to simplify assembly.

The GE320 kit has be expanded to include attachments for an Furuta Inverted Pendulum, which is the basis of the experiments for GE420. The inverted pendulum has been a benchmark in controls education for over 50 years and are still applicable to today's engineering development [4].

BACKGROUND AND MOTIVATION

The need for laboratory experiences in control systems courses has been well established in [5, 6, 7, 8] and others, however there are challenges associated with including them. Some hurdles include: budget constraints, space limitations, class size, and limited teaching resources [6, 9, 10, 11]. Additionally, the increasing popularity of online courses has added a new consideration for laboratories [5, 4, 12].

The literature shows that the cost of equipment per station varies in cost from $80 [7] to $32,493.74 [13]. This research looks to replace the basic functionality of these laboratories with an affordable kit. The target budget of $100 for the kit was used because it is the approximate cost of a textbook, only three times the cost of an iClicker, which is another common piece of technology that students purchase for courses, and the approximate cost of other kits found in literature [7, 15, 14].

In addition to monetary cost, dedicated laboratory space is also limited and class sizes are increasing. These factors place restrictions on the capabilities of face-to-face labs. Additionally, not all students can attend and complete these laboratory experiments due to time, location, or physical disability [16]. Three alternatives to face-to-face laboratory experiences have been proposed in literature: (1) virtual or simulation labs, (2) remote labs, and (3) lab kits.

Virtual labs allow students to run simulations from anywhere. Sometimes they present animations of the control systems' movement to the student on their computer screen [17, 18]. Some drawbacks to virtual labs is that students are not exposed to issues that can arise such as equipment problems, noise, or other uncontrolled real-world variables [19].

A remote lab allows students to interact with physical equipment over the Internet [5, 12, 17, 19]. They usually include streaming audio and video of the experiment [12]. The remote access to the labs offers flexibility in scheduling and access to students off-campus [5]. Remote labs have an advantage over virtual labs because the student is interacting with the physical equipment [11]. A pilot study of remote labs in [19] demonstrated effectiveness of this type of lab compared to face-to-face labs. However, remote labs are not without challenges: network security, equipment and synchronization management, Internet speed, and portability management [12].

A lab kit allows students to take home the laboratory equipment to complete the experiments on their own time [11, 12, 14, 15]. These kits started to become more popular as the cost of the required hardware has decreased [14]. The kits contents vary based on the objectives of the course and can be assembled by the instructor [14, 9], adapted from an existing kit [15] or purchased as a complete kit like Lego Mindstorms NXT [20, 21]. These kits have been well received by students [9, 11, 14].

All of these types of labs still need to meet the course goals and objectives as well as ABET accreditation requirements [8, 12]. There are several goals that can be applied to laboratory experiences based on the outcomes in the ABET Criterion; a student should have the ability to conduct experiments, analyze and interpret data, use modern engineering tools, design experiments, solve engineering problems and function in teams [19]. Specific goals for controls labs based on these goals have followed. In general, the controls laboratory experience should prepare students for a career in control systems [1] by performing the following steps: building the system [6], 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 [5, 11]. Experiments based on DC motors [7, 22] and inverted pendulums [4, 15] have been identified to meet these goals for controls laboratory experiences.

An advantage to using a DC motor for a control system experiment is proportional-integral-derivative (PID) control of the motors position is a popular example [22]. Additionally, a DC motor setup can be expanded to create more complex setups like the inverted pendulum [7]. There are also advantages to inverted pendulum experiments: the types of systems it can represent and the types of control theories that can be applied to control the system. These theories include: bang-bang control, fuzzy logic control, neural network control, PID adaptive control, robust control, hybrid control, predictive control, and feed-forward control [4]. Because of this versatility, both of these experiments will be used as the basis for the kit being developed.

The type of inverted pendulum chosen for this kit is a Furuta Pendulum. It is a two-link inverted pendulum. The first link (Link 1) is directly connected to a DC motor, while the second link (Link 2) is connected to Link 1. Link 2 has a mass attached to the end and is not actuated; it freely spins about the end of Link 1. A diagram of this pendulum is shown in Fig. 1 and the current Furuta Pendulum used at UIUC is in Fig. 2.

METHOD

There were several steps involved in the kit development. First, the objectives of each courses' lab were identified. Then the requirements of the kit were specified to meet the objectives of the course. Finally the prototype of each kit was built.

Course Objectives

The course objectives for GE320 and GE420 are similar to introductory courses at other universities [1, 4, 6, 7, 9, 15]. The following sections list the objectives specific to each course.

GE320 As the introductory control systems course GE320 covers the basics of linear, continuous-time, control de-

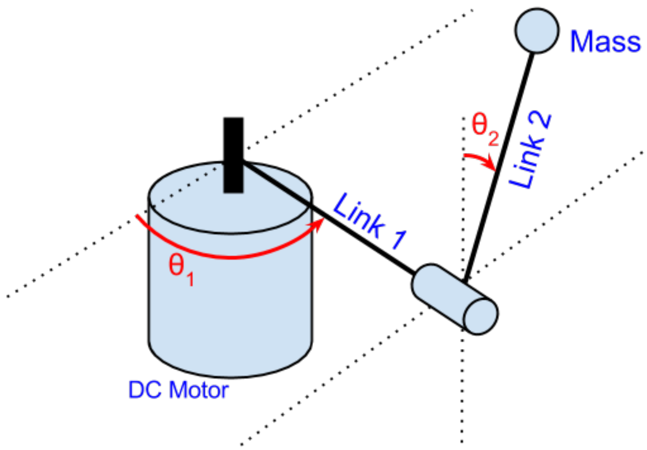

Figure 1. BASIC FURUTA PENDULUM DIAGRAM

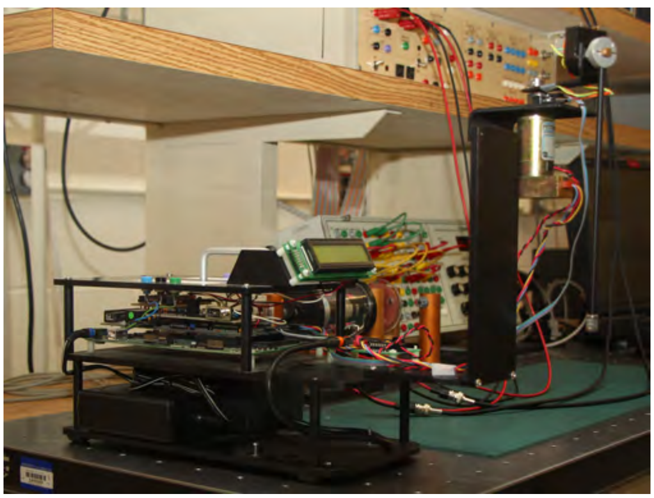

Figure 2. CURRENT FURUTA PENDULUM

velopment. The objectives of the GE320 laboratory experience are to apply the following course concepts: system identification, system frequency response, stability, and PID control. These concepts are applied using a DC motor and the associated sensors.

GE420 The digital control systems course introduces filters and control of linear, discrete-time systems. The objectives of the GE420 laboratory experiences are to apply the following course concepts: linear discrete systems, control using a digital computer, digital signal processing, and digital design. These concepts are applied using a Furuta Inverted Pendulum, digital signal processor (DSP), and the associated sensors.

Kit Requirements

The current cost of laboratory equipment used in the GE320 lab at UIUC is included in Tab. 1 and a photo of a bench in the current UIUC Controls Laboratory is in Fig. 3. In addition to this equipment, GE420 uses a Furuta Inverted Pendulum which costs approximately $1220. However, not all of the equipment used again in GE420. The goal of this research is to replicate the educational functionality of this equipment for under $100.

Table 1. EXISTING EQUIPMENT COST FOR GE320

Item		**Cost**
HP 33120A Function Generator (Discontinued, replaced by Agilent 33220A)	$	2,487.00
HP 34401A Multimeter	$	1,159.00
HP 6632A DC Power Supply (Discontinued, replaced with Agilent E3648A)	$	1,320.00
Custom built patch panel, power supplies, and amplifier	$	475.00
Comdyna GP-6 Analog Computer (No longer produced)	$	1,500.00
DC Motor, enclosure, and sensors	$	450.00
Dell Precision T3400 PC	$	1,094.00
Agilent Technologies DSO6012A Oscilloscope	$	6,159.00
Miscellaneous Wires	$	195.31
Total	*$*	*14,839.31*

Based on the objectives and the budget goal, to replace the current laboratory experiments in GE320 and GE420, the kit needs to meet the following requirements:

1. The kit shall contain a DC motor.
2. The kit shall measure the DC motor position.
3. The kit shall control the position of the DC motor.
4. The kit shall include attachments to create an inverted pendulum.
5. The kit shall measure the inverted pendulum position.
6. The kit shall display all measurements.
7. The kit shall be able to add a controller for the inverted pendulum.
8. The kit shall allow students to achieve the same educational objectives as the current laboratory equipment.
9. The kit shall be portable.

Development

In general, the following steps were used to create the lab kit:

1. Select the components.
2. Setup interface between the Raspberry Pi and MATLAB/Simulink.
3. Prototype a stand to hold the motor and support the potentiometer (This stand will be 3-D printed for the final kit).
4. Wire motor control circuit.
5. Create motor control interface in Simulink.
6. Wire sensor circuit (The analog signal from the potentiometer needs to be converted to a digital signal in order for it to be read by the GPIO interface on the Raspberry Pi).
7. Create sensor interface and display in Simulink.
8. Test the implementation.
9. Create user interface for the students.
10. Write the instructions for the lab experiments.
11. Expand the kit to include the inverted pendulum for GE420.
12. Repeat steps 4-10 for the inverted pendulum experiments.

RESULTS

A kit was created to replace the DC motor portion of the current GE320 laboratory experiments for approximately $130. The breakdown of the equipment and cost are in Tab. 2. A block diagram for this kit is included in Fig. 4 and a photo in Fig. 6. The information in Tab. 3 summarizes the GE320 experiments with the old equipment and how they are replicated with the new equipment and Tab. 4 shows the same comparison for GE420. Figure 5 shows a protoype of the current kit for both classes, by removing the Link 2 attachment the kit can be converted back to the GE320 kit. Both types of equipment currently use cookbook experiments.

In addition to the kit, each laboratory group will need a computer with MATLAB/Simulink and a network connection to the Raspberry Pi. If possible, it is recommended to have the computer and Raspberry Pi on an isolated network to increase the speed of data transfer. The license for MATLAB and Simulink have not been included in the cost of either lab setup because it is assumed that a school with an existing controls curriculum will already have a site license. This site license can be accessed from university computer labs and is also typically offered to students to use on class related activities for free or at a reduced cost. A keyboard, mouse, and monitor will be required to set the initial network settings on the Raspberry Pi.

The students' primary interface for programming the Raspberry Pi is Simulink using the support package provided by Mathworks [23]. Additionally, a device driver for the ADC interface and H-bridge input processing block have been created and provided to the students to use. Based on the type of experiment students create inputs for the motor or closed-loop control laws in Simulink. Then using Simulink's Embedded Coder the software is built and deployed on the Raspberry Pi via the network connection. When the Simulink model is run in External mode, data can be collected and viewed as the code runs via scopes or other sinks provided in Simulink. When the code is run as a standalone application on the Raspberry Pi data can be collected in a file or sent back to the host computer via User Datagram Protocol (UDP) Send and Receive blocks provided in Simulink. When the data is saved to a file on the Raspberry Pi a File Transfer Protocol (FTP) connection can be established to transfer the file to the host computer for analysis.

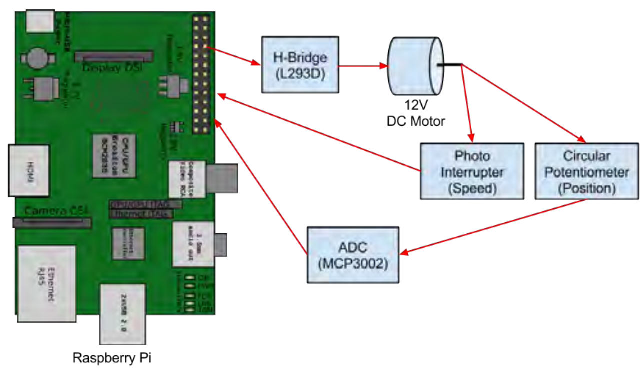

Figure 4. BLOCK DIAGRAM OF GE320 LABORATORY KIT

Within the current equipment in the GE320 kit, motor identification in experiment 2 could not be replicated. For this experiment both voltage and current will need to be varied. It could be added if a variable DC power supply is available for students to use. A DC power supply with this functionality starts around $150. Otherwise, a demonstration could be added to the lecture to cover the application of this type of system identification.

For an additional $15 the GE320 kit can be converted to the Furuta Inverted Pendulum for GE420. A second potentiometer and free swinging arm is added to the end of the arm on the GE320 kit. The position of the inverted pendulum is transmitted to the Raspberry Pi through time-multiplexing on the existing ADC (MCP3002). The experiments will vary between the equipment, however it is believed that the two are educationally equivalent.

Further details on the laboratory experiment instructions, Simulink models, 3-D models, circuit diagrams, and other details can be found at http://rebeccaee.com/labs.

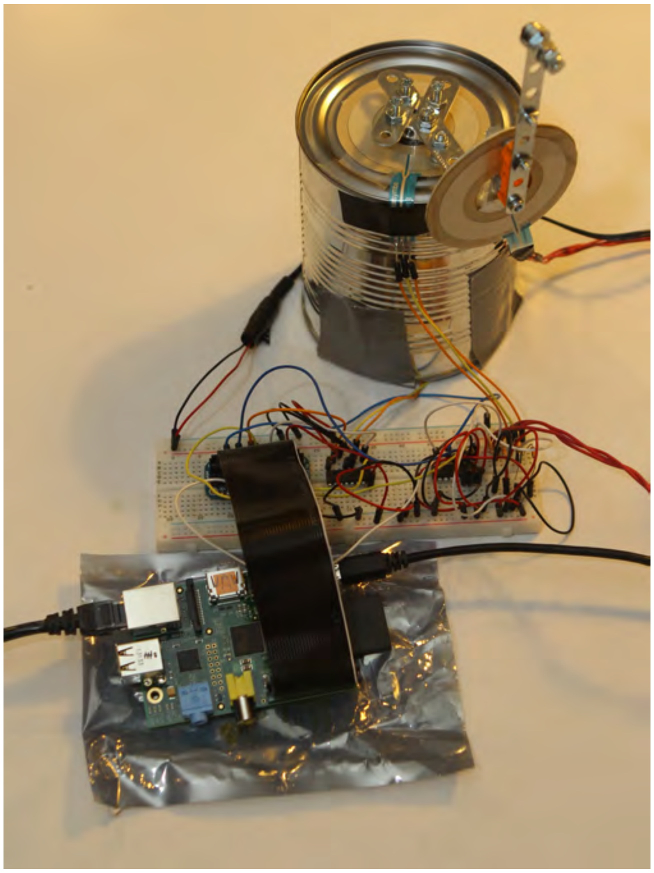

Figure 5. PROTOTYPE OF THE COMPLETE KIT

Table 2. EQUIPMENT COST FOR GE320 KIT

Item		**Cost**
Raspberry Pi Model B	$	39.95
12V DC motor	$	12.95
3-D printed stand for motor and potentiometer	$	5.00
Bread board	$	5.95
H bridge (L293D)	$	2.50
ADC (MCP3002)	$	2.30
Power supply (for Raspberry Pi)	$	9.90
Power supply (for DC Motor)	$	14.95
Potentiometer	$	7.95
Photo Interrupter	$	3.45
Pi T-cobbler breakout and cable	$	6.95
Wires	$	1.60
Resistors	$	0.15
LEDs	$	0.59
SD Card	$	17.09
Total	*$*	*131.28*

CONCLUSIONS AND FUTURE WORK

Conclusions

A kit has been developed that will replace the technical functionality of four out of the six experiments for GE320. It is currently about $30 over the target budget, however with bulk ordering and diligent price comparisons the kit cost could be reduced even further. At this time it is not clear if the educational objectives require experiment 3 to be included in the curriculum. This lab could be replaced or one (or two) of the DC power supplies could be made available for students to borrow. Since experiment 2 is the only lab that needs this functionality directly it does not seem necessary to more than double the cost and size of the kit. Additionally, GE320 experiment 6 could be recreated with the kit by adding a spring to resist the movement of the motor only during this experiment. Based on the initial development, it is believed that the GE420 kit replicates the educational functionality of the existing equipment. This will be investigated in more detail in the future.

Unlike other examples in literature, this kit was designed as a platform to serve a large variety of controls courses at all levels. It supports two widely used controls experiments: DC motor control and inverted pendulums. Another distinction of this kit is that students get hands-on experience designing systems and controls in Simulink, which is a popular tool for controls development in academia and industry. While this kit was initially designed around the existing experiments for GE320 and GE420, it is intended to be a modular and adaptable platform. Building upon this flexibility and the similarities of controls education across disciplines, it is also possible for this kit to be used in electrical, mechanical, and aerospace engineering courses as well. The entire contents of the kit fit in a shoebox sized container making it convenient to move and use outside of the laboratory. This also makes the kit possible to ship to students located off-campus.

Future Work

Now that the kit has been created for GE320 and GE420, there are several extensions that are open for exploration. First, the stand and attachments for the motor need to be designed to be more robust. Then the cookbook instructions for experiments in each class will be developed and tested in the classroom. The effectiveness of the laboratory kits will be measured with an evalu-

Table 3. COMPARISON OF GE320 LABORATORY EXPERIMENTS

Exp.	Before	After
1	Introduction to GP-6 Analog Computer	Introduction to Simulink and Raspberry Pi Interface
2	Motor and sensor characteristics	Motor and sensor characteristics
3	Motor identification via physical and electrical characteristics	Functionality not available within the cost of the kit
4	Motor identification via step and frequency response	Motor identification via step and frequency response
5	Motor control (Proportional, Proportional + Derivative, & Proportional + Speed)	Motor control (Proportional, Proportional + Derivative, & Proportional + Integral)
6	System ID and Control of a non-linear system via the web	System ID and Control of a non-linear system via the web

Table 4. COMPARISON OF GE420 LAB EXPERIMENTS

Exp.	Before	After
1	Equipment Overview	Equipment Overview
2	Introduction to DSP programming with TI Code Composer Studio	Introduction to Raspberry Pi Programming with Simulink
3	More DSP/BIOS	More programming with Raspberry Pi
4	Introduction to the I/O Daughter Card	Introduction to Raspberry Pi GPIO through T-Cobbler interface
5	DAC and ADC Signal I/O	DAC and ADC Signal I/O
6	DC Motor Discrete Transfer Function Identification	DC Motor Discrete Transfer Function Identification
7	PI Motor Speed Control	PI Motor Speed Control
8	Positioning Control of a Motor Using PD, PID, and Hybrid Control	Positioning Control of a Motor Using PD, PID, and Hybrid Control
9	Notch Filter	Notch Filter
10	Discrete Full State Feedback Control of the Furuta Pendulum	Discrete Full State Feedback Control of the Furuta Pendulum
11	Control of the Furuta Pendulum using a Full Order Observer	Control of the Furuta Pendulum using a Full Order Observer

ation similar to the methods in [19] and with a concept inventory adapted from the test proposed in [24]. This will introduce the smallest change into the course and allow for the impact of the kit to be measured directly. Once the kits have been proven effective in these classes they will be introduced into other courses including graduate level courses. Additional attachments and experiments, such as spring-mass-damper systems and other inverted pendulum set-ups will also be investigated. Changes to the curriculum to a more problem-based pedagogy will also be explored.

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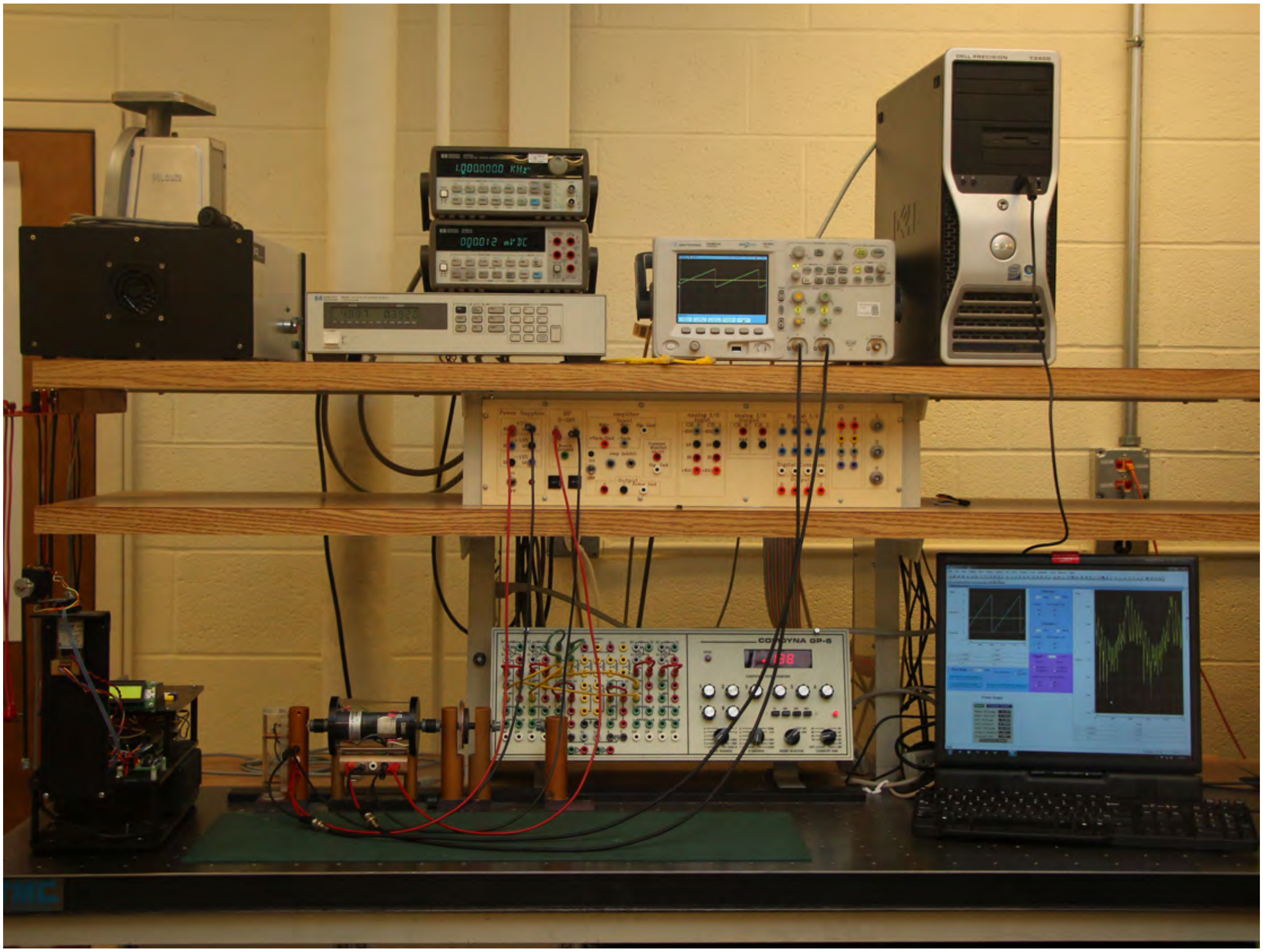

Figure 3. CURRENT CONTROLS LABORATORY

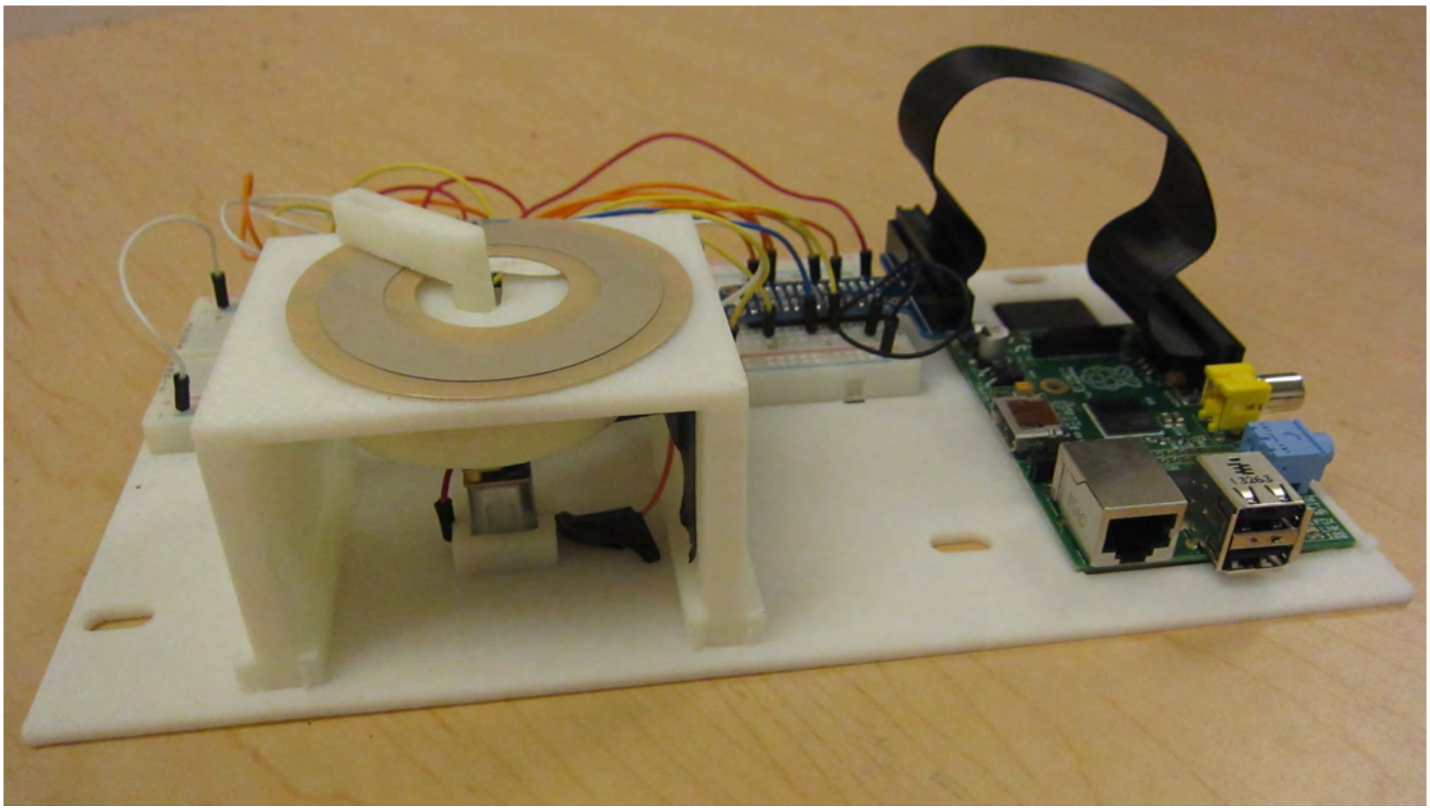

Figure 6. GE320 KIT