2018 ASEE Annual Conference & Exposition
Paper ID #21219

# A Cost-effective Laboratory Setup for Teaching System Dynamics and Controls

**Dr. Pavan K. Karra, Trine University**

Pavan Karra is Associate Professor at Trine University where he teaches in the field of Dynamics and Controls. He can be reached at karrap@trine.edu.

©American Society for Engineering Education, 2018

# A cost-effective laboratory setup for teaching system dynamics and controls

**Karra, Pavan, Trine University**


## Abstract

System Dynamics and Controls class at Trine University had been handicapped by lack of equipment for experimental realization of concepts learned in class. A single existing Quanser setup ($5000 per unit) had been used for demonstration purpose but the students lacked the immersive experience a typical lab would provide.

A similar, but more cost-effective equipment ($400 per unit), has been designed and seven units have been built and have been deployed in a laboratory setting. Three-four students share each unit. The hardware includes Raspberry Pi 3 (a credit card-sized computer), a 14-bit position encoder, a DC motor driver, and a 12V DC motor. The equipment bill of materials and some challenges during assembly are included in the paper.

Labs have been developed based on the designed equipment and labs were run during Fall 2017 semester, with seven groups at 3-4 students per group. Topics covered in the lab include digital filtering, time domain and frequency domain characterization of first order and second order systems, feedback control of first and second order systems, steady state errors, control system design using root-locus and performance of PID controllers. A final project, which used the equipment, was undertaken by the students during the semester.

A survey was conducted at the end of the semester to obtain students' feedback about how the equipment affected their learning of concepts in the course. The survey results showed that the equipment had positive impact on student learning. Based on the student performance in the final exam, and comparing it to the student performance last year, the student average has increased but did not increase statistically-significantly, mainly due to small sample size.

For Fall 2018 semester, the group size will be two and the study will determine the effect of groups size on student learning.


## Introduction

Since 2012, Mechanical Engineering (ME) program at Trine University requires student to take one of the two courses: System Dynamics and Controls (SDC) and Mechanical Vibrations. On average, about half the ME graduates take SDC.

Prior to Fall 2016, SDC was a lecture-only course. A laboratory component has been added to System Dynamics and controls course in Mechanical Engineering department at Trine University in Fall 2016. The course is worth three credit hours. The course, prior to Fall 2016, had three hours of lecture. In Fall 2016 this has been converted to two hours of lecture and two hours of lab for the same three credit hours.

In Fall 2016, for the laboratory, the students were split into about seven groups of 3-4 students per group. The groups would work on the existing single rotpend equipment from Quanser. The topics covered in the lab included, time domain and frequency domain characterization of first order and second order systems, feedback control of first and second order systems, control system design using root-locus and performance of PID controllers.

In Fall 2016, due to there being a single module and seven groups, the students would spend only about 5 minutes per lab/experiment on the equipment. The rest of the time would be spent on data processing. The students did not get to spend much time on the hardware and how different pieces of hardware interacted with each other. The students also did not get exposed to the hardware troubleshooting that would be typical of a challenging lab experience. This situation resulted in a few students commenting in the years before that more time with the equipment would have been preferred.

The objectives the proposed module was to provide student groups with their own equipment so that the students will have more time to understand the hardware and how the subsystems work. The proposed module was expected to improve student understanding of implementation, in a real-life scenario, of concepts from the class such as delineation between hardware and software, functionality of hardware such as absolute encoders and DC motors, implementation of feedback control, implementation of PID control, and finally to avoid student dissatisfaction due to insufficient number of modules.

Modules like the proposed one have been used in courses like SDC. Ryan Krauss and Chad VanderRoest[1] have designed a 3D printed balancing robot but it was published after our effort started, besides, the fact that our students lack the Microcontrollers background required also makes the module proposed in the paper[1] less than ideal.

The module proposed in the paper is like the one proposed by Rebecca Reck [2], but slightly more robust to make sure the module runs robustly for the whole semester without suffering from glitches. The increased robustness increased the cost in mechanical parts, compared to the module proposed in the paper [2].

Work toward the design and fabrication of the module proposed in this paper began in Spring 2017, as a final project in the course Introduction to Mechatronics. The students’ design was refined and improved in Summer 2017.

In Fall 2017, seven modules, similar in functionality to the equipment from Quanser, have been deployed for the SDC Lab. The following sections describe the fabrication, the labs run, the student feedback on the labs, the effect of the labs on student learning, and the future improvements proposed for the module.

## Hardware Description and Bill of Materials

The bill of materials for the setup is given below in Table 1:

**Table 1: Bill of materials**

| Qty | Item | Vendor | Unit Cost | Amount |
|---|---|---|---|---|
| 1 | Pololu Dual MC33926 Motor Driver Shield | Pololu | $ 29.95 | $ 29.95 |
| 1 | Pi Screw Terminal Breakout | Amazon | $ 19.95 | $ 19.95 |
| 1 | 8mm to 8mm Shaft Coupling | Amazon | $ 8.30 | $ 8.30 |
| 5 | 608ZZ 8mm x 22mm x 7 mm Double Shielded Premium Ball Bearing | Amazon | $ 0.99 | $ 4.95 |
| 2 | 4mm to 8mm Aluminum Alloy Motor Shaft Coupling Joint | Amazon | $ 6.45 | $ 12.90 |
| 2 | 2 Pcs 8mm x 150 mm Straight Metal Round Shaft Rods | Amazon | $ 8.74 | $ 17.48 |
| 1 | 450 V 25 A 12 Position Terminal Electric Barrier Strip Block 9-22AWG | Amazon | $ 6.42 | $ 6.42 |
| 1 | ALITOVE DC 12 V 5A Power Supply | Amazon | $ 10.99 | $ 10.99 |
| 1 | Magnetic Encoder | Digikey | $ 15.96 | $ 15.96 |
| 10 | Set Screw Shaft Shaft Collar | McMaster-Carr | $ 2.08 | $ 20.80 |
| 8 | 3" Female Threaded Hex Standoff 6-32 Thread Size | McMaster-Carr | $ 3.83 | $ 30.64 |
| 1 | 6-32 Thread Size, 1/2" Long 18-8 Hex Drive Rounded Head Screw | McMaster-Carr | $ 3.72 | $ 3.72 |
| 4 | 10 mm Female Threaded Hex Standoff M2.5 Thread Size | McMaster-Carr | $ 1.15 | $ 4.60 |
| 1 | M2.5 Thread Size 5 mm Long 18-8 Phillips Rounded Head Screws | McMaster-Carr | $ 3.40 | $ 3.40 |
| 1 | M2.5 Thread Size 10 mm Long 18-8 Phillips Rounded Head Screws | McMaster-Carr | $ 3.76 | $ 3.76 |
| 1 | M2 Thread Size 10 mm Long Hex Drive Rounded Head Screw | McMaster-Carr | $ 7.74 | $ 7.74 |
| 3 | 1/4" x 6" square 6061 Aluminum Flat | MetalsDepot | $ 8.92 | $ 26.76 |
| 1 | Digilent 290-006 | Mouser | $ 19.99 | $ 19.99 |
| 2 | Break Away Headers - Straight | SparkFun | $ 1.50 | $ 3.00 |
| 2 | Module 0.5, 64 Teeth, 20 Pressure Angle, 303 Stainless Steel Gear | SPDSI | $ 31.71 | $ 63.42 |
| | **Project Material Cost** | | | **$ 314.73** |

The module built using the parts provided in Table 1 is shown in Figure 1. Functionality of important components is provided below.

## Raspberry Pi:

The computer ("microcontroller") used for this project is Raspberry Pi, Model 3. Raspberry Pi [3] is a credit-card sized 64-bit computer with a Quad-core 1.2 GHz Broadcom processor. It has 1 GB RAM and on-board wifi adapter. The Quad-core processor allows for control loops to be executed at rates up to 7000Hz, even when executing an finite-impulse-response (FIR) filter of order 5.

## Motor Driver:

The driver to run the motor was purchased from Pololu. The driver also has current sense which produces an analog voltage proportional to the current draw, this feature will be used in future but currently not used. The driver can drive motors from 5V to 28V and with currents up to 3A per channel [4]. DC brushed motors can be controlled using pulse-width-modulation (PWM) using this driver. The driver can handle PWM frequencies up to 20 kHz.

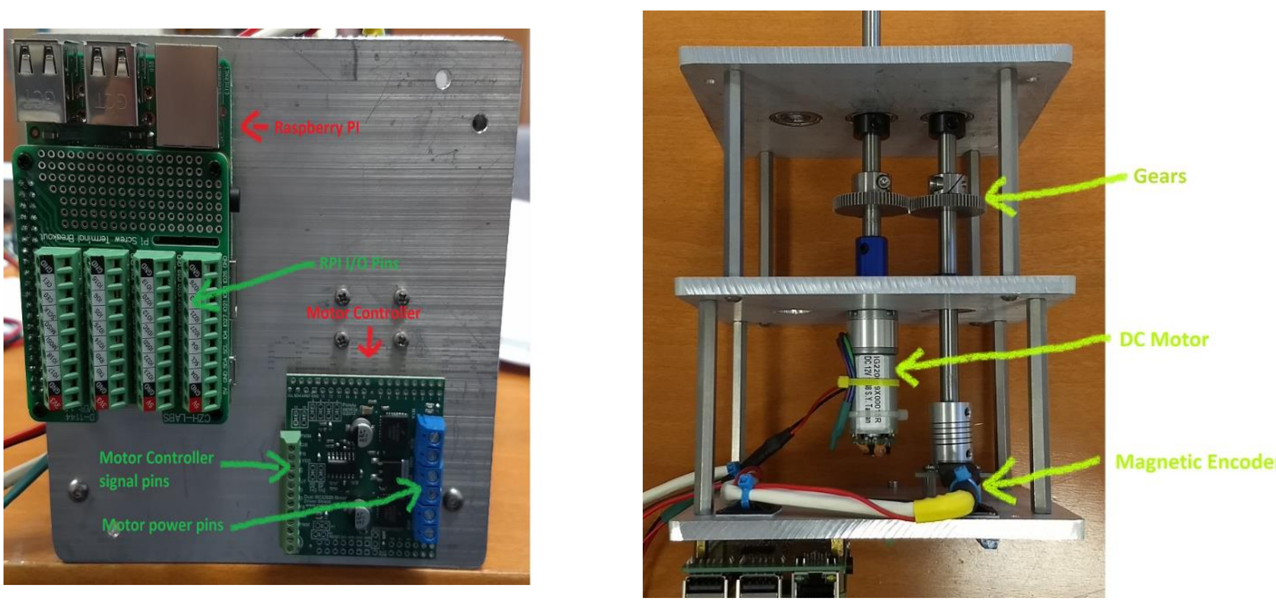


**Figure 1: Experimental Module used for SDC Lab**

### Pi Screw Terminal Breakout:

To provide easy and robust access to RPi pins a breakout board has been used [5]. The breakout board has pins labeled as per the BCM pin mapping as designed by Raspberry Pi Foundation. The screw terminals make for robust connections.

### Motor:

A 12V Digilent motor has been used as the DC motor. The motor has an internal gear ratio of 1:19 [6]. The motor has a no-load current of 200 mA and a no-load speed of 789 RPM. Stall current is 2.4A, well below the capability of the motor driver with a stall torque of 2.2 kgf.cm. The motor's specifications are disclosed in the datasheet referenced.

### Position (and angular speed) Sensor:

This is one of the mose important component of the entire module. A 14-bit absolute magnetic encoder AS5247 [7] is used to determine the position of the DC motor shaft. The encoder is purchased as breakout board from Mouser [7]. The communication protocol is SPI (Serial Peripheral Interface). The encoder board is connected in unidirectional, 3-wire mode to the Raspberry Pi. The encoder has a 14-bit resolution resulting in angular resolution of $0.22^{o}$. The frequency of reading the angle is limited only by the RPi. Since the angle is measured at high frequency (up to 70000 Hz), the angular speed is calculated by taking derivative of the angle measure.

One aspect of the magnetic encoder is the magnet. The placement of the magnet with respect to the sensor is critical to the accurate functioning of the encoder. The distance needs to be 1-2mm.

The encoder provides two different values as measured by top and bottom dies. This provides redundancy in the angle measurement. Even though incremental encoder output has not been used in the module here they are nevertheless available and can be used if needed.

## Labs and Final Project

The purpose of the labs and the final project were to provide hands-on experience to students of implementation of feedback controls, and implementation of PID controls.

The labs taught the students the concepts on how to implement controls loops and the project assessed the students' ability to implement the control loops.

## Labs:

Eight labs were executed using the module. The first lab was an introductory lab which was designed to make the students familiar with hardware and software. The remaining labs were divided into two sections. The first section was about system identification and the second about feedback control. In each half, first and second order systems were covered.

A brief description of each lab and the concepts covered during the lab are provided below:

1. Lab 1: Introductory lab, familiarizes students with wiring, hardware and software.

2. Lab 2: First order system identification in time domain: Identifying the transfer function of the system using step response. The input is voltage and the output is angular speed of the motor. Since angular speed is obtained using the derivative of angular position, it is noisy and has to be filtered. An FIR filter of order 5 is used to filter the noise. Terms representing inertia and damping are identified using the step response.

3. Lab 3: First order system identification in frequency domain: the input to the system is sinusoid with variable frequencies. The output is the amplitude of angular speed of the motor. A bode plot is plotted and compared with results from Lab 2.

4. Lab 4: Second order system identification in time domain: determination of inertia and damping in the system using initial condition response of pendulum. Simulate response using obtained parameters and compare with experimental results.

5. Lab 6 (Lab 5 was done using different equipment): Feedback control of first order system. Speed control of DC motor.

6. Lab 7: Feedback control of second order system. Position control of DC motor using proportional gain.

7. Lab 8: Feedback control of second order system. Position control of DC motor using proportional gain with velocity feedback. The velocity feedback provides damping. This is PD control.

8. Lab 9: Eliminating steady-state errors using PI control. Speed control of DC motor. Integral control eliminates steady-state error.

For each lab, the students submitted a memo-style report which included the justification for experiment, the procedure, the calculations and the conclusions.

## Final Project:

A final project was also executed by students using the same module they used for labs. The final project was to build and execute a pick-and-place robotic arm. The robotic arm would grab a ping-pong ball and place it in a container which is at a pre-determined angle from the place the ball was picked. The destination container was a tube whose diameter was only slightly higher than the diameter of the ball. This meant that the position of the robotic arm had to be controlled accurately.

The project was contest in which the groups who transfers the most number of ping-pong balls in 5 minutes scores the maximum score and the score of each other group is ratiometric to the number of balls transfer their group.

Different groups used different control strategies to execute the project. Some students went with low proportional gain and made their arm robust while other groups used PI control to avoid steady-state error and high p-gain. The final project turned out to be successful for all teams since the range of balls transferred in 5 minutes ranged from 64 balls to 120 balls.

## Student Feedback

Two surveys were conducted, one after the labs were completed, and one after the final project. The reason for two surveys is that the final project, being more concrete than labs, was expected to provide the student a better perspective on the labs.

Both the surveys were anonymous.

The following are the response the students provided.

**Table 2: Student responses after labs but before final project**

| **Question (N = 18)** | **Strongly agree** | **Agree** | **Neutral** | **Disagree** | **Strongly Disagree** | **Question Average (out of 5)** |
|---|---|---|---|---|---|---|
| The experiments relate to the concepts covered in class | 7 | 10 | 1 | 0 | 0 | 4.33 |
| The experiments helped you better understand the material covered in class | 3 | 9 | 6 | 0 | 0 | 3.83 |

| | | | | | | |
|---|---|---|---|---|---|---|
| My (student's) physical intuition improved because of these labs | 4 | 11 | 2 | 1 | 0 | 4.00 |
| I enjoyed doing the experiments | 1 | 10 | 5 | 2 | 0 | 3.56 |

**Table 3: Student responses after final project**

| Question (N = 16) | Strongly agree | Agree | Neutral | Disagree | Strongly Disagree | Question Average (out of 5) |
|---|---|---|---|---|---|---|
| The experiments relate to the concepts covered in class | 6 | 9 | 1 | 0 | 0 | 4.31 |
| The experiments, along with final project, helped you better understand the material covered in class | 5 | 8 | 3 | 0 | 0 | 4.13 |
| The final project improved my understanding of SDC | 7 | 6 | 2 | 1 | 0 | 4.19 |
| I enjoyed doing the final project | 7 | 6 | 2 | 1 | 0 | 4.19 |

As can be seen from Table 2 and Table 3 students report an improved learning during the final project. It was assumed that the final project will solidify the concepts learns learnt during the labs which was confirmed by the survey.

Students also agree that the labs and final project add value to their learning but don't enjoy doing them. This was expected since the labs and the final project were designed to be challenging in terms of hardware troubleshooting and writing the relevant code for each lab/final project.

## Effect on Student Learning

The next aspect which needs to be measured is the effect the module had on student learning.

The following figure shows the comparison of student performance from Fall 2016 to Fall 2017.

**Table 4: Comparison of student performance in Final Exam, Fall 2016 vs Fall 2017**

| | Fall 2016 (N=15) | Fall 2017 (N=20) |
|---|---|---|
| **Average** | 74.7 | 78.9 |
| **Standard Deviation** | 19.6 | 12.2 |

Conducting a two-tailed t-test, the improvement from Fall 2016 to Fall 2017 has not been found to be statistically significant ($p = 0.460$). This is because of small sample size.

As mentioned earlier, 3-4 students were assigned to each group. It would have been ideal if there were only two students per group as it was expected to improve learning. It has been noticed that out of 3-4 students in each group, a student, on average, in each groups did not have much contribution to the success of labs/final project. More modules are planned to be deployed in Fall 2018 to alleviate this problem.

The final exam for course tests whether key learning objectives have been met but the final exam results were not recorded question-wise and hence a determination to make whether an improvement in learning has been made on a concept is difficult to make at this time. This will be kept in mind for the future work related to the current study.

## Future Improvement of the Setup

As mentioned earlier, because of the binding of external gears, the performance of the modules was less than ideal. Future improvements include replacing the existing DC motor with a through-shaft DC motor which eliminates the necessity of gearing.

Currently, seven modules have been put to use with each module serving 3-4 students. For Fall 2018, another seven modules will be added so that each module serves only two students. This way, student learning and hands-on experience is expected to improve further.

## Conclusion

A module has been designed, built, and implemented in SDC lab to provide immersive hands-on experience of typical lab equipment. The module consists of aluminum plates, a DC motor, a magnetic encoder, and a motor controller. PWM is used to control the motor voltage.

The concepts covered in the labs included system identification of first and second order system, and feedback control of first and second order systems. A final project was assigned to solidify the concepts learned in lab.

Two surveys have been conducted before and after final project which showed that the students' rated the modules at or better than 4 out of 8 in both surveys. The students' rating of the module increased slightly after the students finished the final project.

Finally, the student performance in the final this year was compared with their performance in the previous year. The student performance has not improved statistically significantly, mainly due to small sample size.

As opposed to the previous years' student responses, this year there were no comments about lack of sufficient number of modules which impeded their learning.

A few glitches have cause less than ideal performance of the module. A DC motor with through-shaft will need to replace the existing DC motor to achieve robust performance of the module. Reducing the size of groups is also expected to improve student learning. Both the proposed improvements will be implemented in Fall 2018.

## References

1. Ryan, Krauss, Chad Thomas VanderRoest, MAKER: A 3D Printed Balancing Robot for Teaching Dynamic Systems and Control, Paper ID #20399, , 124th ASEE Annual Conference, 2017.

2. Rebecca Reck, BYOE: Affordable and Portable Laboratory Kit for Controls Courses, Paper ID #13467, 122nd ASEE Annual Conference, 2015.

3. "Raspberry Pi 3 Model B." Raspberry Pi, Raspberry Pi Foundation, Accessed, 12/31/2017.

4. Pololu Dual MC33926 Motor Driver Shield for Arduino. (n.d.). Retrieved December 31, 2017.

5. Electronics-Salon Pi Screw Terminal Block Breakout Module, for Raspberry Pi." Amazon.com: Industrial & Scientific, Amazon.com, Accessed, Dec 31, 2017.

6. DC Motor/Gearbox (1:19 Gear Ratio): Custom 12V Motor Designed for Digilent Robot Kits." Digilent, Digilent.com, Accessed Dec 31, 2017.

7. Datasheet "AS5247-MF_EK_AB ams | Mouser." Mouser Electronics, mouser.com, Accessed on Dec 31, 2017.