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Low-Cost DC Motor Control System Experiments for Engineering Students

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Abstract

By and large, the control system theory curriculum in many Engineering schools is limited to computer simulations, mostly because of the limited control lab equipment suppliers and modest resources. The Electrical and Computer Engineering (ECE) program's faculty and graduate students were tasked to design a low-cost system that connects the theoretical concepts learned in class and real-world applications. This system was designed with a modular approach to develop new experiments using the existing system. The developed system is an integration of National Instrument's (NI) LabVIEW software, NI's myDAQ (a portable and easy-to-program low-cost data acquisition device), a DC motor with a built-in rotary encoder, and a PCB with the motor drive circuits. The circuit wiring for the whole system has been designed and developed into a PCB design for compactness and ease of use. The students use graphical programming to control the motor and record its response utilizing the myDAQ as an interface between LabVIEW and the DC motor. Lab experiments that emphasize on design, simulation, and development of virtual instruments to implement motor control have been developed. These experiments train students in various topics of control system theory, such as identification, modeling, speed, and position control. The entire system is housed in a 12" X 12" polycarbonate case, for safety and laboratory desk organization purposes.

To assess the level of effectiveness of this newly designed control system laboratory, the student performance was assessed using relevant grading rubrics. A student feedback survey was also performed to help improve the learning experience. The developed control laboratory system proved to be a low-cost and effective hands-on learning experience. Students were able to study several DC motor control designs for desired control specifications. Further revisions of the lab instructions and experimental setups have been in progress based on student feedback and instructor observations.

I. Introduction

Historically, linear controls laboratory equipment has been expensive and non-portable in most cases [3]. The linear controls laboratory workstations in Electrical and Computer Engineering program within Youngstown State University have been equipped with a spring-mass mechanical system that occupies half the desk space of each workstation. The existing system has not been calibrated for a few years, resulting in huge system errors during the control experiments. In addition, the replacement of the equipment with newer ones for the experiments to meet the control theory curriculum requirements appears to be very expensive. Alternatively, since there has been rapid development in various cost-effective tools and mechanisms for control systems experiments using microcontrollers and other kinds of pocket labs [9], it is in our best interest to find economic and flexible alternatives for the control systems experiments. A DC motor was chosen as the control system to build the laboratory experimental set-up because of its ubiquitous yet crucial role in research, industry, and laboratory experiments. The simplicity and low-cost features of DC motor make them an excellent choice for incorporating flexibility into experiments, while still maintaining reliable performance [7]. This paper presents a low-cost in-house developed DC motor control system for undergraduate engineering students. The developed laboratory is ensured to meet the course goals and objectives as well as ABET

accreditation requirements [10]. Also, the developed laboratory methodology is being effectively optimized in terms of bench space and cost.

II.   The Laboratory Workstation

The controls laboratory is equipped with 8 workstations. Each one comprises a combination of the following hardware and software tools:
- PC with LabVIEW
- NI myDAQ data acquisition device
- myDevBoard prototype board with a motor powering circuit
- DC gearmotor with encoder

NI's Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is one of the most useful platforms that prove to be a suitable environment for system design and development, thereby standing as a reliable teaching tool in the applications of controls theory [6]. The NI myDAQ is a low-cost portable data acquisition (DAQ) device that uses NI LabVIEW based software instruments, allowing students to measure and analyze real-world signals [1]. A DC motor control system can support many experiments, and therefore is explored and used in this experiment setup [4].

The complete experimental hardware setup is shown in Figure 1. The NI myDAQ connects to the PC equipped with LabVIEW software via a USB (Universal Serial Bus) cable and to the myDevBoard prototype board via the 20-position screw terminal connector [1]. The designated analog and/or digital physical channels of the myDAQ are wired to the motor interface and driver circuit which is hand-wired on the myDevBoard prototype board. The main components of this circuit are the operational amplifier (1), a pair of npn and pnp darlington transistors, and a DC gearmotor. The NI myDAQ and motor interface circuit shown in Figure 2 is powered using a +/-9V DC power supply. A Pololu 6V brushed DC 120 rpm 9.68:1 metal gear motor is interfaced with the NI myDAQ and prototype board circuit assembly. The motor is integrated with a 48 cpr quadrature encoder on the motor shaft, thereby providing 48*9.68 = 465 counts per revolution of the gearbox's output shaft [2]. The DC gear motor is connected to the circuit shown in Figure 2 via the motor encoder red lead to power, black and green leads to the ground, blue lead to +5V on the myDevBoard, and yellow lead to the designated myDAQ channel [2].

The NI myDAQ, myDevBoard, and the DC motor are assembled within a 12" X 12" transparent housing made from clear impact-resistant polycarbonate. The gear motor with encoder is mounted on one side of the square housing. The front side of the housing is kept open for easy access to the circuit on the prototype board. The other remaining side is drilled for connection cables to pass through. In addition, the laboratory instruments such as the bench power supply, digital multimeter (DMM), and banana-alligator cables are required for performing the lab exercises.
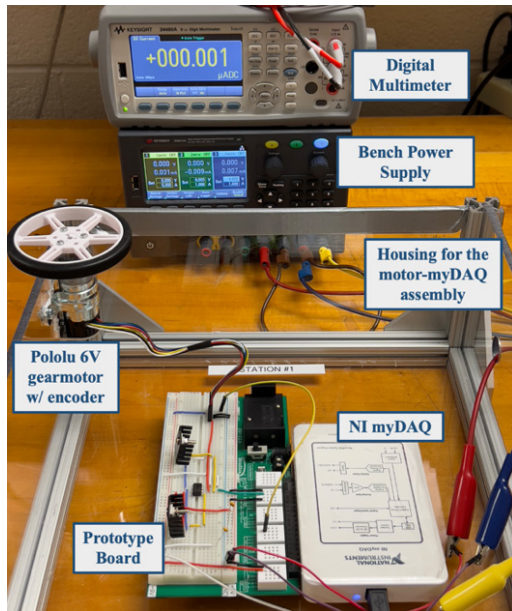
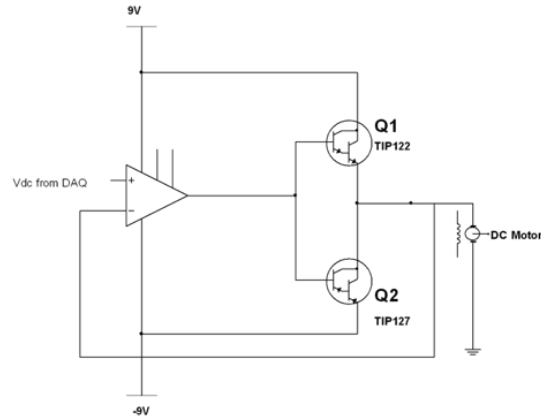Figure 1: Experimental Setup

Figure 2: NI myDAQ - motor interface circuit

A. Bill of Materials

The complete experimental set-up of the reliable and economical control laboratory cost around $367 per single workstation. The bill of materials (BOM), including the details on hardware and software tools involved in each workstation, are listed in Table 1. Additionally, the data acquisition device and accompanying software purchased are not restricted to usage in the control laboratory alone and can be utilized for various experiments and educational purposes.

Lab Set-up	Description	Bulk Purchase price per unit ($)
Data Acquisition & Software	myDAQ with NI LabVIEW and Multisim	$249.97
	myDevBoard - Prototype Board	$40.48
Gearmotor Assembly	LP 6V 9.7:1 Metal Gearmotor with 48 CPR Encoder	$42.97
	Pololu Multi-Hub Wheel w/ Inserts 80x10mm	$3.97
	Pololu 20D mm Metal Gearmotor Bracket	$3.47
Circuit Components	NPN Transistor (TIP122)	$0.55
	PNP Transistor (TIP127)	$0.49
	TO-220 Heatsink with 1 hole	$0.39
	5-Piece Heat Sink Mount Kit for TO-220 packages	$8.95
	IC LM741CN Operational Amplifier	$0.69
	Multilayer Ceramic Capacitors	$0.12
	Pin Strip Headers and wires	$7.00
12"x12" Housing	Slot Rail, Bracket, End-Feed Triple Nut, Clear Impact-Resistant Polycarbonate	$8.00
	Total	$367

Table 1: BOM for a single workstation

III.   Assignments for Controls Systems Experiments

The objective of constructing and designing the DC motor system using NI myDAQ and LabVIEW is to enhance students' understanding of the correlation between control system theories taught in the classroom, their practical applications in the real world, and the software tools frequently employed by engineers [5]. Therefore, the lab assignments accompanied with the developed experiment set-ups involve exercises on getting familiar with the LabVIEW programming environment, NI myDAQ data acquisition system, DC motor direction and speed observations, motor identification and modeling, investigation of the open-loop and closed-loop system, PID speed control and PID position control.

A. Intro to LabVIEW and NI myDAQ

The first laboratory exercise involves getting familiar with the LabVIEW software and the NI myDAQ hardware. This exercise focuses on gaining first-hand experience with some of LabVIEW's graphical programming environment and the NI myDAQ implementation and capabilities. This exercise explores different virtual instruments present within the software and teaches students to build a simple Virtual Instrumentation (VI) file. As part of the programming exercise, the students build a simple thermometer that measures temperature in both Celsius and Fahrenheit. This exercise enables the students to be familiar with locating different numeric, Boolean, and graphical tools along with getting a sound understanding of the program's data flow. The students also learn to configure the software's front panel and block diagram for the desired system. This LabVIEW exercise is entirely based on simulation and no data acquisition hardware is involved yet.

To familiarize themselves with the myDAQ data acquisition system, students are tasked with reviewing the NI myDAQ user guide, which covers physical analog channels, digital lines, and other specifications such as the sampling rate, voltage range, number of counters, input/output configurations, and more. The students are also asked to set up the physical interface between the NI myDAQ, the myDevBoard prototype board, and the DC motor. The completion of this laboratory exercise is assessed through successful simulation of the LabVIEW program and understanding of the NI myDAQ specifications and interface.

B. Motor Identification and Modeling

The goal of this experiment is to develop the transfer function of the lab DC motor. The open-loop transfer function to be obtained is:

$$G(s) = \frac{\Omega}{E_a} = \frac{K/JR_a}{\left[s + \left(\frac{K^2}{JR_a} + \frac{B_m}{J} \right) \right]}$$

where K: motor's torque constant (N/m/s)
J: motor's mass moment of inertia (kg m^2)
R$_a$: motor's armature resistance (Ω)
B$_m$: motor's friction coefficient (N/m/s)

The motor parameters are obtained by performing calculations on the measurements of the motor's current and shaft speed for different applied voltages. Once the DC motor system

parameters are identified, the open-loop transfer function G(s) is established. Then, the transient response of the modeled system is obtained in LabVIEW. Figures 3a & 3b show the LabVIEW block diagram and front panel respectively for motor identification. The transient behavior of the system is then verified using MATLAB by plotting the transient response of the motor's transfer function. The obtained plots of the transient response from LabVIEW and MATLAB are then compared to verify the accuracy of the LabVIEW results to the MATLAB simulations. Figure 3c shows the MATLAB plot for the transient response of the derived open-loop DC motor system, which is comparable to the one observed in Figure 3b.
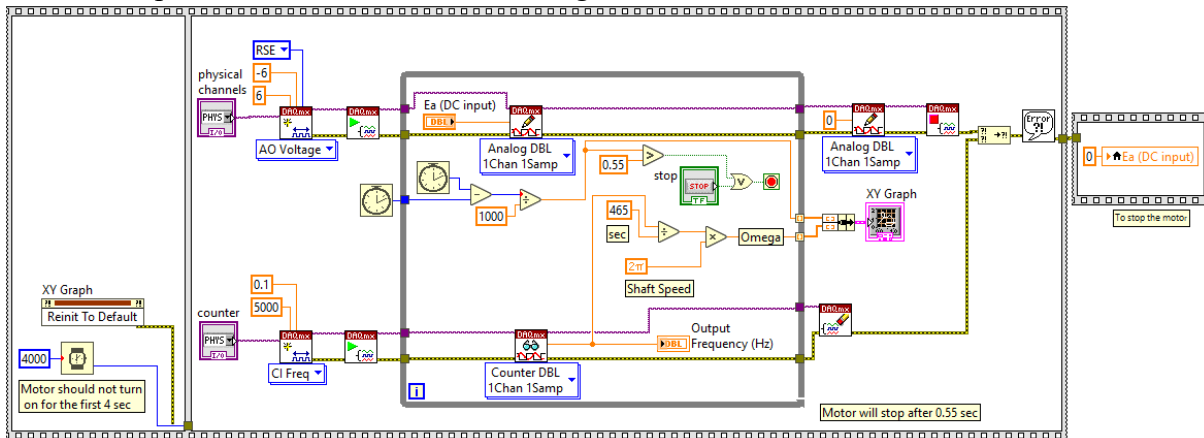
Figure 3a: LabVIEW block diagram for motor identification exercise
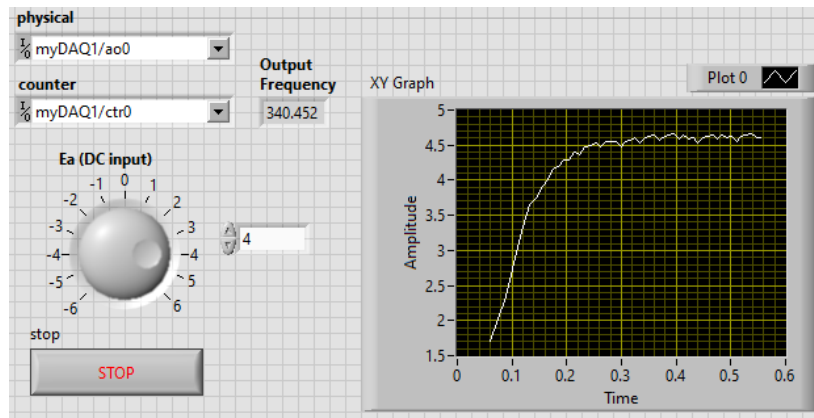
Figure 3b: LabVIEW front panel for motor identification exercise
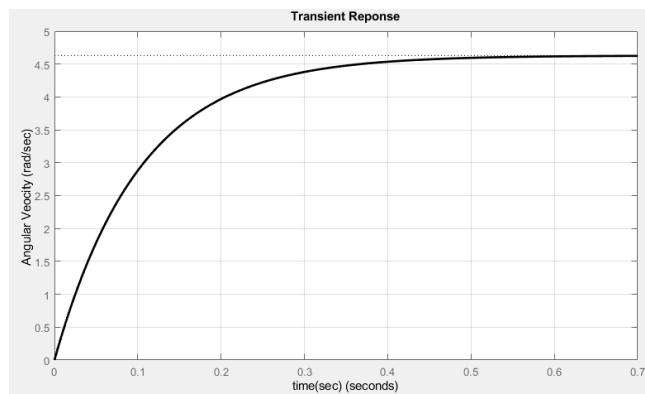
Figure 3c: MATLAB plot for motor identification exercise (transient response)

C. Open and Closed Loop Performance of DC Motor System

The goal of this assignment is to investigate the response of the motor system in the open-loop and closed-loop configurations. The block diagrams representing the motor open loop and closed loop configurations are shown in Figures 4 a & b.
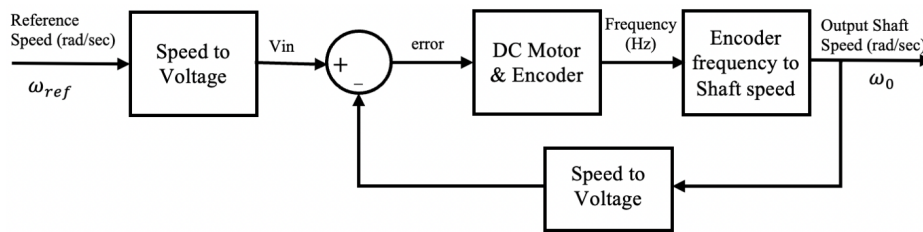

Figure 4a: DC motor open-loop system

Figure 4b: DC motor closed loop system

To begin this exercise, the transient response for open and closed loop systems is obtained in MATLAB and the response parameters such as rise time, settling time, overshoot, steady state value, and error are analyzed. Then, the LabVIEW VIs are developed to communicate with the physical motor system in both open-loop and closed-loop configurations. The LabVIEW plots of the transient response are then compared to that of MATLAB. Figure 5a & 5b show the respective LabVIEW block design and front panel for the DC motor closed-loop system.
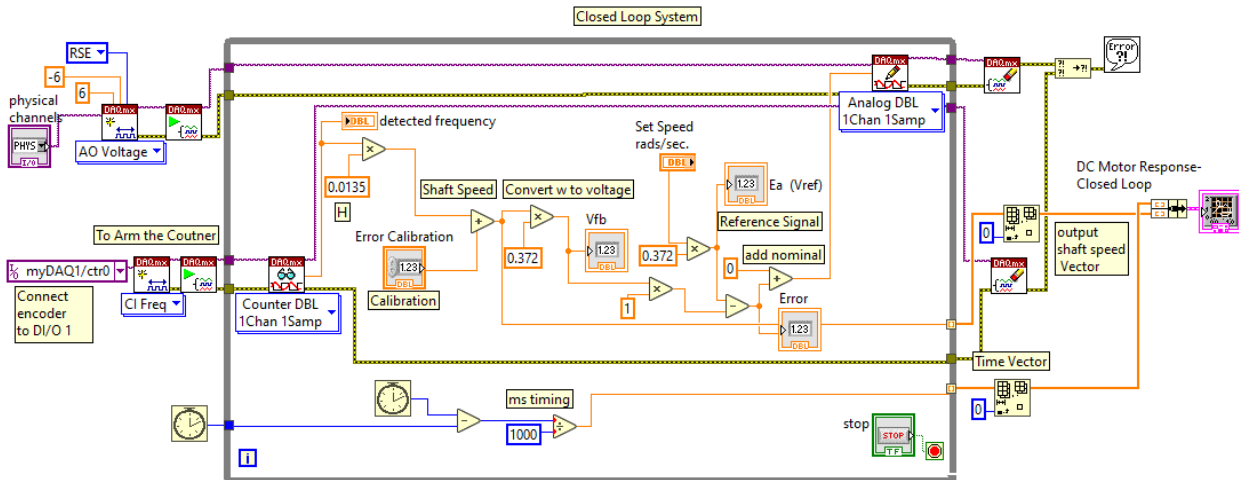

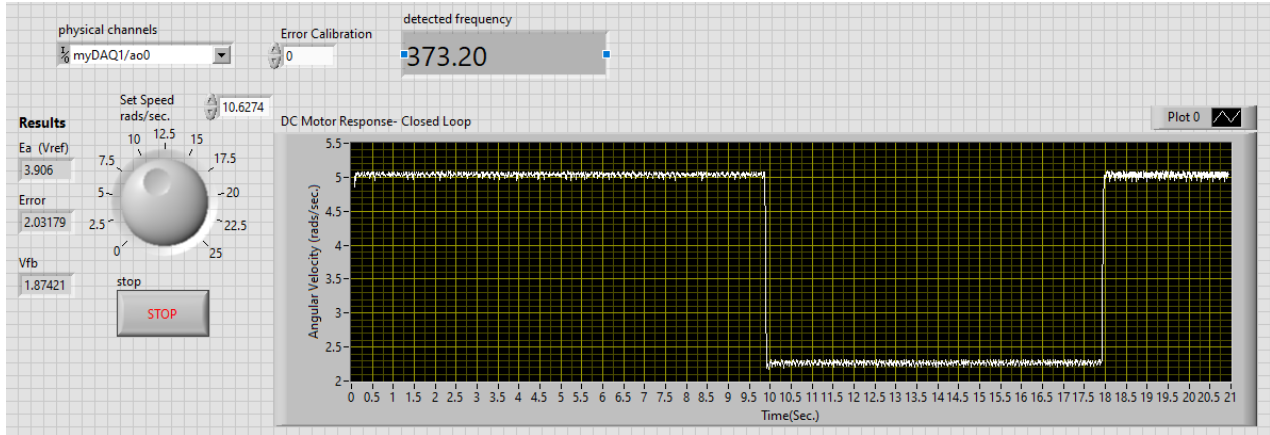Figure 5a: LabVIEW block design of the closed-loop configuration

Figure 5 b: LabVIEW front panel of the closed-loop configuration

D. PID Controller – Speed and Angular Position Control

A Proportional-Integral-Derivative (PID) controller is a widely used feedback control mechanism in industrial controls to regulate a system's behavior [7]. A PID controller comprises of three compensator gain parameters: the Proportional gain (K_p), the Integral gain (K_i), and the Derivative gain (K_d).

Let the error signal, e(t) be defined as the difference between the desired output indicated by the reference signal r(t) (setpoint) and the actual output y(t) (process variable); e(t) = r(t) – y(t). The proportional component generates a signal proportional to the error signal. The proportional control component is used to improve the rise time [14]. The integral component integrates the error over time to reduce steady-state errors, while the derivative component calculates the error's rate of change to improve the system's response time and reduce overshoot. By combining these components in a weighted sum, the PID controller can adjust the system's behavior to reach the desired setpoint. Each of the PID controller components affects the controller's response characteristics, such as its stability, responsiveness, and steady-state error. Figure 6 shows a basic PID algorithm block diagram, where r(t) is the desired setpoint, e(t) is the error signal, and the feedback signal is the process variable [13]. The general effects of each controller gain (K_p, K_d, K_i) on a closed-loop system are summarized in Table 2 [12].
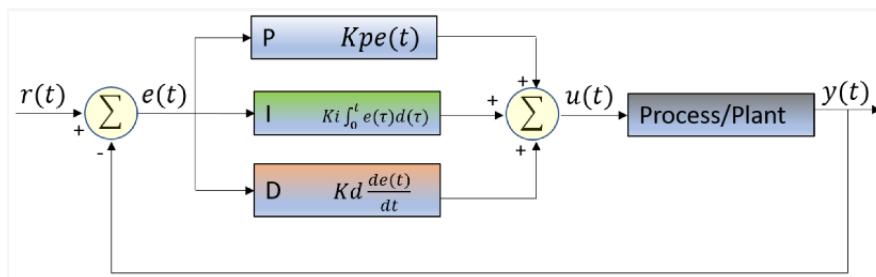

Figure 6: Basic PID block diagram

Closed Loop Response	Rise Time	Overshoot	Settling Time	Steady State Error
Increase K_p	Decrease	Increase	Small Change	Decrease
Increase K_i	Decrease	Increase	Increase	Eliminates
Increase K_d	Small Change	Decrease	Decrease	No Change

Table 2: Effects of PID controller parameters on closed loop system

In this laboratory exercise, the "guess and check" method is employed for PID tuning [12]. This approach involves setting the Ki and Kd terms to zero initially, and then gradually increasing the Kp until the loop's output starts to oscillate [8]. As the proportional gain is increased, the system becomes faster, with increased overshoot. However, it is important to maintain stability. Once a certain overshoot (typically 20-30%) is achieved, the proportional term is kept fixed, and the integral term is increased to reduce the steady-state error. After setting the proportional and integral terms, the derivative term is increased to reduce overshoot and improve the settling time.

The students are to implement a PID controller for motor speed control and angular position control in a closed-loop configuration, with the aim of meeting the desired requirements for damping, overshoot, and steady-state error. The students utilize the "guess and check" method on MATLAB simulations to obtain the gains of the PID controller that will lead to the desired system response. Once the desired response is observed in MATLAB, the controller gains are then translated to LabVIEW for implementation on the DC motor system. This lab exercise requires students to obtain different transient responses of the system: overdamped, underdamped, marginally stable, and unstable, by adjusting the PID gain values. Figures 7a and 7b are the MATLAB plots and LabVIEW plots for an overdamped response respectively. Figures 8 and 9 illustrate the LabVIEW front panel plots for an underdamped and an unstable response respectively. For the angular position control part, the motor position measurement is done through LabVIEW VI and then a PID controller is implemented for desired angular position control. Figure 10 shows the block diagram of the PID compensated position control system. Figure 11a & 11b shows the LabVIEW block diagram and front panel for the PID controller for angular position. There is no absolute position measurement with the motor used in this set of experiments, thus the position referred to in this paper is a relative position [11].
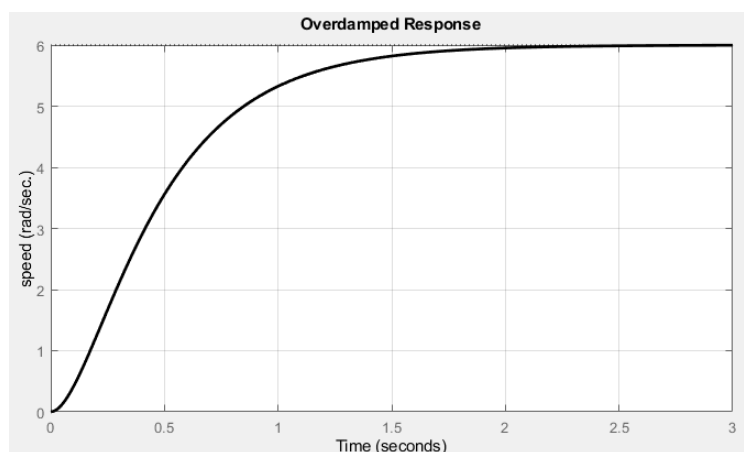

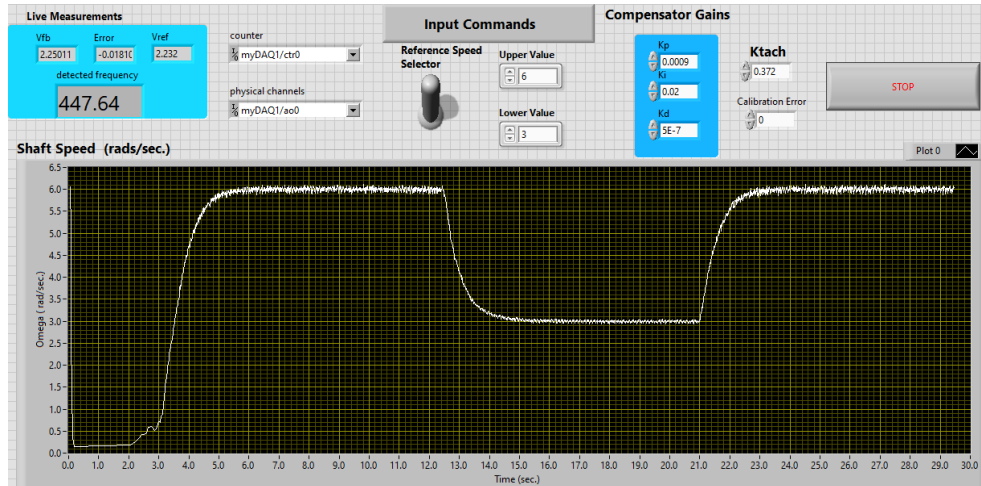Figure 7a: MATLAB plot for overdamped response

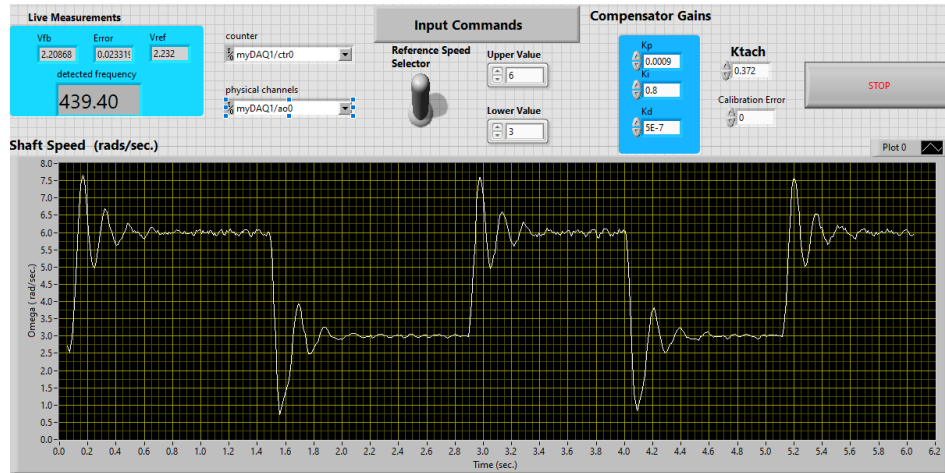Figure 7b: LabVIEW front panel plot for overdamped response

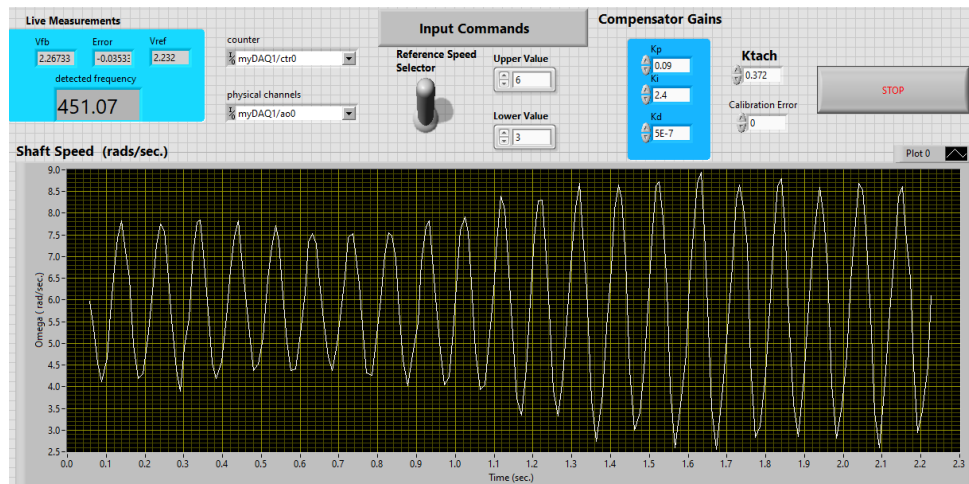Figure 8: LabVIEW front panel plot for underdamped response

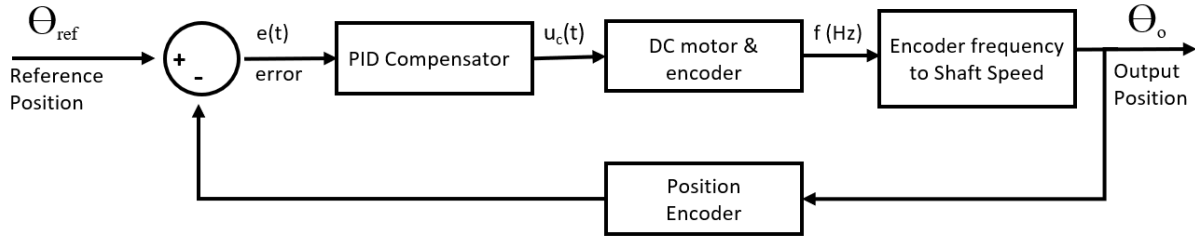Figure 9: LabVIEW front panel plot for unstable response
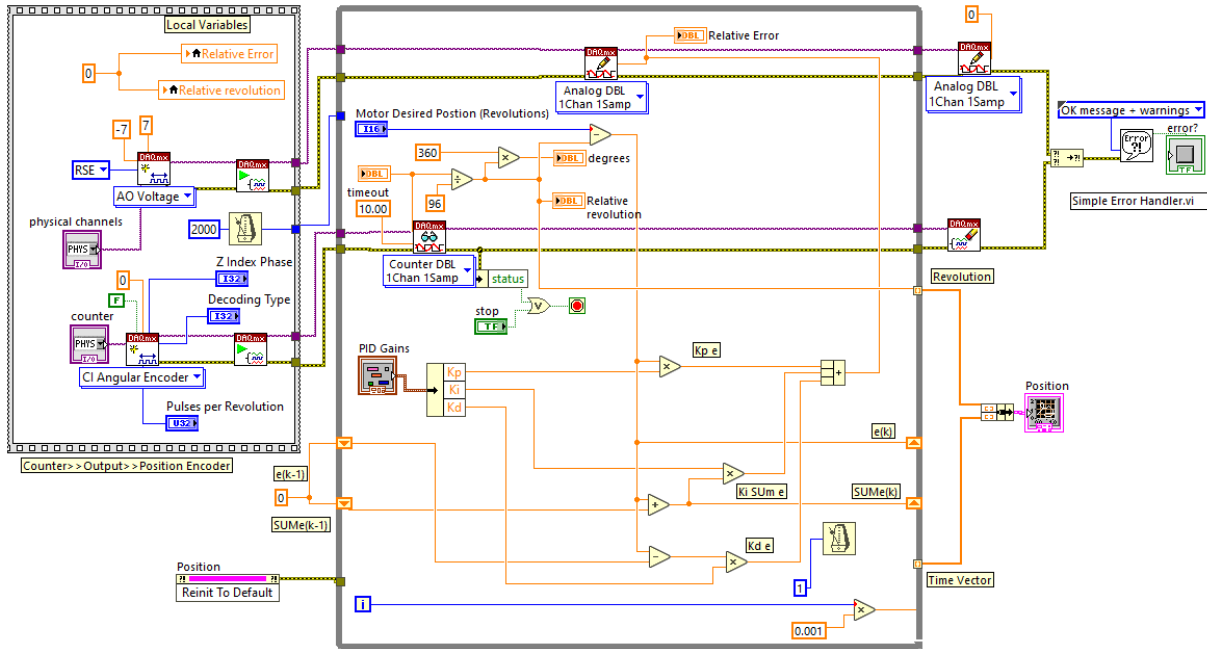
Figure 10: Compensator position control system

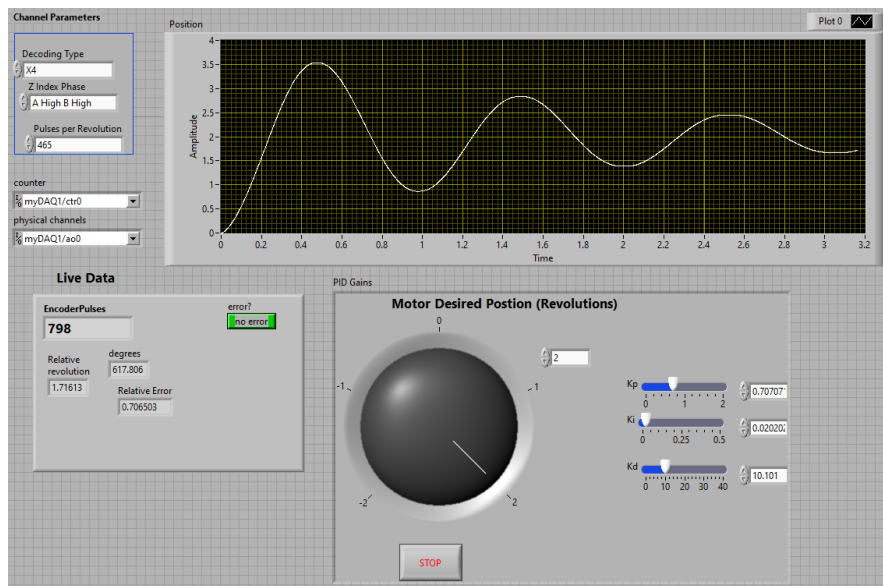Figure 11a: PID Angular Position Controller Block Design

Figure 11b: PID Position Control front panel

IV.   Revision

The experimental setup has proven successful in carrying out all the assigned laboratory exercises. However, there is still some room for improvement. One aspect for improvement is organizing the wires to keep the prototype board less crowded and to avoid the possibility of incorrect wiring. Another aspect of improvement can be reducing the bench space by replacing the polycarbonate casings with a 3D-printed platform. This would also improve safety by omitting the sharp edges observed in the square casings.

The first revision was made by converting the protoboard circuit into a printed circuit board (PCB). The Altium Designer software was used to design the motor interface and driving circuit. Refer to Figures 12a and 12b for the schematic and the printed circuit board. The use of PCB eliminates the need for manual wiring in each laboratory exercise, saving time and enabling students to concentrate more on understanding the LabVIEW and control aspects of the laboratory assignments. Replacing the protoboard circuit with PCB for each station increased the per-workstation cost by $45, but significantly reduced the wiring and circuit troubleshooting time.

The experimental set-up with the PCB is tested for all assigned lab exercises. The initial version of the PCB was built with surface-mount transistors and applicable heatsinks. However, it was discovered that the transistors were overheating, resulting in unreliable results, particularly during the PID controller exercises. To address this issue, a second version of the PCB was created using through-hole transistors and its corresponding heat-sink assembly, which was utilized in the original prototype board circuit. This revised PCB was tested in all lab assignments, specifically during the PID controller exercises, and it proved to be dependable, resolving the problem of overheating transistors. The PCB is made to be interactive and easy to use, with test points for each signal and power line allowing students to debug their projects via hardware investigation on an oscilloscope or other lab equipment. These laboratory skills are critical for students pursuing an interest in electronics, as computer simulations may not always match real-world hardware behavior, requiring debugging to comprehensively understand the design or system functions.
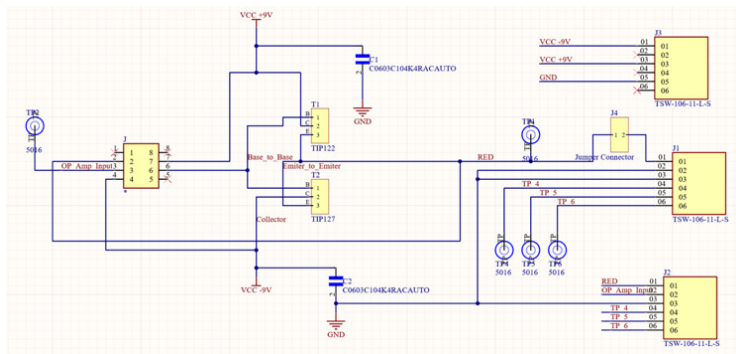

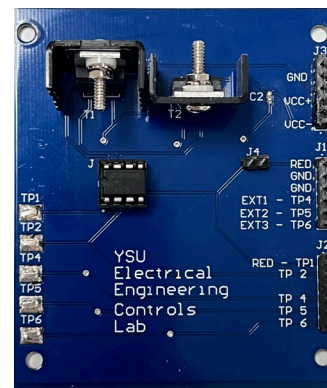Figure 12a: Altium Designer Schematic for the PCB.   Figure 12b: PCB

V.   Assessment and Conclusion

The laboratory setup that was created has been very beneficial for undergraduate engineering students, providing them with improved accessibility and flexibility during their experiments with the DC motor control system. This is due to the utilization of LabVIEW graphical programming and the precise modeling of the system in real time. To assess the effectiveness of the laboratory assignments, the grades of the students were collected and analyzed. The results showed that 92% of the students displayed outstanding learning outcomes in the control laboratory. The evaluation of student performance in the lab was conducted using a comprehensive assessment rubric that considered several critical factors, such as their ability to solve complicated problems, validate results using design and simulations, analyze results, participate in group discussions, adhere to safety regulations, and demonstrate technical proficiency in the laboratory report. Figure 13 illustrates the student performance grading rubric used in the laboratory exercises, while Table 3 provides a summary of the student's scores in the lab. Furthermore, a feedback survey was administered to the students at the end of each laboratory assignment to determine areas for further improvement.
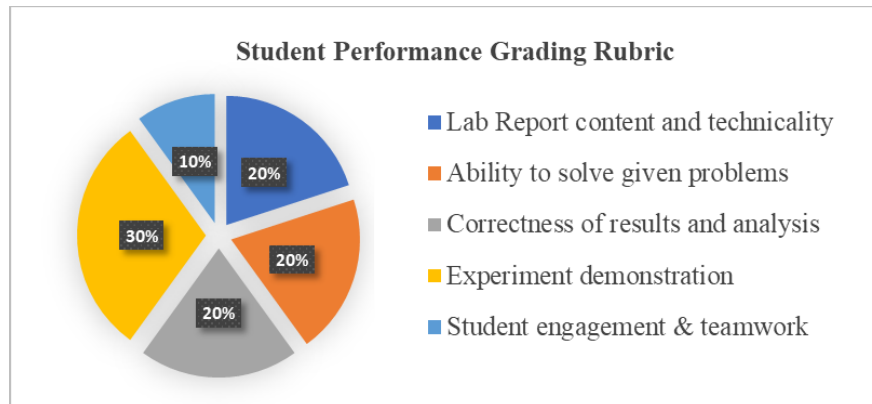

Figure 13: Laboratory Performance grading Rubric

Lab Assignment Classification	Percentage of students scoring:	
	> 90%	> 80%
Intro to LabVIEW and NI myDAQ	100%	100%
Motor Identification, Modeling & Direction Control	100%	100%
Open & Closed Loop Performance of DC motor system	80%	100%
PID Controller - Speed and Angular Position Control	76.67%	100%

Table 3: Summary of Student Performance

To evaluate the effectiveness of the new laboratory equipment, the student's comprehension and performance in the control course were compared before and after the implementation of the updated laboratory equipment. This was done by analyzing the test scores on PID controller design questions before and after the laboratory equipment was updated. In a class of around 35 students, the average score on the selected questions was 71.92% before the update and 84.6%

after the update, indicating a 17.6% improvement. These results demonstrate that the students had a better understanding of PID controllers after the new laboratory exercise.

The DC motor system constructed for the controls laboratory is a low-cost and practical approach for hands-on experiments on controls system theories. The preliminary experiments are based on modeling the DC motor, open-loop, and closed-loop analysis, and designing the PID controller for speed and angular position control. The experiment setup described in this paper can be expanded to include phase lead and phase lag controllers, enabling a more comprehensive and effective undergraduate curriculum in control systems.

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