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Work-in-Progress: All-In-One, Open Source Mechatronics Actuator Education Platform for Active Learning Curriculum

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Abstract

This paper discusses the design and construction of a multi-actuator, open-source education platform to enhance undergraduate mechatronics laboratory curriculum experience in the topic area of actuator technologies. Utilizing hands-on learning as the primary pedagogical approach, students gain applied knowledge in mechatronics by fostering the development of critical engineering skills. The proposed laboratory curriculum encompasses an all-in-one mechatronics actuator test platform for the study of fundamental actuator technologies, including a direct current brushed motor, stepper, and radio control servo motor that is generally taught in an undergraduate mechatronics course. This complete actuator test station design serves as a hands-on learning tool to characterize and operate different actuator technologies with defined learning outcomes, which similar commercial products can be expensive and time-consuming for educators to develop. The proposed motor test station facilitates a brushed motor, allowing students to learn how to implement different motor drive modes, such as drive-coast, drive-brake, and locked anti-phase, at the integrated chip level using a H-bridge. Similarly, the platform supports hands-on stepper motor control implementation of full-step, half-step, and micro-step drive modes. Additionally, the servo motor offers a control system actuator with feedback sensing, providing students with practical experience in control system development using low-level microcontrollers commonly employed in mechatronics. Experimental verification was conducted to analyze the onboard encoder and current sensing, to enable modeling and system characterization performance analysis to align with student learning outcomes. Our open-source design consists of off-the-shelf direct current brushed motor, radio control servo motor, and a two-phase stepper motor mounted on a 20 cm by 20 cm printed circuit board with LED status indicators. A 40-pin ribbon cable with test platform pin access can be mounted to a breadboard for motor control rapid laboratory development. Instructions of the test platform's mechanical design, integrated circuit and wiring diagram, and lab curriculum will be accessible on GitHub for engineering educators to build this low-cost educational tool within their engineering program. In conclusion, this proposed mechatronics actuator education test platform promises to significantly enhance education accessibility, serving as an invaluable learning tool for mechatronics students to acquire a hands-on learning experience.

Introduction

Incorporating a hands-on laboratory curriculum is a great way to solidify theoretical concepts to real-world practice in a classroom setting. Having a versatile physical tool to experiment with will go a long way toward helping students retain information with engineering practice. Students working on a mechatronic project have to make an engineering selection of the type of motor(s) they will integrate and operate for their system. There are different types of motors to choose from and knowing the characteristics of each motor type will aide students in sizing the appropriate motor that meet their desired performance requirements, helping students learn how to cooperate in interdisciplinary situations [4]. Allowing students to practice engineering decision-making will allow them to digest and absorb scientific knowledge through observation and experimentation [1-3]. For some universities, lab equipment used to showcase experiments, can be expensive and are unable to leave the laboratory, which can be a huge constraint [1], [3]. For instance, the Mechatronics Actuators board developed by Quanser features several types of motors that have learning objectives for students to learn how to operate them, but can be considered an expensive education platform, a few thousand dollars, that may be difficult to acquire for a class set [8]. As COVID-19 has shown, affordable education tools to allow more students hands-on practice that could provide experimentation outside the school setting [2].

The purpose of this work is to show the viability of our developed open source Mechatronics Actuator Education Platform (MAEP), in which students will be able to perform experiments on three common types of motors; a DC brushed motor with encoder, a radio control (RC) servo motor, and a bi-polar stepper motor used in mechatronics. This compact actuator test platform will allow mechatronic undergraduate students to learn how to characterize and operate motors, to be able to test the theoretical concepts acquired in the classroom. The MAEP is much more affordable than similar commercial off-the-shelf (COTS) products, and has the potential to allow engineering programs include such equipment into their mechatronics courses that otherwise were not able to. Developing motor control laboratory experiments, the brushed DC motor (BDC) is compared on how well we can derive its speed through an integrated circuit (IC), quadrature counter, and through the microcontroller unit (MCU) interrupt method. For the stepper motor, we will build a low-cost motor controller with a L293b motor driver and compare the resolution of steps against a COTS stepper motor driver A4988. Lastly, the RC servo will show how accurate the servo position is compared to the feedback position being reported from the feedback signal.

A study was performed with students utilizing the MAEP in a BDC motor lab where they compare a commercially available open-source lab manual to review BDC motor control versus an in-depth motor lab involved characterizing motor performance based on different drive modes. A student survey was administered to determine education values in active vs traditional classrooms, but only compare two active settings [9].

MAEP Design

The design criteria for developing MAEP was to incorporate different types of motors to be packaged into an all-in-one test station for students to interact with and perform experiments. The initial design accommodated four motors: an RC servo, a bipolar stepper motor, a BDC motor, and an expansion slot for future additions like a brushless DC motor or brake motor for characterization control development. The MAEP was constructed using a 2 mm thick printed circuit board (PCB) with allocated mounting holes for each motor with their dedicated pin connectors. These connectors routed internally to a 40-pin connector on the main PCB's side. A 40-pin ribbon cable then connects to a secondary PCB designed for easy breadboard integration. SolidWorks software facilitated the design of the motor mounts, which were then 3D printed using polylactic acid (PLA) filament material.

The design of the MAEP prioritized affordability, accessibility, and adaptability for users. Figures 1 and 2 show the CAD design concept for motor mounting with key PCB components to the PCB platform design created using Autodesk EAGLE software. The PCB rests on an acrylic base with cutout handles for easy access to the mount screws. This compact design offers portability, making it suitable for labs or even remote usage for distance learning. Our proposed educational platform demonstrates significant cost savings of $130 per unit, where 10 platforms were constructed for a lab section of less than 20 students. The price is less than comparable COTS devices, which potentially cost thousands of dollars per unit. The design CAD files to manufacture mounting components and EAGLE circuit schematics to fabricate the PCB platform can be accessed via GitHub for download by following the link here [11].

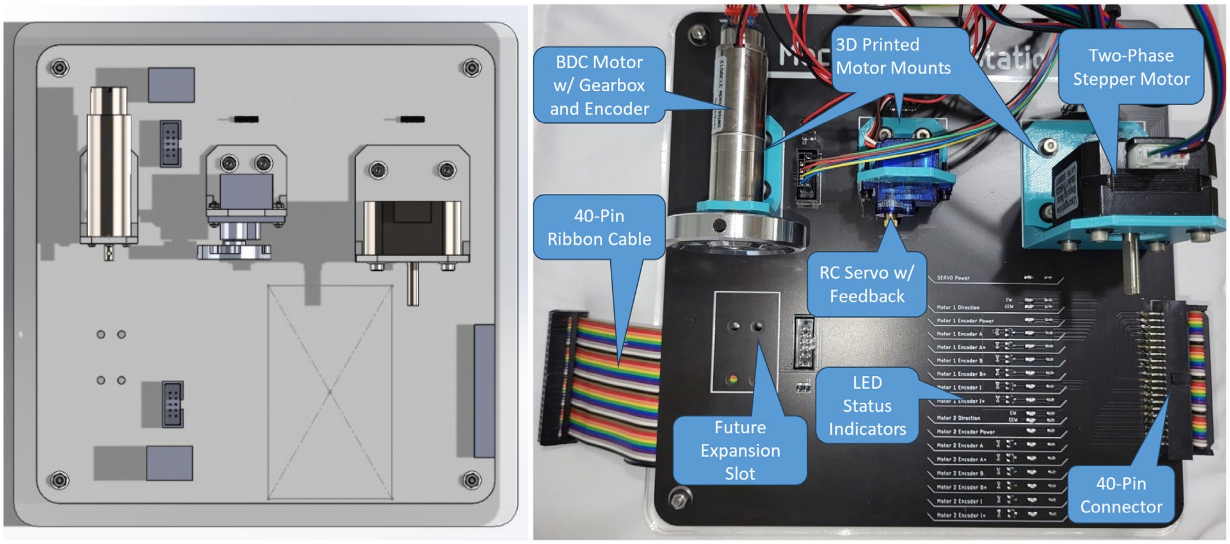


Figure 1: SolidWorks CAD assembly of the MAEP (left). Actual built test platform of the different motors and their mating connectors with 40-pin ribbon cable (right).

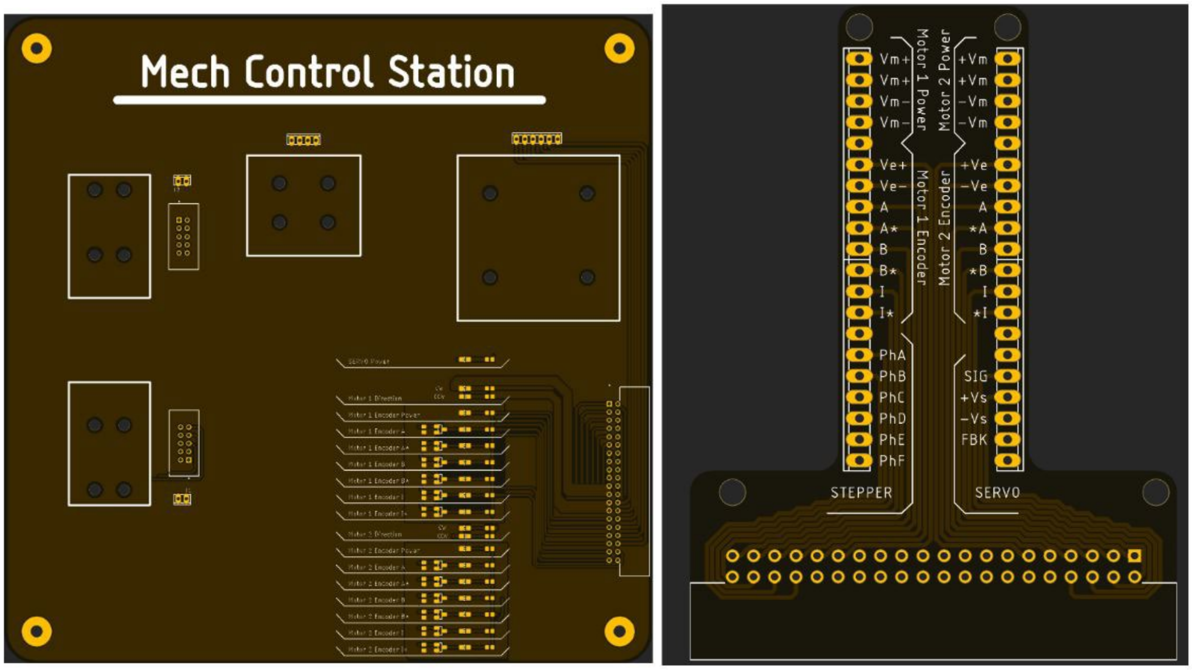


Figure 2: Motor mounting side PCB EAGLE schematic (left). T-shaped expansion board PCB EAGLE schematic of all motor pin connection with labeling (right).

Experimentation - BDC Motor with Encoder Sensor

Our initial tests focused on the BDC motor, which is a Maxon DCX19S motor with a GPX19 planetary gearhead having a gear ratio of 35:1. The BDC motor housed an ENX16 EASY encoder sensor with 256 counts per turn. This was the motor used, but other BDC motors may be retrofitted for this platform with adjustment to the motor mount. We built a circuit to experiment with each drive mode while simultaneously capturing sensor data to monitor the performance of the motor running on the test station. The circuit employed several integrated circuits (ICs):

- INA219 current sensor measures current, voltage, and power across the motor.
- L293B H-bridge motor driver that has four built-in transistor switches to control the current flow applied to a load.
- SN74AHC14 hex Schmitt-Trigger inverter provides Boolean operation for digital control signal to the H-bridge IC.
- LS7366R quadrature counter to count quadrature signals from incremental encoder sensor as the motor rotates.

An Arduino Mega 2560 microcontroller unit (MCU) is used to control the motor and acquire sensor readings. Figure 3 shows an Arduino Mega MCU, connected to the L293B via control input signals. The INA219 current sensor is connected to the MCU via Inter-Integrated Circuit (I2C) protocol and is powered by the 5V rail. The encoder has the capability of having four signals used channels ChA, ChB, ChA/, and ChB/, however, a 2-line encoder readout of using only ChA and ChB to be connected to the LS7366R quadrature counter and MCU. The LS7366R utilizes a Serial Peripheral Interface (SPI) with the MCU and is powered by the 5V rail. ChA and ChB of the encoder are connected directly to pins 2 and 3 of the MCU to access the dedicated interrupt pins to perform the interrupt function routine for counting encoder channel pulses. The BDC motor is powered with a nominal voltage of 24V and four diodes are placed at the motor output leads of the L293B to serve as a flyback diode circuit to snub back EMF voltage during rapid on/off motor control operation.

Figure 3 illustrates the T-shaped breadboard connector, providing access to the motor pins of the test platform (not shown). To the right of the breadboard PCB is the L293B motor driver, which is wired to the PCB, MCU, and INA219. The MCU control signals and motor pins is connected to the L293B H-bridg with the Hex Schmidt-Trigger provide an inverted boolean operation for direction control. The INA219 current sensor and LS7366R quadrature counter are connected to the MCU via their respective serial connection. To the right, figure 3 displays the wiring circuit schematic for operatig the motor in bidirectional control.

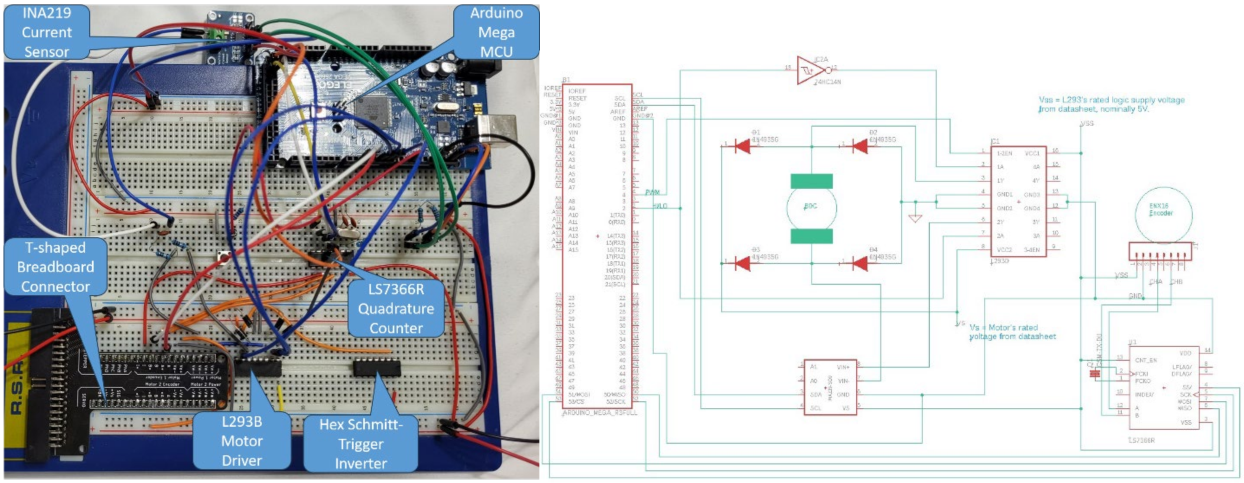


Figure 3: Setup for BDC drive modes circuit (left). Wiring schematic for bidirectional control with all sensors connected (right).

The first experiment was to demonstrate the effectiveness of different methods to reading motor position by comparing a LS7366R IC hardware counter versus MCU software interrupts to count pulses. A triangle wave input command signal was created in the Arduino Integrated Development Environment (IDE) sketch code to begin spinning the motor one full revolution clockwise (CW), two full revolutions counterclockwise (CCW), and then two full revolutions CW over 10 cycles. The motor rotating position in degrees is determined by the following equation:

$$\text{motor position (deg)} = pulse\ count * \frac{360}{cpt * gr * 4}, \tag{1}$$

where $pulse\ count$ is the pulse counts either by LS7366R or interrupt method onboard the MCU, cpt are the encoder sensor counts per turn, and gr is the motor gearbox gear ratio. As the encoder is a quadrature counter, the pulses will be counted four times the cpt as given in the equation above. The objective of the initial experiment is twofold: first, to record the motor shaft position and compare each pulse counting method; and second, to assess whether they consistently report the same position at varying duty cycles to determine the extent of any discrepancies between measurements. This experiment used pulse width modulation (PWM) to drive the BDC, where it was incremented from 0 to 100% duty cycle in 25% increments. Figure 4 reveals difference between the IC and interrupt method when operating at a 25% duty cycle, with the interrupt method having an increasing phase shift over time, producing a three second delay over a 90 second test run.

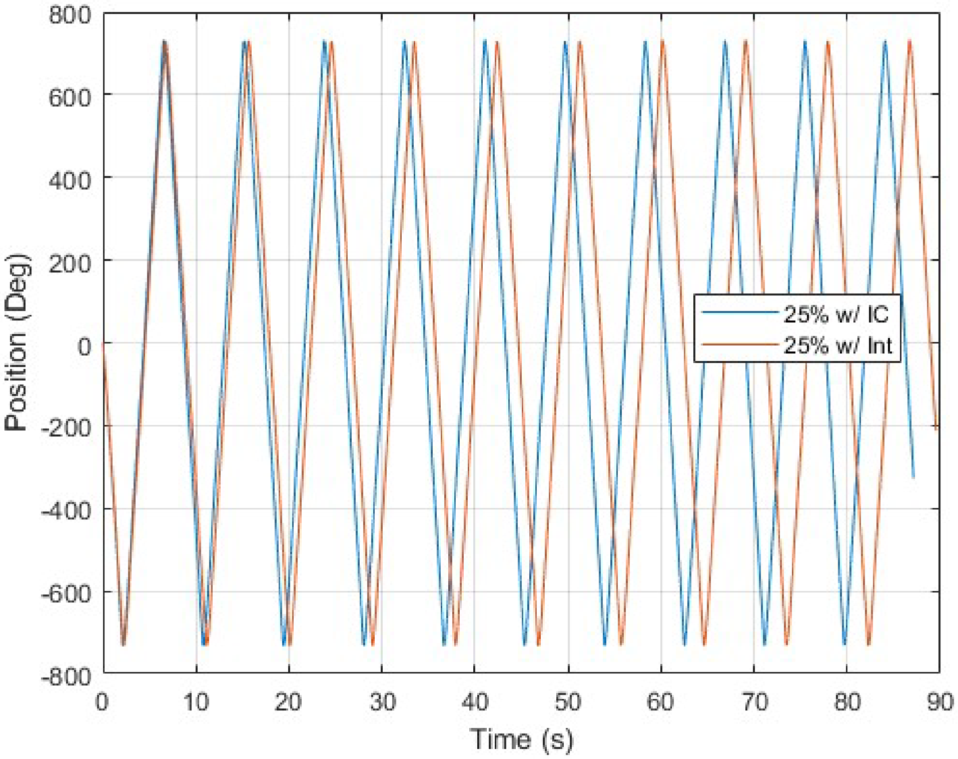


Figure 4: Plot of time vs position measured while performing at 25% duty cycle.

Similar results were found at commanded PWM duty cycles at 50, 75, and 100%, where the interrupt routine method produce latency over time in operating the motor. This experiment provided a consideration for how a student should measure motor position if they plan to operate for a long duration of time.

MAEP Lesson Plan

The MAEP facilitates a hands-on learning experience in an introductory mechatronics lab course. Through a series of labs designed for each motor type, students gain familiarity with the motors' functionalities and applications, empowering them to select the most suitable motor for a mechatronics system. A first lab focuses on the BDC motor, where students compare different drive modes to operate a motor. Next, they explore operating a RC servo motor with feedback. Finally, a lab operating a two-phase stepper motor using two different driver methods, to compare the precision movements achievable with each driver.

Lab One - BDC Motor Drive-Modes

The BDC motor lab introduces students to learn how to operate a motor with three different drive modes: drive-coast, drive-brake, and Locked Anti-Phase (LAP) [6]. The lab is divided into two sections. In section one, students use the MAEP BDC motor to complete a commercially available motor lab manual for a standard bidirectional speed control by Freenove [10]. Section two focuses on critical thinking and utilizes a custom MAEP BDC motor lab manual to explore the three drive modes that a BDC motor can operate with different performance output. Before building the circuits for each lab section, students were asked to create the circuit schematics using electronic design automation software, like EAGLE (an example schematic is shown in Figure 3), for design planning before wiring the circuit to their breadboard. Th commercial lab manual offers a more passive learning experience. Its lengthy background information, pre-built Fritzing diagrams, and pre-written code allow students to simply replicate demonstrations, limiting critical thinking opportunities [10].

The MAEP lab builds on the initial validation experiment, allowing the students to practice using an encoder to measure the motor's position and speed. The custom MAEP BDC motor lab provides brief instructions for students to build and implement code to the microcontroller, while adjusting the motor driver circuit based on the desired drive mode. Students will then record measurements such as the steady-state motor speed with its respected duty cycle command.

The students' first task involves powering on the encoder and manually rotating the motor shaft by hand approximately one revolution to verify accurate position readings. Subsequently, they operate the motor at various duty-cycle intervals, recording the steady-state speeds to construct a duty-cycle versus speed curve [5]. This experimental process is repeated for each drive mode, including drive-coast, drive-brake, and LAP mode. The students should get a similar curve as shown below in Figure 5 in the change of motor performance depending on the drive mode ran for the motor.

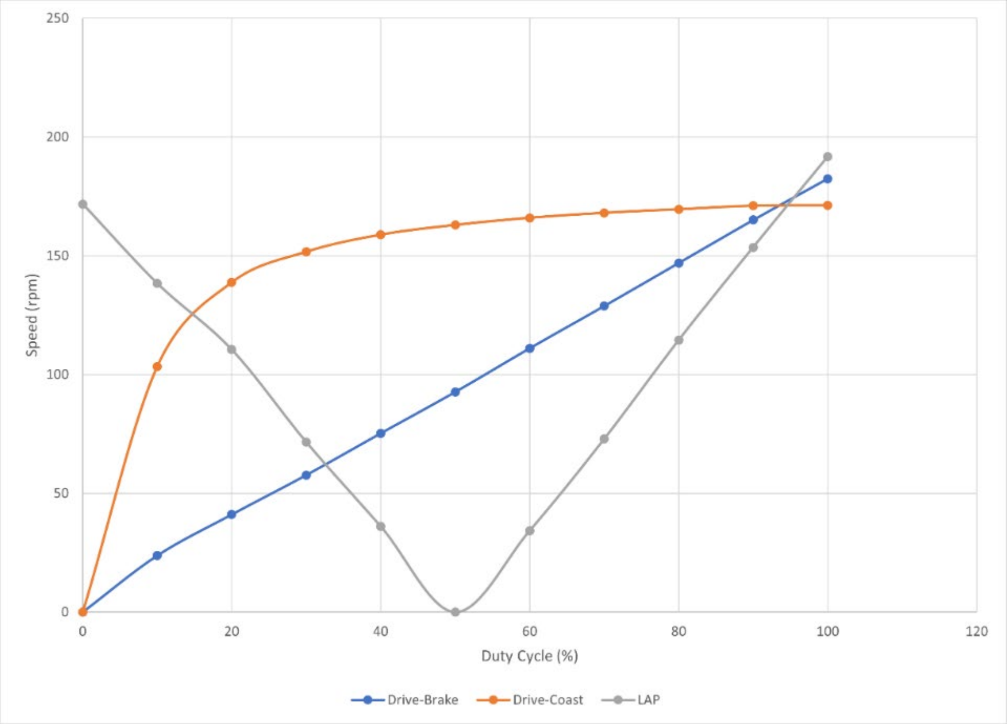
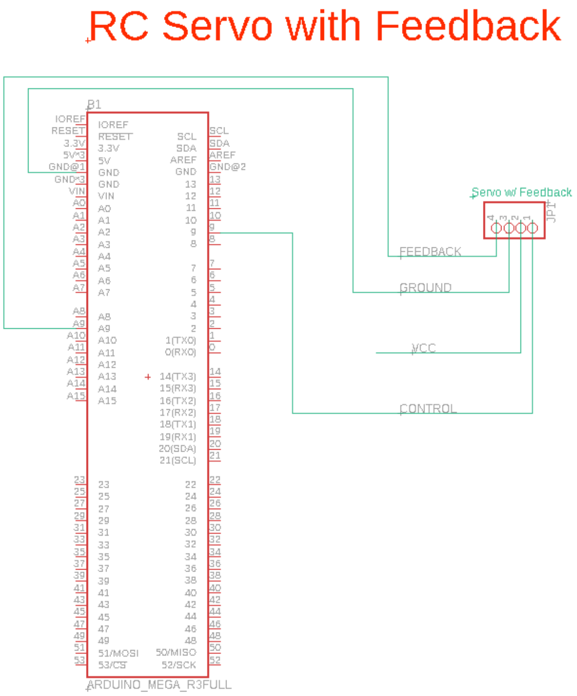


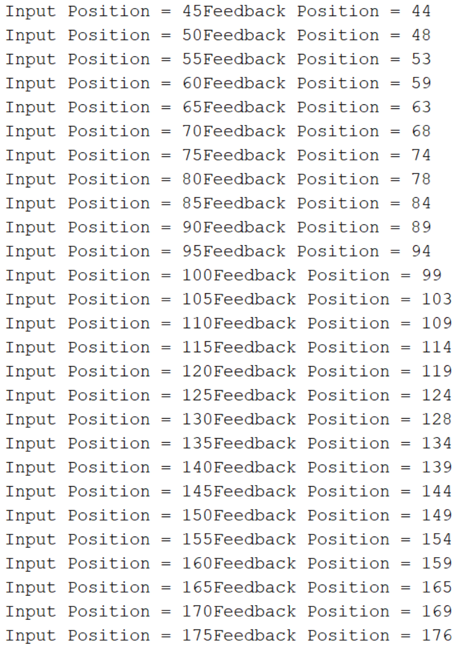
Figure 5: Duty cycle-rpm curves for all three drive modes.

Figure 5 above demonstrates the drive-brake mode has a more linear relationship between duty cycle command versus speed as compared to drive-coast. This allows students to empirical show the theoretical relationship between speed and change of applied voltage to the motor. The LAP mode shows a similar linear relationship, but provides the advantage of change in direction control as it approaches 50% duty cycle.

Lab Two - RC Servo with Feedback

Lab two focuses on investigating the feedback mechanism of a RC servo motor and comparing the commanded position with the actual position. As described in the previous lab, students are tasked with developing wiring schematics for the RC servo, such as EAGLE. They will then connect the servo to an Arduino MCU, with the feedback line connected to an analog pin and the control line linked to a digital pin with PWM capability. Utilizing Arduino libraries, students will create code to send position commands to the servo and display both the feedback and input positions on the serial monitor [7]. As the feedback is represented as a voltage reading integer ranging from 0 to 255, students will need to calibrate the feedback to display values in degrees. A comparison between the input position to the feedback position can be evaluated. Figure 6 below illustrates the wiring schematic for the servo circuit, along with a comparison of the input position versus the feedback position. It is strongly recommended that motor power be supplied from an external source [6].





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Input Position = 45Feedback Position = 44
Input Position = 50Feedback Position = 48
Input Position = 55Feedback Position = 53
Input Position = 60Feedback Position = 59
Input Position = 65Feedback Position = 63
Input Position = 70Feedback Position = 68
Input Position = 75Feedback Position = 74
Input Position = 80Feedback Position = 78
Input Position = 85Feedback Position = 84
Input Position = 90Feedback Position = 89
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Input Position = 155Feedback Position = 154
Input Position = 160Feedback Position = 159
Input Position = 165Feedback Position = 165
Input Position = 170Feedback Position = 169
Input Position = 175Feedback Position = 176
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Figure 6: EAGLE schematic of RC servo circuit (left) and feedback position (right).

The feedback position is within +/- 2 degrees of the input command showing the desired position command for a RC servo has some steady-state error based on its true position. This allows an opportunity for student lab development to create an outer closed-loop controller using the feedback signal to improve the precision of position accuracy for the servo performance.

Lab Three - Two-Phase Stepper Motor

In the third lab, students will focus on controlling the stepper motor and comparing two different stepper motor drivers, a commercially available A4988 driver to a L293B H-bridge that requires software development to operate a stepper motor. The first step involves developing wiring schematics for each stepper motor driver. Next, students will create a table detailing which motor coil inputs need to be energized, and in what sequence, to rotate the stepper motor in full-steps, half-steps, and microstepping [5]. By recording the position, they can conduct a step response analysis for each motor driver. This analysis will allow students to assess which motor driver is easier to use and which one demonstrates better responsiveness. The A4988 driver has a very straightforward set up to go change drive mode from full-step to microstepping of sixteenth-step mode. It can be challenging to set up an L293 H-bridge to perform at high micro-stepping modes depending on the processor speed of the MCU being programmed.

In summary, here are the expected outcomes for students to complete the series of labs using MAEP.

Table 1: Lesson Plan and Expectations for motors using MAEP station.

Lab	Lesson	Expectations
1. BDC	Drive-Coast Mode	• Develop wiring schematic. • Run BDC with microcontroller and motor driver. • Build and implement code for drive-coast mode.
	Drive-Brake Mode	• Develop wiring schematic. • Run BDC with microcontroller and motor driver. • Build and implement code for drive-brake mode.
	Locked Anti-Phase (LAP) Mode	• Develop wiring schematic. • Run BDC with microcontroller and motor driver. • Build and implement code for LAP mode.
	Develop Code to Plot Motor Position	• Build and implement code to read the encoder position
2. RC Servo	Displaying Feedback Position	• Develop wiring schematic. • Run RC servo with microcontroller. • Build and implement code to control servo and read feedback.
3. Two-Phase Stepper	Creating Stepper Controller w/ H-bridge (L293B)	• Develop wiring schematic. • Run stepper with microcontroller and motor driver. • Build and implement code to control stepper in various steps.

Results

A survey was administered in a lab section of ten students after completing the BDC motor lab, in comparing the two lab manuals of a standard commercial lab tutorial versus the custom MAEP lab learning how to operate a BDC motor. These questions are on a Likert scale from 1 to 5, where 1 is strongly disagree and 5 is strongly agree.

Table 2: Survey questions and results from student questionnaires comparing the commercial lab to the MAEP lab.

Factor	Question	Commercial Lab Average	MAEP Lab Average
Confusion	Did you find this lab frustrating and confusing?	1.63	2.80
Engineering Confidence	How confident are you in understanding and operating a DC brushed motor if asked to perform as a full-time engineer at a company?	3.25	3.20
Advancement Confidence	How confident do you feel in advancing the lab by integrating a sensor (e.g., encoder) or creating custom code for control (e.g., PID Control)?	3.83	3.86
Engagement	Did you find this lab interesting and engaging?	4.00	4.29
Software Skill Confidence	Do you feel confident in programming a microcontroller to drive a motor?	4.13	4.14
Reference Lecturers	This lab was beneficial towards me learning the lecture material on motor drive control?	4.57	4.57
Manual	Were the supplied written materials (lab manual) helpful in conducting the tests?	4.71	4.00
Electronic Skill Confidence	Do you feel confident in wiring and setting up a motor circuit?	4.71	4.33

There were eight responses for the commercial lab survey and seven responses recorded for the MAEP lab survey. From Table 2 above, the students found the custom MAEP lab somewhat more confusing. This can be due to the MAEP lab being more challenging as the students needed to come up with their own circuit design and to build code mostly from scratch, while the commercial lab had a passive approach that circuit diagrams and code was provided to complete the lab. A final observation is the MAEP was found slightly more engaging with the MAEP lab performing 0.29 points above the commercial lab. With a larger sample size of student surveys, analyzing the results of which, could help increase levels of engagement for future MAEP lab manual revisions.

Conclusion

The proposed open-source design shows promise in significantly enhancing accessibility to education, serving as an invaluable learning tool for mechatronics students within hands-on laboratory setting. This relatively cost-effective platform offers versatility, allowing for a multitude of experiments, thereby providing students with a practical test platform to apply theories taught in the classroom. In Figure 5, we observe the change in performance for different motor control drive modes of operating a BDC motor. A drive-coast mode, demonstrated a non-linear relationship between duty cycle and speed, while LAP and drive-brake exhibit a linear relationship. Additionally, after calibrating the RC servo feedback, it is evident that the feedback closely aligns within 1-2 degrees of the input. A stepper motor lab can provide practice to programming the stepping tables with an L293 H-bridge while giving the theoretical understanding how a stepper driver operates when using a commercial stepper motor driver such as an A4988. The compact MAEP design allows various adaptation for its use in a mechatronics laboratory curriculum, even facilitates its use at home for remote learning. Beyond basic mechatronics courses, the platform holds potential for future research endeavors, particularly in control development, particularly concerning the BDC for classical and modern control strategies using a feedback encoder [12]. Survey results indicate that despite the MAEP lab being perceived as slightly more confusing than the commercial lab, students found the new lab more engaging. It's important to note that these survey results are derived from a small sample size. Future research endeavors into the MAEP should aim to obtain a larger sample size to provide a more accurate assessment of the platform's usefulness.

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