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Development and Use of an Adaptable Arduino-Based Control System for Bench-Top Process Control Experiments

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Abstract

Students' chemical engineering laboratory experiences are challenging to approximate flexibly, and at low-cost and small-scale. As a result of this challenge and the COVID-19 quarantines, many students were left without adequate experimental experience.

In this paper we present the framework for an Arduino-based system that can be used in varied bench-top process control experiments. These hands-on experiments are used within the context of a lab course taught concurrently with a Process Dynamics and Control theory course and provide an opportunity for students to apply the classroom theory to real systems to enhance their learning. Students gain experience with system identification, digital Proportional Integral Derivative (PID) controller implementation, and PID tuning. Since students are programming their own controller, they gain skills in coding of the microcontroller and practical implementation issues, such as modifications for anti-reset windup and bumpless transfer, as well as control loop troubleshooting. Data acquisition is performed via a Python script that collects Arduino output data for later analysis by the students.

The controller system is adaptable to multiple experiments by utilizing inexpensive and easily available sensors and actuators appropriate to the process to be controlled. Experiments performed include a liquid level controller, a ball-in-tube apparatus position controller, a CSTR concentration controller, a resistive heater temperature controller. Training exercises using a simple LED and light sensor system for controlling light intensity were utilized to quickly get all students comfortable with programming, system identification, and PID implementation. In addition, the controller system is extensible to more than the basic PID algorithm. The programmable nature of the microcontroller allows for the use of alternate controller algorithms, such as feedforward control and nonlinear control. The electronic instrumentation used allows for the use of two sensors and two actuators, allowing for extensions into cascade or multi-input multi-output (MIMO) control.

Students were surveyed regarding their experience with these experiments and the overall effect they believe the lab work had on their learning. These survey results indicate a well-rounded learning experience, as perceived by students, when both types of experiments are used in the lab course. These survey data are also presented in this paper.

Introduction and Background

An understanding of process control is a core component of a chemical engineering education and an associated course is taught in essentially all chemical engineering departments. In the most recent survey of process control courses conducted through the Chemical Engineering Division of the American Society for Engineering Education (ASEE), it was found that about

44% of responding process control instructors assess students using some sort of laboratory activity [1]. While there is significant evidence to suggest student learning of process control concepts is enhanced through hands-on experiences [2], [3], the majority of process control courses do not integrate hands-on labs, perhaps due to limited access to process control equipment. Indeed, the division process control survey concludes that "increasing enrollments are challenging the incorporation of physical laboratory exercises" into process control courses.

Unit operations laboratory courses are often where students obtain hands-on control experience. While these labs have a wide variety of equipment, only a fraction of that equipment may be appropriate for process control experiments, limiting options for control experiments as enrolments fluctuate. Perhaps due to these limitations, the most common laboratory experiences to be conducted virtually was found to be the process control experiment portions of the unit operations laboratory courses [4].

In addition to issues of equipment availability, the inner workings of the control software and hardware that come packaged with many engineering laboratory apparatuses are often proprietary, obscuring controller implementation. Furthermore, unit operations equipment often take significant time to reach steady state, and students must gauge the impact of their tuning choices from behind a screen, without the timely feedback. While this sort of experience is realistic and pilot-scale experience is invaluable, the student interaction with the system is more akin to a simulation than a hands-on experience, but with added delay in feedback.Both experiences have their pedagogical value, the learning opportunities may be greater with a more immediate and hands-on experience [5].

Small bench-top control experiments can help improve the immediacy of feedback on controller setting changes, but they represent a particular hurdle due to their need for dedicated sensors, real-time data acquisition, and actuators. Advances in consumer microcontrollers, such as those based on the Arduino and CircuitPython platforms, have recently provided educators with low-cost opportunities to augment their labs and allow students to take hands-on learning home with them. These microcontrollers have become commonplace in engineering and computer science disciplines [6]-[9]. While chemical engineering curricula have been slower in adopting microcontrollers as pedagogical tools than other engineering disciplines, they have found their way into our curriculum, primarily for data acquisition uses.

The most recent survey of unit operations courses recognized the new importance of microcontroller in our laboratories [4]. Yan et al., for example, constructed a liquid level control arduino module focusing on the safety aspects of process control, demonstrating improved learning and increased awareness of process safety [10]. We have demonstrated that benchtop experiments, assembled by students, have significant potential to solidify their understanding in a first-year design laboratory [11]-[14]. We have also demonstrated the use of low-cost bench-top Arduino experiments for teaching both fluid dynamics and process control [15].

In this paper we describe a general-purpose low-cost approach to bench-top chemical engineering control experiments, developed as a means to facilitate a process control laboratory, taught in conjunction with a traditional process control course. Students enrolled in these courses are typically in their final year of their undergraduate Chemical Engineering degree. These students have experienced 3 prior semesters of Chemical Engineering laboratory courses and are well acquainted with hands-on work. In addition, students have been using the Python programming language for computation and problem solving throughout their Chemical Engineering curriculum. This laboratory was developed under both the constraints of limited unit operation equipment and during the COVID pandemic. As part of its development, a low-cost 3D-printed Arduino-based control unit was developed to be flexibly used on a wide variety of bench-top control systems. The small-scale experiments are meant to enhance and compliment students' use of pilot scale equipment and address gaps in their path to connecting 1.) process control theory, 2.) its discrete implementation in software, and 3.) the ultimate physical impact of their choices on the entire system.

Methods - Lab course delivery

The project laboratory course in which the microcontroller-based control units were utilized focused solely on process control projects and was offered concurrently with the process dynamics and control course. Topics for investigation in the assigned lab projects were synchronized with the theoretical learning of the process control course. Two main group projects were assigned during the course of the semester. Group Project 1 focused on system identification of the assigned process and Group Project 2 focused on PID controller implementation on a given process to meet process objectives. Two smaller individual projects were also assigned prior to each group project. Each of these individual projects was designed to serve as a quick introduction to the concepts and coding that would be needed in the upcoming group project. Figure 1 shows the student progression through assignments during the semester. Represented are the two possible "tracks" students would follow.

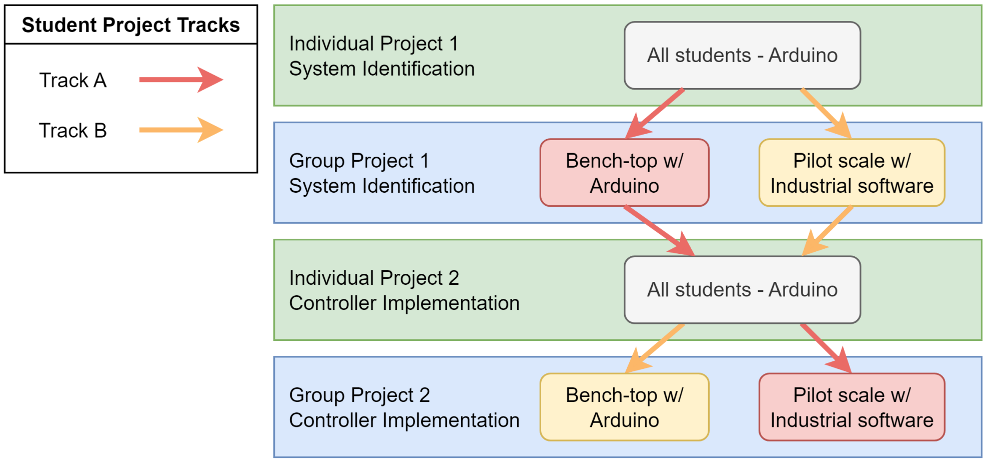

Figure 1. Student tracks through process control lab projects during the semester.

For each group project, students were assigned in teams of three to either pilot scale equipment that was already instrumented and outfitted with third party control software or bench scale equipment with the low-cost sensor, actuator, and Arduino microcontroller system. Student groups were rearranged at the time of the second project so as to provide experience with whatever system was not used in their first project.

In between the two group projects, students completed two individual projects focused on becoming familiar with the use of simple sensors/actuators, the Arduino microcontroller, and data acquisition. These individual projects were used to introduce students to the Arduino C programming environment. Once the individual projects were completed, each student had experience executing Arduino code on a very simple sensor-actuator-process system. The code and concepts are directly transferable to the bench-top Arduino experiments in the subsequent group projects. In this way, all students were prepared to complete the bench-top Arduino experiments and there was no advantage or disadvantage to being assigned these experiments over the pilot-scale industrial software experiments.

Methods - Survey

Senior Chemical Engineering students, who took both the process control and dynamics theoretical course and the process control lab course, were surveyed regarding their self-perceived gains. The survey was administered after the conclusion of the semester in which students were enrolled in these courses. Survey responses were anonymous and no demographic data were collected because of the small class size, to protect the anonymity of the respondents. Questions were related to course objectives for both the Process Control theory course and the laboratory course. Questions were chosen to investigate learning in three areas: control theory, control in practice, and attitudes and behaviors regarding project tasks. Students were asked to assess their learning from both the bench-top Arduino project and the pilot scale project separately. Of the 45 students enrolled in the courses, 20 students completed the survey.

The survey was self-administered and consisted of questions on which students rated their learning gains based on a 5-point Likert scale. Survey responses were collected anonymously. The scale used ranged from “no gains” to “great gain”. Questions were based on the Undergraduate Research Student Self-Assessment (URSSA) survey [18], but adapted to fit within the context of the topic of process dynamics and control. The survey questions and rating scale are shown in Table 1.

Table 1: Self-Assessment Survey Questions for Learning Gains in a Process Control Lab Course

Understanding of control theory	**Control in Practice**
Q1 Understanding of sensors and their operation within a control loop	Q8 Ability to instrument a process (sensors and actuators) for control

Q2 Understanding of Process modeling	Q9 Comfort in taking data from a process
Q3 Understanding of closed loop feedback control	Q10 Ability to design a control experiment
Q4 Identification of process inputs (cause) and outputs (effect)	Q11 Ability to analyze data determine model constants
Q5 Understanding of PID algorithm	Q12 Ability to tune a PID controller
Q6 Importance of final control element	Q13 Ability to determine when a process is under good control
Q7 Understanding of process nonlinearities and their effect on process control	Q14 Ability to troubleshoot a poorly performing control loop

Attitudes and Behaviors	**Self-Assessed Learning Scale**					
Q15 Confidence to engage in real-world control application	no gains	a little gain	moderate gain	good gain	great gain	not applicable
Q16 Curiosity about the topics of process modeling	1	2	3	4	5	NA
Q17 Curiosity about the topics of process control						
Q18 Persistence in pursuit of concept understanding						
Q19 Persistence in pursuit of project completion						

Apparatus

Each of the bench-top Arduino experiments consisted of the basic building blocks of a process control loop: a process, a sensor to indicate a key process output variable, the controller, and a final control element to adjust a process input. A representation of this loop and the data acquisition system is shown in Figure 2. An Arduino microcontroller was programmed to receive data from a sensor, compare the sensor data to a user-defined set point, perform control calculations, and send a signal to a final control element.

This system provides flexibility in type of process and choice of sensor and final control element to fit the process objectives. Sensors can be selected from a variety of low-cost and easily available options that are compatible with Arduino boards. Sensors that measure process variables such as temperature, flow rate, humidity, light intensity, and many other parameters are available through multiple online retailers. These sensors can be connected to Arduino boards using digital or analog input/output pins and communication protocols such as I2C. Any final control element that can be powered by a 12 V DC supply can be used with the system. Options include small pumps, fans, resistive heaters, and motors.

A digital implementation of the PID algorithm was used in this lab course. However, since all control calculations are programmed by the student in the Arduino C script, the algorithm is not limited to PID, nor is there a limitation to use only feedback control. A more advanced control algorithm could be programmed into the Arduino script, ranging from simple gain scheduling for nonlinear control to an implementation of model predictive control (MPC). Addition of another sensor would open options of using cascade or feed forward enhancements to feedback control. Addition of another sensor and another final control element would allow for MIMO control.

All data are reported through a USB serial connection to a laptop computer. A python program reads the data as it is reported via a Pyserial communication protocol and stores it for further analysis.

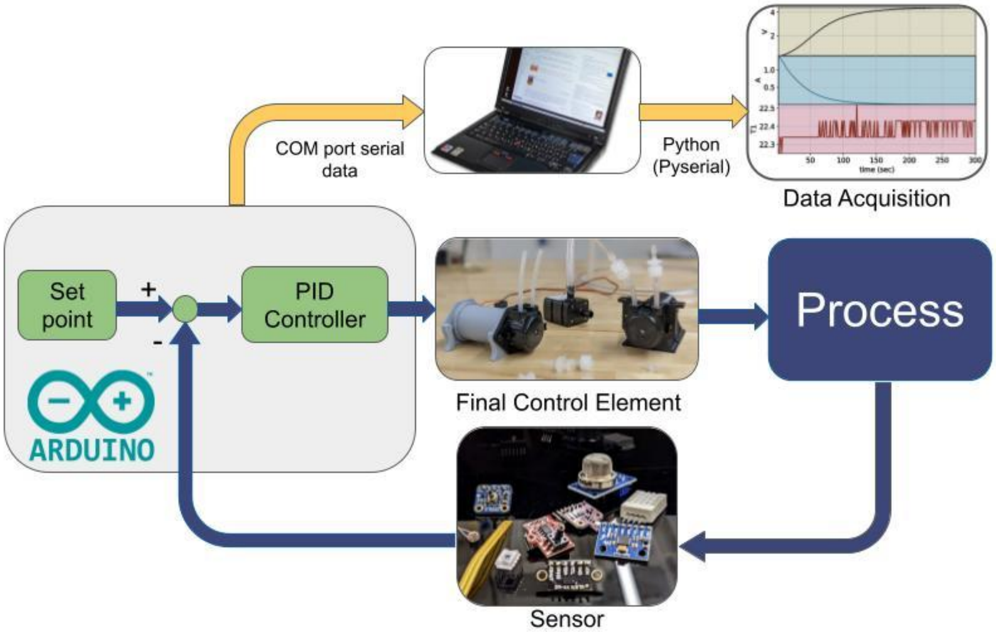

Figure 2: Bench-top Arduino controller and data acquisition system configuration.

Specific implementations of the above framework are described in further detail in the following sections.

Training Experiment

In order to familiarize students with the Arduino platform, a simple experiment was designed that could be performed in a single class period. A schematic of the apparatus is shown in Figure 3 and consisted of an Arduino Nano, an RGB LED, a photoresistor, and several other supporting passive electronic components. The goal of the experiment was to control the brightness of the LED. The brightness of the LED was measured indirectly by measuring the resistance of the photoresistor. This surrogate brightness reading could then be used in the PID algorithm to determine if the LED needed to be brighter or dimmer. The desired brightness level was realized by sending a pulse-width modulated (PWM) signal to the LED. The skeleton code for this experiment also included a first-order filter to the brightness measurements to add artificial time-delay dynamics to the system.

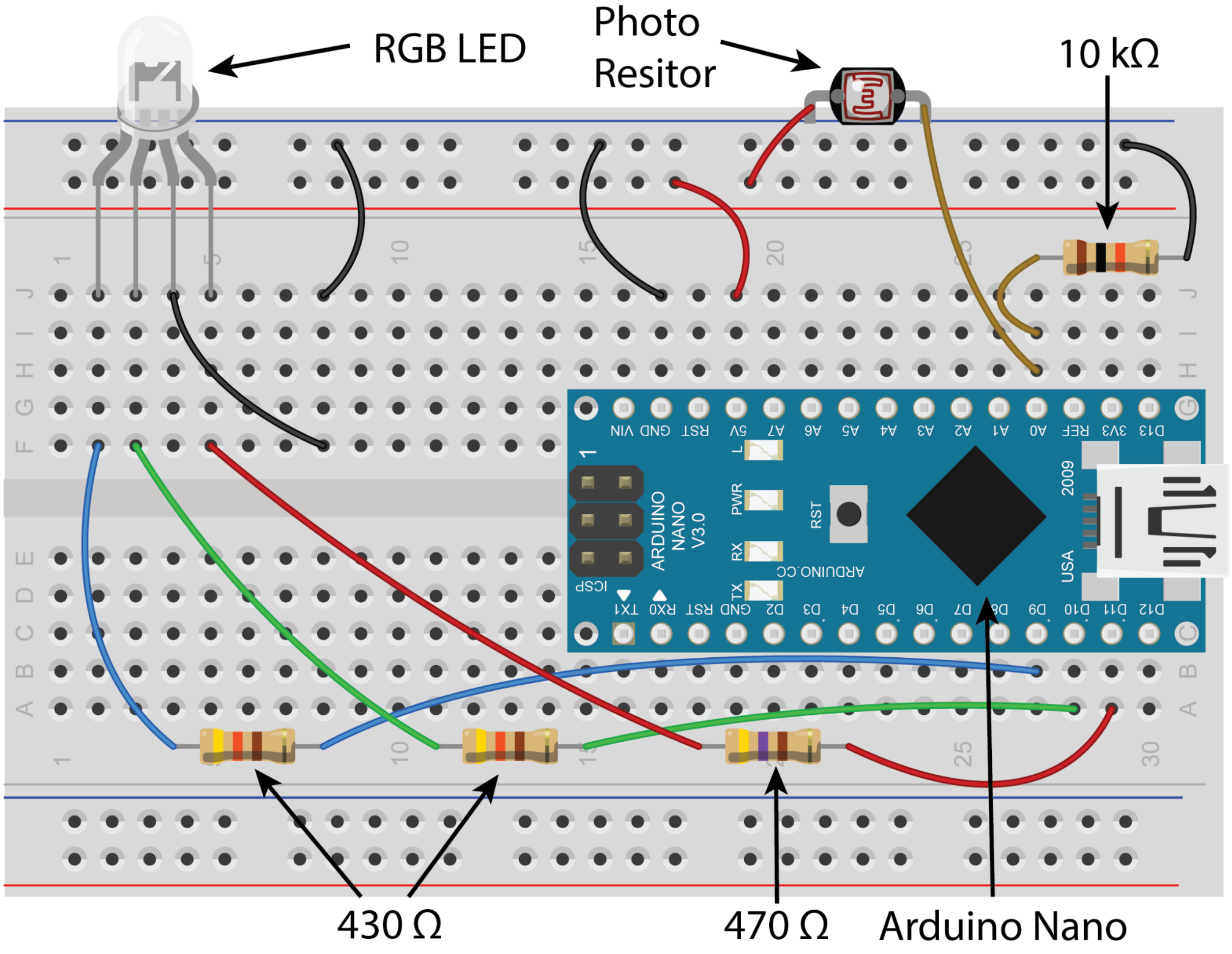

Figure 3: Breadboard schematic of the apparatus used in the training experiment.

The Control Module

The central component of each benchtop apparatus is the universal control module, which is shown in Figure 4. This module was designed to be quickly integrated into any of the experiments. It contains an Arduino Nano which can interface with both analog and digital sensors through its general-purpose input and output (GPIO) pins. Ports to a few of these pins are present on the top of the control module. The Arduino uses the inputs from the sensors to calculate the desired value of the manipulated variable (MV) and then realizes this by sending a PWM signal to a 12V H-bridge motor driver (L298N). The motor driver amplifies the PWM signal and outputs it to the banana-plug ports which are also on top of the control module. Through the digital pins the voltage on the H-bridge output may also be reversed, extending the control options. The Arduino and motor driver are housed in a 3D-printed box to protect the sensitive electronics and expose only the ports and pins that are necessary for the experiments.

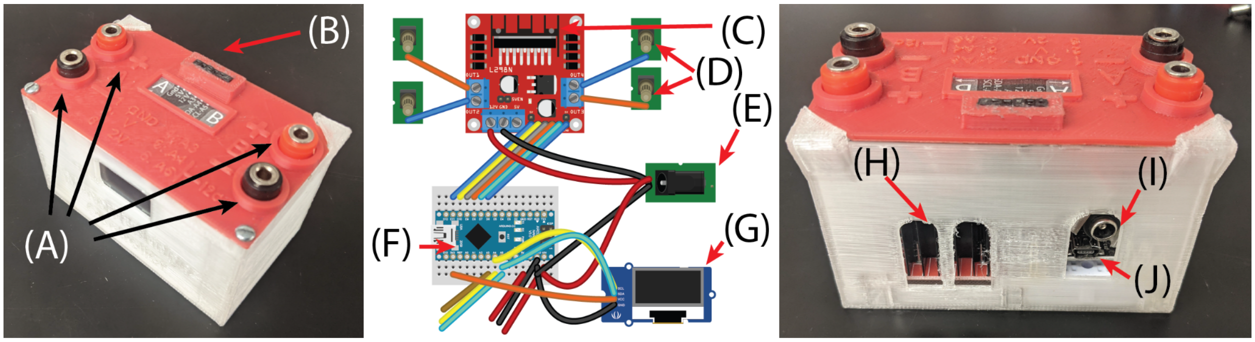

Figure 4: The universal control module used in each of the benchtop experiments. (A) PWM outputs. (B) Arduino pin ports for interfacing with sensors. (C) L298N H-bridge PWM motor driver. (D) PWM output ports, also shown in (B). (E) 12V DV power jack. (F) Arduino Nano microcontroller. (G) Display (optional). (H) Heat sink vents for H-bridge. (I) 12V DV power jack. (J) Micro-USB port for programing the Arduino Nano.

The module is powered externally by a 12V DC power source. The micro-USB port of the Arduino is accessible on the back of the module so that the microcontroller can be programmed by a PC. The control module is capable of interfacing simultaneously with multiple sensors and can control up to two actuators at a time. The total cost of each controller module is approximately $8 US.

This control module was used in four different experiments, a liquid level controller, a continuous stir-tank diluter, a miniature heater, and a ball in tube device. Diagrams of each of these experiments are shown in Figure 5. The students were provided with a skeleton code for the control module which they were required to modify for their specific experiment. The following three sections describe the equipment used in each of the experiments.

Continuous Stir Tank Diluter

The miniature diluter consisted of a tank (mason jar), an electric stir motor and several pumps for inputs to the tank. The goal of this experiment was to control the outlet concentration of the diluter by manipulating the power to a dye pump. A peristaltic dosing pump (AE1207) was used to pump a concentrated dye solution into the tank. A second peristaltic pump, whose power was not manipulated but held constant, was used to pump water into the tank. These two streams were mixed in the tank by the electric stir motor, and the resulting solution drained from the tank continuously through a siphon. The siphon tube passed through an Arduino-based photometer so that the concentration of the solution could be measured indirectly by measuring the light absorbance of the solution. The photometer communicated the absorbance measurements to the control module via a connection to one of the analog pins on the module. The Arduino then used these measurements to determine the dye-pump power level which was needed to attain a certain outlet concentration. This power level was then realized by sending a PWM signal to the motor driver, which was powering the dye pump.

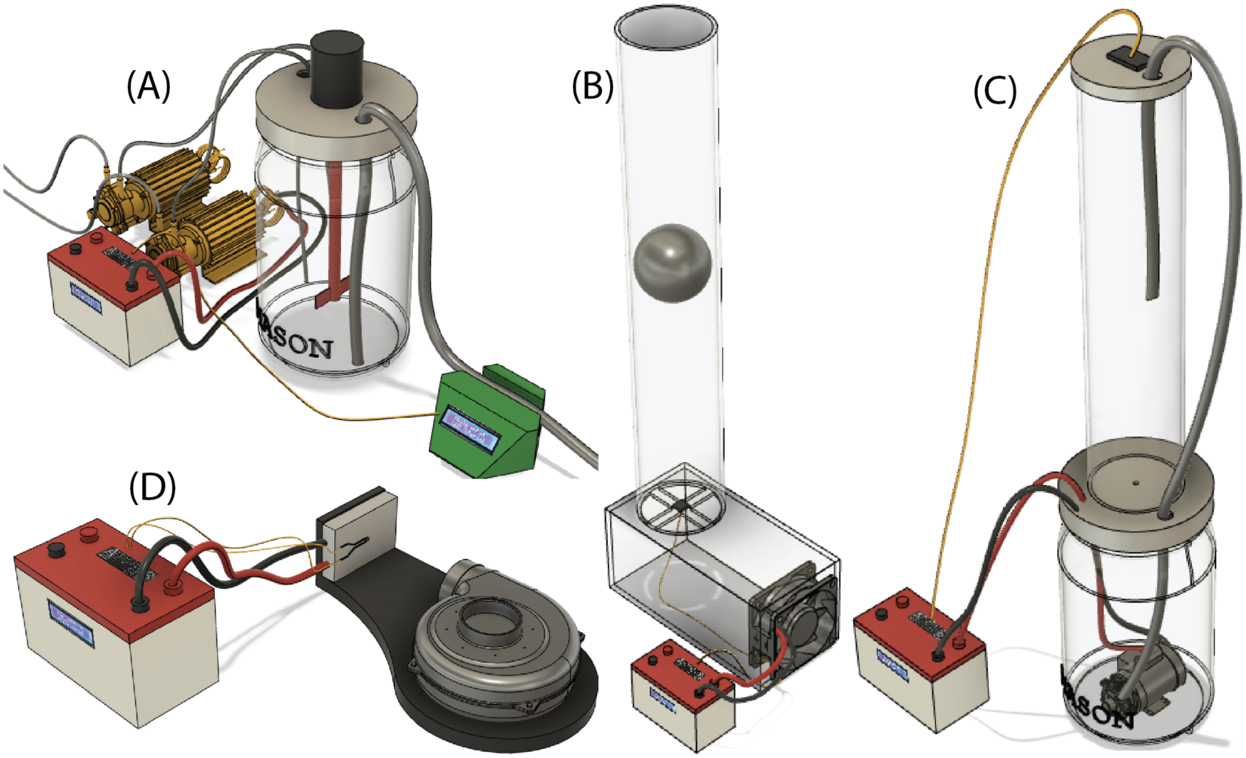

Figure 5: The benchtop experiments that used the universal control module. (A) Continuous stir tank diluter. (B) Ball-in-tube device. (C) Liquid level controller. (D) Mini heater.

Ball-in-Tube Device

The ball-in-tube device in this work is the same that was used by Hillard et al. [15] and consisted of a styrofoam ball inside an acrylic tube. A PC fan (QFR0812DE-F00) blew air into the base of the tube, causing the ball to hover inside the tube. The goal of this experiment was to manipulate the power to the fan to cause the ball to hover at a set height. The control module could be interfaced with a VL53L0X LIDAR range finder was used to measure the height of the ball inside the tube. This information was used in the PID algorithm to determine the fan speed needed to achieve the desired ball height. The control module realized this fan speed by sending a PWM signal to the fan.

Liquid Level Controller

The miniature liquid level controller consisted of a 12 in. tank made from a 2 in. diameter acrylic tube. The goal of this experiment was to control the water level inside the tank by manipulating the power to a pump. Water was pumped from a reservoir (mason jar) into the top of the tank using a submersible pump (QR30E Brushless 12V-DC) and rubber tubing. The water continuously drained back into the reservoir through a hole in the bottom of the tank. The level of the tank was measured using a VL53L0X LIDAR range finder which was fixed to the top of the tank and faced down toward the surface of the water. The LIDAR sensor transmitted its measurements to the Arduino via the serial input pins on the top of the control module. The submersible pump was powered by the PWM outputs of the control module. The arduino used these measurements and a PID control script to determine the pump power needed to reach a certain fill level in the tank. Since the submersible pump was powered by the PWM output ports on the control module, its power could be controlled by the Arduino.

Miniature Heater

The miniature heater consisted of a 5V-DC fan, a 12V PTC ceramic heating plate (B07WGFSVGN) and an MF52-Thin thermistor. The goal of this experiment was to control the temperature of the heater by manipulating the power that it received. The electric fan was powered externally, and its power level remained constant (this module could be altered to adjust the fan speed, alternatively). The outlet air stream from the fan was aimed at the surface of the heater. The Arduino measured the resistance of the thermistor via one of the analog pins on the top of the control module. The Arduino's script converted these measurements to temperature and then used this temperature measurement and the PID algorithm to determine the heater power level needed to reach a setpoint temperature. This power level was realized by sending a PWM signal to the motor driver which was powering the heater.

Results and Analysis

Control Module Performance in the Lab

The low-cost nature of these benchtop experiments that are built in-house can lead to some unreliable components and occasional need for repair. Furthermore, each setup requires some documentation for the student to understand how to connect leads for each experimental system, and they may easily make errors in their equipment setup. As such, some troubleshooting on the part of the student, TA, and faculty was needed for the bench-top experiments that would not be typical with a pilot-scale unit operations equipment. However, in the troubleshooting experience, the student gained experience with the inner working of the control system. Also, the modular and low-cost nature of the equipment allows for easy ability to swap out a problematic controller, sensor, or actuator.

Survey Results

The student survey results were compiled and are presented as box plots, including the sample median and mean, in this section. Question response data were paired by question number between the two experiment types, the bench-top Arduino experiments (A) and the pilot-scale industrial control software experiments (B). A Wilcoxon Signed-Rank test with a p-value of less than 0.05 was performed on these data pairs to determine if statistically significant differences existed between the medians between the rated gains from the two types of experiments. Question Q7, Understanding of process nonlinearities and their effects on process control, showed a statistically significant difference in median rating between the two groups. While the median difference was either not statistically significant or there was not a difference in calculated median in the other questions to the same level of confidence, there are interesting suggestions that will be discussed further below. It is likely that a greater number of survey respondents would increase the statistical significance of median difference with additional questions.

Questions regarding gains in understanding with respect to the elements of a control loop are grouped in Figure 6. While not statistically significant, there are indications that students perceived greater gains in their learning by engaging with the bench-top Arduino experiments, especially as pertained to understanding of sensors and their use within a closed loop system and determination of process inputs and outputs. These findings indicate that student engagement with each of the control loop elements separately, and the connection of these elements into the closed control loop that is required by the bench-top Arduino experiments are beneficial for students' learning about control loop elements and their function within the closed loop. Similar gains in understanding of the PID controller algorithm and the importance of the final control element in the closed loop were obtained through both types of experiments.

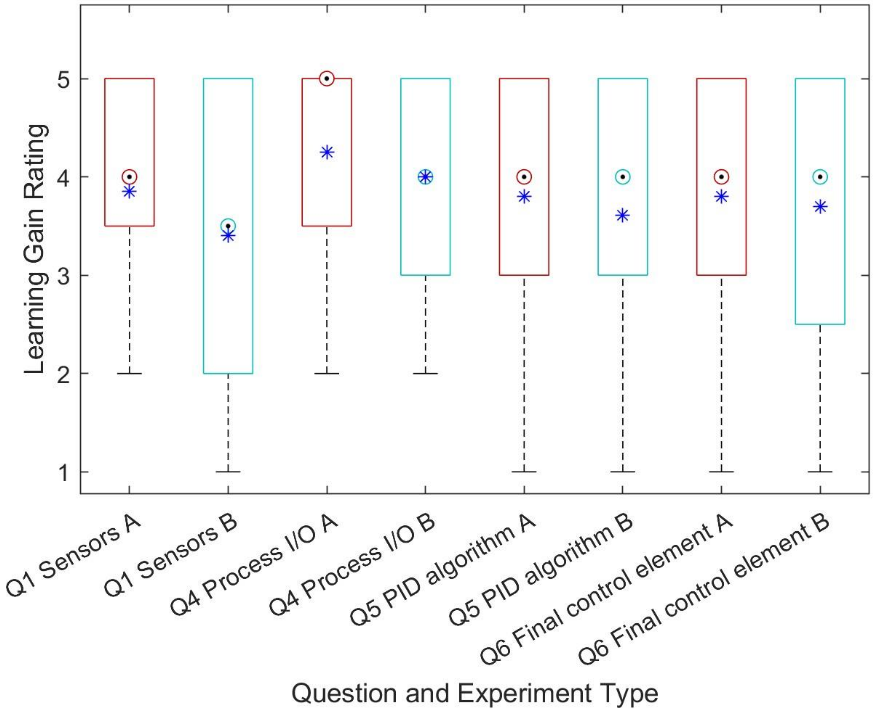

Figure 6: Self-perceived learning gains in understanding of theory relating to control loop elements. Asterisks indicate means, targets indicate medians.

Figure 7 shows the results of student rated gains regarding their learning in topics of the dynamics of closed loop control systems. Very similar understanding gains seem to be obtained with respect to process modeling and closed loop feedback control between the two types of experiments. The statistically significant greater perceived gain in the understanding of process nonlinearities and their effect on feedback control with the pilot scale experiments could be due to the uncomplicated nature of the set-up for these experiments. For these types of experiments, the equipment is already installed and instrumented, and data collection systems are already in place with 3rd-party software. Students do not have to spend time and effort with these activities, and can instead concentrate on testing the process at different locations within the window of possible operation. Students are then able to observe the differing effect magnitude and timing that process input changes have on process outputs throughout that window.

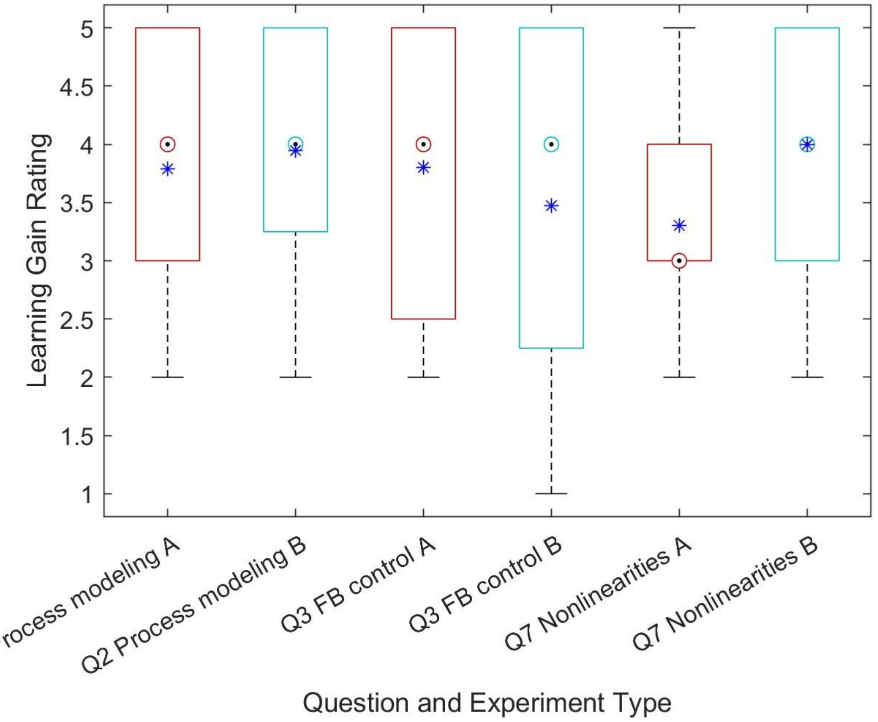

Figure 7: Self-perceived learning gains in understanding of theory relating to control loop dynamics. Asterisks indicate means, targets indicate medians.

Self-perceived learning gain distributions in the areas relating to process instrumentation, experimental design, data collection, and data analysis are displayed in Figure 8. A small difference in mean is observed between the two types of experiments in student gains with respect to the ability to instrument a process. Although not statistically significant, this possible difference in distribution and resulting mean may indicate that the requirement for students to instrument the bench-top Arduino experiments improves their confidence to be able to do so on other processes. Essentially equivalent levels of gains are observed in process data acquisition, control experimental design, and data analysis to obtain process model constants. This equivalency indicates that both types of experiments are serving students well in that students perceive their learning gains are good in these areas of control application.

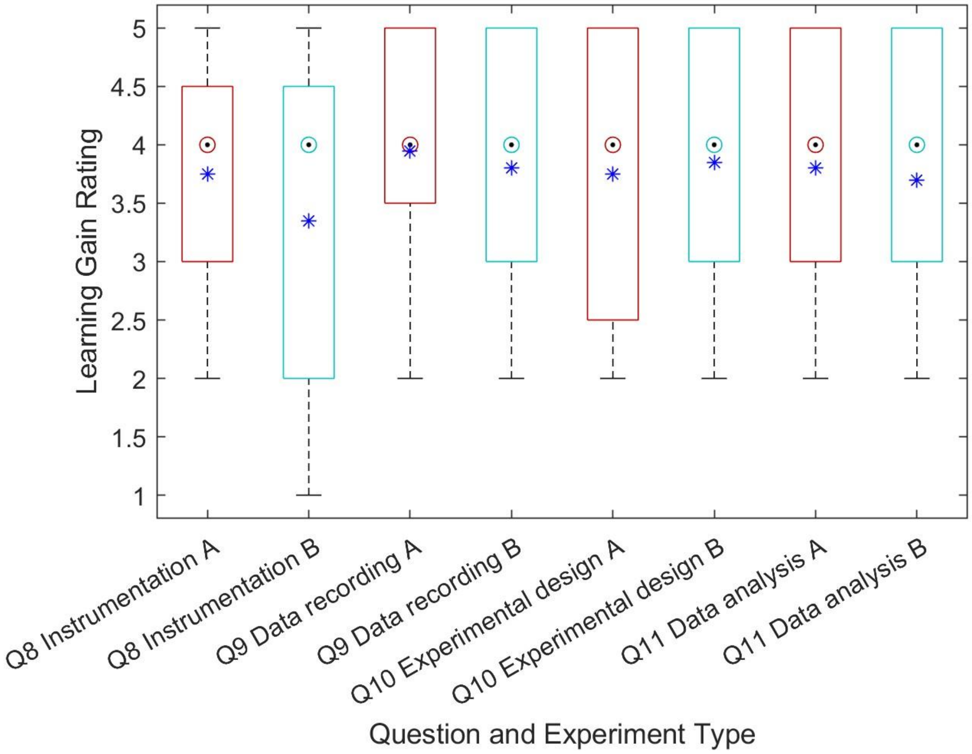

Figure 8: Self-perceived learning gains in practical aspects of control relating to control loop instrumentation and experimentation. Asterisks indicate means, targets indicate medians.

Figure 9 presents the distributions of survey responses to questions regarding PID controller tuning, assessment of good control of a process, and control loop troubleshooting when control performance is not good. Although there is not a statistically significant difference between the medians of the distributions, the distributions for the bench-top Arduino experiments appear to be tighter and clustered more toward the upper end of the rating scale. A similar conclusion can be drawn from these data, however, that both types of control experiments are serving the students well in these areas resulting in good self-perceived gains across the board.

Results from survey questions regarding gains in confidence to apply control in the real world, and curiosity about process modeling and control topics are shown in Figure 10. These data may indicate some interesting trends, even though the difference cannot be stated with statistical confidence. The bench-top Arduino experiment appears to improve student-perceived gains in confidence in their ability to engage in real-world application of control, and could be attributed to the fact that students were responsible for more of the implementation of the control loop with these types of experiments. The perceived gains lean the other direction when it comes to gains in curiosity about process modeling and control topics, with perceived gains appearing to be greater with the pilot-scale experiments. One possible explanation is that students have less to

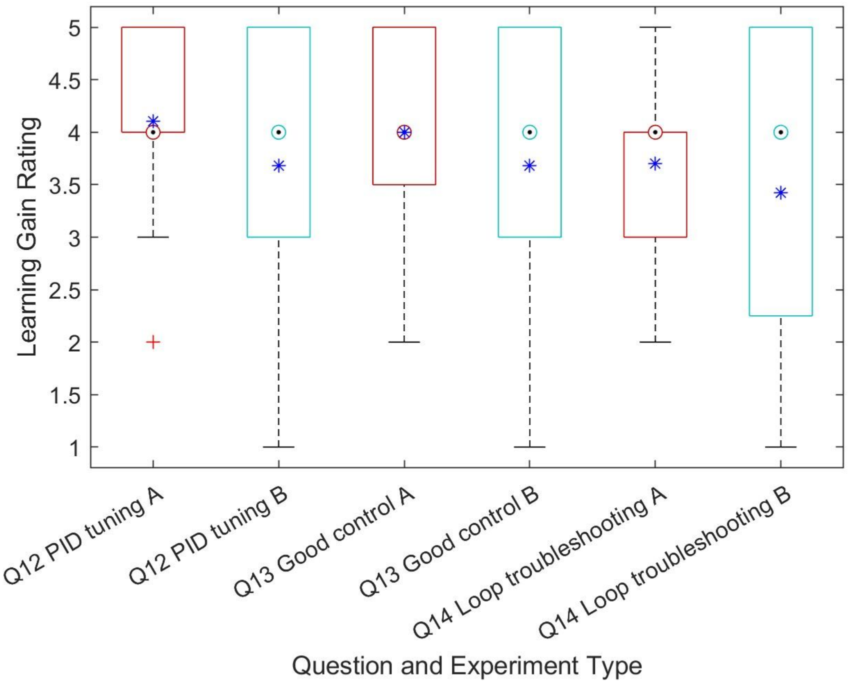

Figure 9: Self-perceived learning gains in practical aspects of control relating to controller performance. Asterisks indicate means, targets indicate medians.

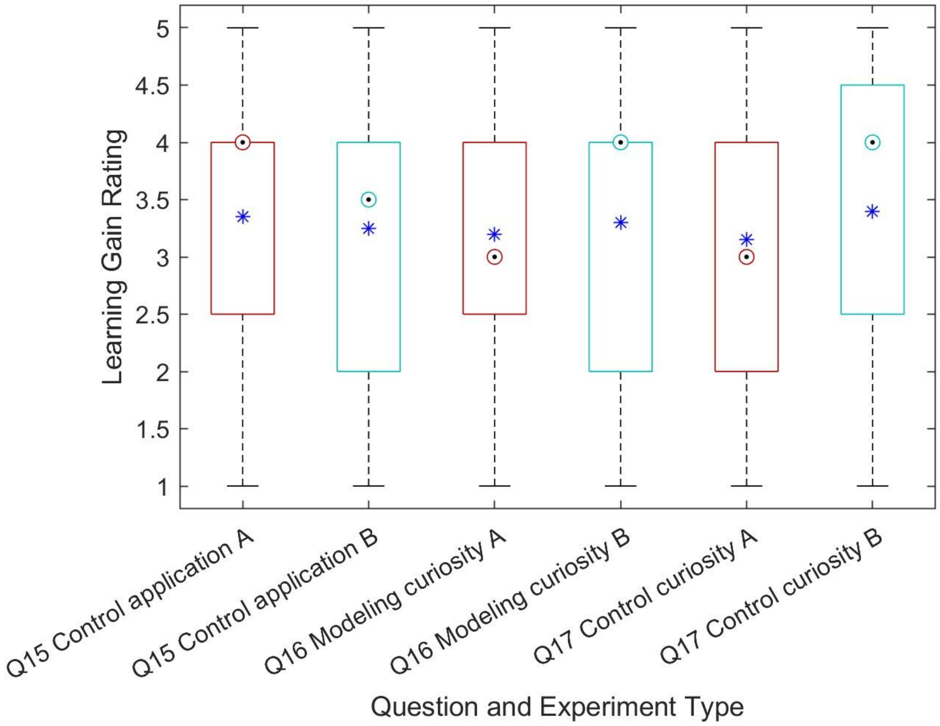

Figure 10: Self-perceived learning gains in behaviors and attitudes about control relating to confidence in applying control and curiosity about aspects of control. Asterisks indicate means, targets indicate medians.

do in the instrumentation, data acquisition, and software programming in these experiments, leaving more cognitive space for curiosity in these topics. It is also possible that students see the pilot-scale experiments as closer to a real-world experience as a control engineer, and thus they may see these experiments as more useful to them in the future, resulting in greater curiosity toward the topics. This possible student perspective was not specifically studied in this work and would be a topic for further research.

Figure 11 shows survey results from questions about persistence in control concept understanding and project completion. There is no appreciable difference between perceived gains in project completion persistence between the two types of experiments. The indicated, but not statistically significant, difference in median of perceived gains with respect to persistence in concept understanding leans toward greater gains with the pilot-scale experiments. As before, it is possible that this result may be influenced by the reduced work and cognitive load of these types of experiments, leaving students willing to expend more effort in pursuing understanding of the important concepts. Similarly, if students think of the pilot-scale experiments as more related to real-world experience, their persistence toward understanding could be affected. This would be a useful topic for further study.

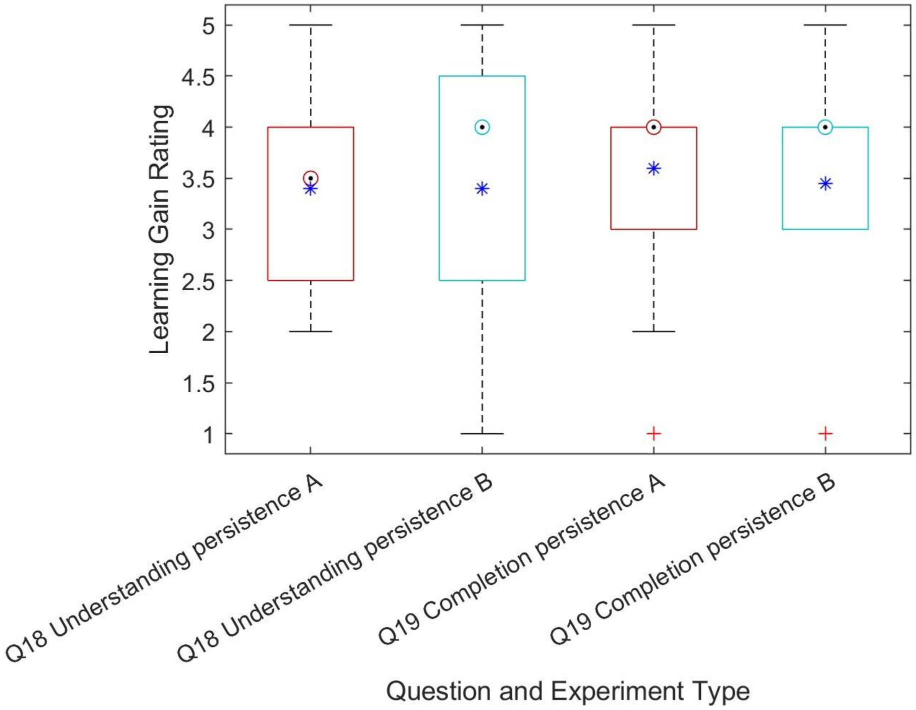

Figure 11: Self-perceived learning gains in behaviors and attitudes about control relating to persistence in theoretical understanding and project completion. Asterisks indicate means, targets indicate medians.

Even though we were not able to achieve statistical significance in the observed differences in medians with all but question Q7, the survey results still indicate some important takeaways. Bench-top Arduino experiments appear to improve perceived gains in areas relating to individual control loop elements, PID tuning for good control, troubleshooting, and confidence to apply control in the real world. Pilot-scale experiments appear to improve perceived gains in understanding of process nonlinearities, curiosity about control topics, and persistence in understanding. Taken together, exposure to both types of experiments appears to provide a well-rounded complimentary experience with control application and enhancement of control theory learning.

Instructor Reflection

Although purely anecdotal, some reflection by the instructor of the courses described in this work regarding the observed changes brought about by the addition of these bench-top experiments may be informative. The instructor has been teaching the Process Control theoretical course since 2015 and the Process Control lab course since it began in its current format in 2021. The addition of the bench-top Arduino projects made possible the dedicated Process Control lab course and ensured that each student had much more opportunity to perform experiments within the topic area. Since the beginning of the lab course with the increased projects, the instructor has noted an increase in deeper "why" and "what if" questions asked in the theory course. In addition, inquiries regarding and pursuit of careers in the Process Control field seem to have increased in the same time period. Both observations are worth investigating in future research.

Conclusions

In this paper, we have presented a low cost, easily extensible Arduino-based control module for bench-top control experiments in a Chemical Engineering 4th year Controls Laboratory course. These units were easily assembled from readily available hobbyist electronics components. Students were given these bench-top Arduino experiments, as well as traditional pilot-scale experiments with industrial instrumentation and control software. Their experience with both types of experiments provided a well-rounded control lab experience, with self-perceived learning gains in multiple dimensions learning ranging from control theory to application. Students rated their gains greater in some dimensions for experience with the bench-top Arduino experiments and greater in others for the pilot-scale experiments. Taken together, both types of experiments complement one another in terms of learning outcomes. These bench-top Arduino control experiments can be added to existing installed pilot-scale experiments to enhance student experience, or can be used as an alternative when pilot-scale equipment is not available.

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