Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #47592

Introducing Programmable Logic Controllers in Undergraduate Chemical Engineering Process Control Laboratory using a Liquid Level System

Tata Serebryany, University of Washington
Jennafer Marsh, Brigham Young University
Hayden Scott West
Dr. Stacy K Firth, University of Utah

Stacy K. Firth is an Assistant Professor (Lecturer) in the Department of Chemical Engineering at the University of Utah. In her role, she focuses on Engineering education in grades K-12 and undergraduate education. She has developed an inclusive curriculum for a year-long Engineering exploration and projects course that is now taught in 57 Utah high schools. She also developed and provides professional development workshops for Elementary and Secondary science educators to support their teaching of Engineering within K-12 classrooms. She has developed and implemented a senior-level projects laboratory course in the Chemical Engineering curriculum at the University of Utah, giving students hands-on experience with the concepts she is teaching in their Process Control theory course. Stacy received a BS and MS in Chemical Engineering from the University of Utah. She then earned a PhD in Chemical Engineering at the University of Texas at Austin. Her research was focused on algorithms used in the processing of semiconductor wafers and resulted in two patents.

Introducing Programmable Logic Controllers in Undergraduate Chemical Engineering Process Control Laboratory using a Liquid Level System

Tata Serebryany, Jennafer Marsh, Hayden West, Stacy Firth

Abstract

The disparity between industry's application of process control and its coverage in undergraduate curricula has been well documented. At the undergraduate level, process control courses primarily focus on theoretical concepts such as process dynamics, controller algorithms, and controller tuning. However, industrial process control applications require the use of industrial control systems (ICS) that include several layers of hardware, software, and communication technologies to control plant operations. A crucial component of an ICS are the specialized computers used for real-time automation that receive inputs from field devices (like sensors) and make decisions to control outputs (like valves or motors) based on pre-programmed logic. It is these systems into which the algorithms, such as the Proportional-Integral-Derivative (PID) algorithm, for control calculations are embedded. Programmable Logic Controllers (PLCs) are frequently used to perform this function. While PLC education is available in other engineering departments, specialized programs, and certificate courses, it remains largely absent from chemical engineering curricula. The few programs that have introduced PLC teaching modules, focus on system usage rather than design and implementation or rely on computer simulations, despite the recognized need for hands-on experimentation. This lack of PLC education represents a gap in knowledge that would be important for all students who will work in an industrial environment, especially those going into the field of process control.

Over the past year, we introduced a liquid level system controlled by Opto-22's Programmable Automation Controller (PAC) architecture and Opto-22's Edge Programmable Industrial Controller (EPIC) training center in the Senior Process Control Lab. The PAC architecture is analogous to PLC in industrial automation and EPIC is an updated version of this architecture. These systems were specifically designed to provide students with practical experience in connecting, programming, and tuning Proportional-Integral-Derivative (PID) controllers using the Opto-22 platform. Based on student feedback, the introduction of this system has led to improvements in their understanding of process control concepts and in their perceived preparedness for industry.

In this paper, we present instructions for creating a PLC teaching module, covering everything from physical assembly to phrasing laboratory assignments. We report on data from student surveys and feedback sessions, which reflect the effectiveness of this laboratory experience on student confidence in applying process control concepts in an industrial setting and their perceived preparedness for industry roles. Finally, we discuss the broader implications for chemical engineering education, specifically how real-world control systems can help bridge the gap between academic training and industry demands.

Introduction and Background

Process control is widely used in all areas of engineering. It plays a critical role in ensuring the efficient and safe operation of chemical processes and manufacturing. Control requires the monitoring of various parameters, such as temperature or pressure, and manipulation of control elements, often valves or pumps, to maintain desired conditions. The goal of process control is to maximize the yield of the desired products while maintaining safe conditions. One of the common methods of process control is implementing a Proportional-Integral-Derivative (PID) controller. PID controllers can be used for a wide variety of control systems, from simple feedback loops to multi-stage cascade controllers accounting for multiple disturbances in a system.

Studies from many decades ago, as well as recent research have indicated that there is a significant disconnect between practical application of process control in industry and what is being taught at the undergraduate level, and call for more robust education in practical process control [1],[2],[3],[4]. An NSF-sponsored study conducted by the American Institute of Chemical Engineers has relayed industry requests for a bigger focus on implementation of process control as opposed to theory [5].

Many courses exist within other engineering departments, expanded studies, and certificate programs that focus on PLC education [6], however only a few chemical engineering core courses currently teach PLC [7]. The chemical engineering department at Colorado Boulder has identified this education gap and developed a series of finite state machine PLC teaching exercises for the controls teaching lab [7],[8]. Certain other programs have proposed software solutions to this problem by implementing simulation-based PLC teaching [9]. However, most indicate that real experiments are necessary to complement computer simulation in student learning, and simulations are chosen due to financial constraints [10].

Methods

Lab Course Delivery

The PAC programming activity was incorporated into the senior-level projects lab course. This lab course is focused solely on system identification and control implementation and is offered concurrently with the process dynamics and control course. The principle lab projects during the semester are two group projects on the available small pilot scale lab equipment (Liquid Level and Training Module), each of which uses the Opto-22 PAC system for control and data acquisition. The assignment objectives were matched to the progression of topics in the control course, with the first projects being focused on process identification and modeling, and the later projects being focused on control implementation and tuning. Two smaller individual projects were also assigned prior to each group project to give student exposure to microcontroller programming within the context of process control. These individual projects utilized the Seeed

Studio XIAO RP2040 microcontroller, programmed using CircuitPython. The Opto-22 PAC configuration on either the Liquid Level experiment or the Opto-22 Training Module was assigned to lab groups during the main lab projects. Student groups which were not assigned to the liquid level experiment rotated in succession through working with the Opto-22 Training Module for one 3-hour lab period during the course of their principle lab project. Figure 1 shows the student progression through assignments during the semester. Student groups were assigned to do their rotation during either the first or second group project period.

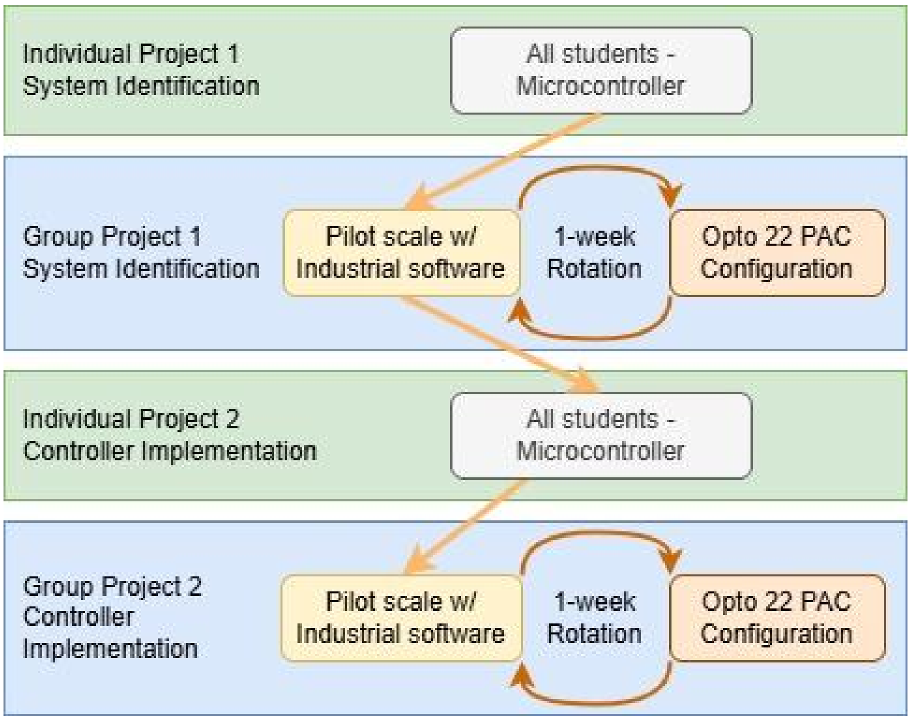


Figure 1. Student progression through process control lab projects during the semester.

Following this progression through the course gave students experience with microcontroller programming of data acquisition and algorithms, and configuration and operation of industrial level control software.

Survey and Reflections

Students were surveyed at the conclusion of the semester to ascertain their perception of their learning gains from the microcontroller experiments, pilot scale experiments, and the Opto-22 PAC configuration. Survey questions were drawn from Firth, et.al. [11], and were expanded to include a section for perceived learning gains from the PAC configuration. These questions asked students to rate their learning gains (1 = no gains, 2 = a little gain, 3 = moderate gain, 4 = good gain, 5 = great gain, or NA = not applicable). In general, survey questions were grouped to examine learning gains in three areas: understanding of control theory, control in practice, and attitudes and behaviors around the learning process within the topic of process dynamics and control.

A reflection assignment was the course deliverable for the PAC configuration activity. Students were asked to reflect on their experience with the PAC configuration in order to help them integrate the experience with the other learning activities of the course relating to theoretical and practical knowledge of control systems. Students were asked to explore five key areas to aid in this integration. First, they describe the setup and function of the control systems and instruments they used, highlighting the interaction and significance of each component. Second, they address the challenges faced during instrumentation setup and software configuration, linking these to their ability to apply troubleshooting methods and ownership of their own learning. Third, students identify the application of control theory within the configuration task, demonstrating how algorithms and input-output interfaces fit within the context of the PAC system. Fourth, they relate their lab experiences to broader industrial applications, emphasizing the importance of precision and reliability in control systems across various sectors. Finally, the assignment prompts reflection on personal and professional growth, focusing on skill development relevant to their future careers in chemical engineering. This structured reflective approach enhances learning and prepares students for complex real-world engineering challenges. See Appendix B for the assignment memo.

Apparatus

Opto-22 Training Module

The Training Module assignment utilized the Groov EPIC Learning Center (GRV-EPIC-LC) from Opto-22, as well as their free online learning tutorials. The Learning Center includes a groov EPIC processor, power supply, and modules for handling inputs and outputs. It comes with software tools for system setup, control programming, and data communication. A temperature probe sensor/heater bundle and other interactive elements (LEDs, push button, sound alarm, potentiometer) for simulating process control operations are included.

Portable Liquid Level System

A new liquid level system has been designed and constructed for use in the process control laboratory (Figure 1). A mobile cart made to act as the desk and work station was selected to allow for in-class demonstrations as well as laboratory use. The liquid level vessel is a 4ft tall 6" acrylic tube, and a pressure transducer is used as the level sensor. A MasterFlex pump is used to circulate the water from the reservoir to the cylinder through 9.50 mm thick tubing. The outlet allows for gravity draining using interchangeable outlets of varied sizes or even an additional pump. Water in the system returns to the reservoir and can be recycled for multiple uses. An electrical box is mounted on the side of the cart to reduce the risk of water interaction with electrical components. The cart was built to the design specifications of Figure 3. Costs of all cart components are listed in Appendix A.

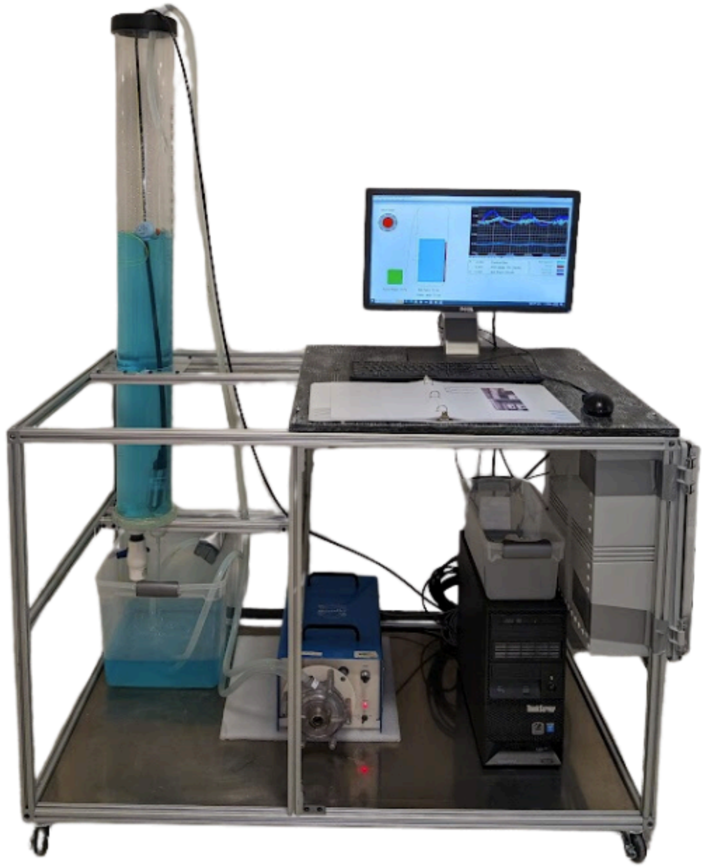


Figure 2: Assembled liquid level cart, background removed.

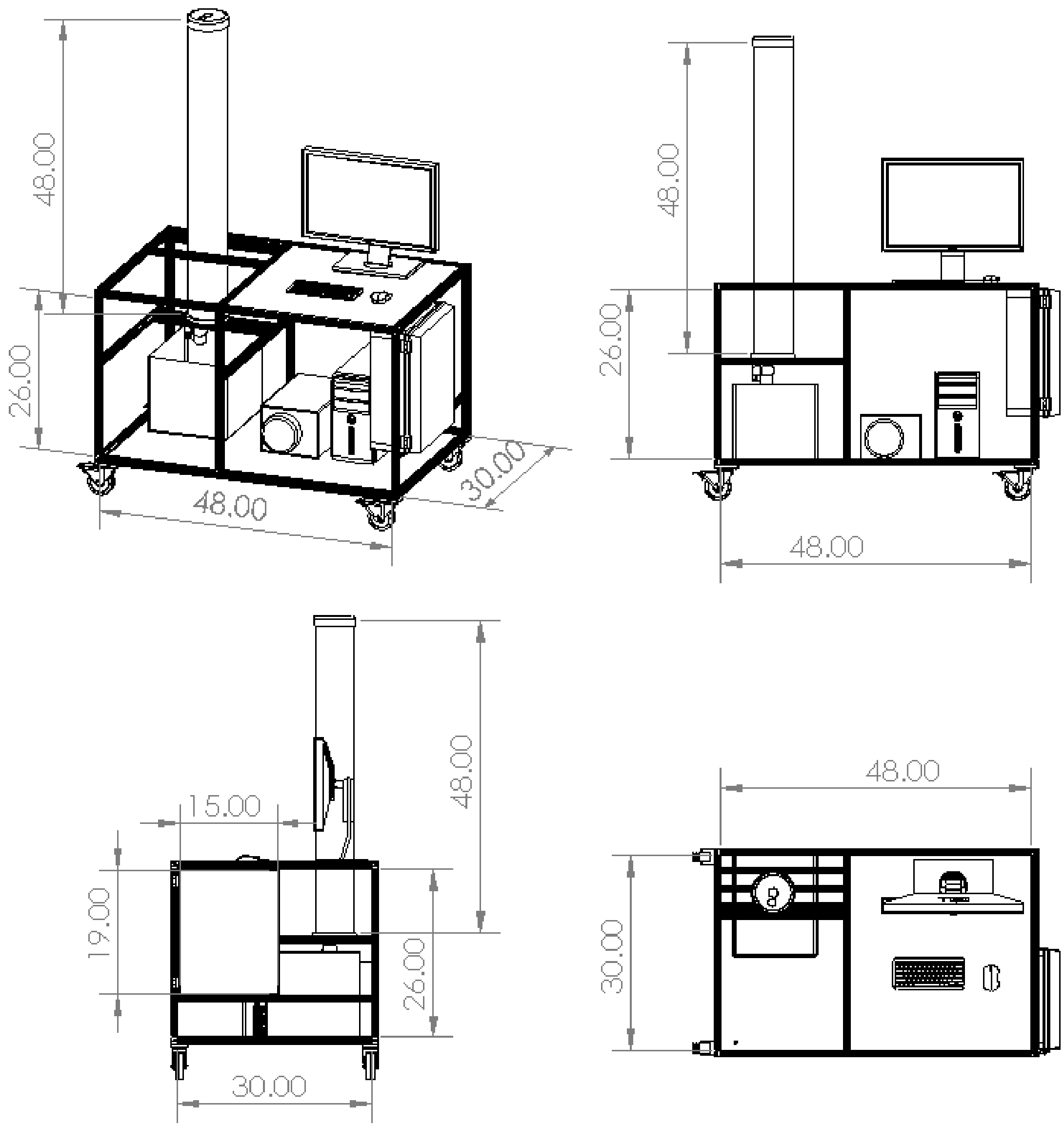


Figure 3: Liquid Level Cart Rendering With Dimensions in Inches.

The Opto baseline setup was created using an Opto R1, an analog input module, and an analog output module. These were wired with a pressure sensor and a peristaltic pump. A 24V and a 5V power brick were used to power this setup. This was then programmed into an Opto-22 strategy and display system to create a PID controller for the height of the water. The water level is directly correlated to the pressure, so a simple conversion of psi to cmH2O was used to calculate the water height. The PID takes the desired water level, converts it to its corresponding pressure in psi, and uses that as its setpoint in the PID algorithm.

The baseline Opto strategy also contains calculations for water height from measured pressure. These calculations are used for the PID loop and to ultimately display the water level. The final major feature of the Opto system is a chart that shuts down the system, to ease the process of stopping everything for time efficiency or if something goes wrong with the system.

The Opto display contains basic information when running the system. This includes the water height, PID constants, and set point. The display allows the user to switch between auto (PID) mode and manual control of the pump speed. The display also visually shows the water height and setpoint so that they can be easily compared. A real-time plot graphs the set point, water height, and pump speed over time. All of the values shown on the display are also saved to a data file so the data can be collected and analyzed.

Tutorials
Three tutorials have been developed to assist the completion of parts 1-3 of each assignment respectively, while educating students on the basics of the Opto-22 SNAP PAC system: Wiring, Strategy, and Display. The examples below pertain to the liquid level set-up. Analogous strategy and display tutorials were created for the Training Module activity, which uses EPIC Groov equipment—an updated platform from the SNAP PAC.

First, the students follow a step by step tutorial with images to learn Opto-22 electrical wiring. The rationale behind each connection is explained. All wires are prepared and labeled corresponding to the step (Figure 4, 5). Students are provided with an electrical box with the modules positioned in place and are asked to wire the system to get data from the pressure sensor and control the pump. Before and after images of the electrical box can be seen in Figure 6.

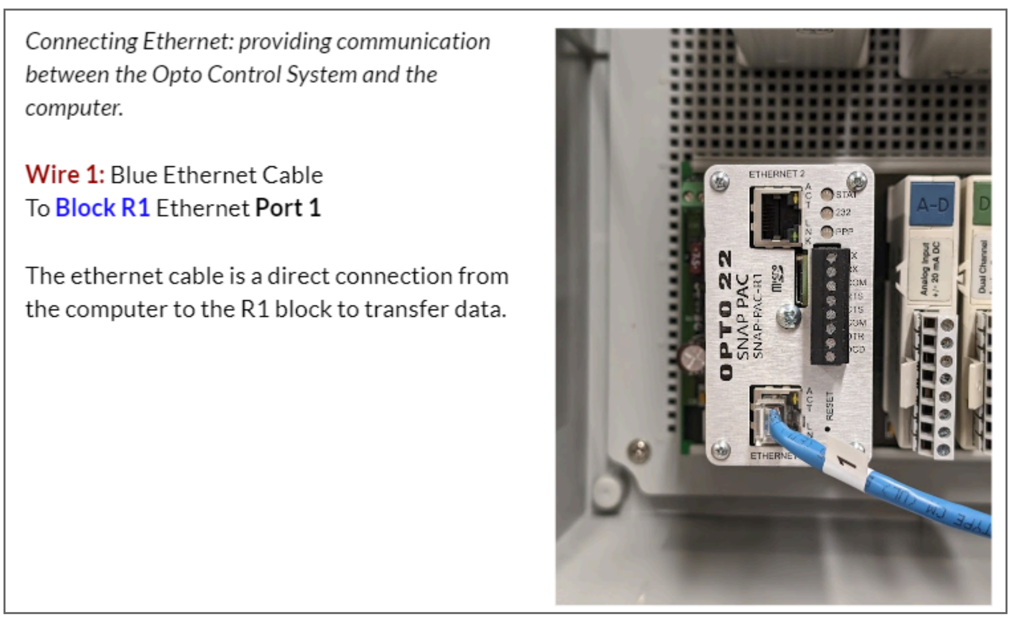


Figure 4: Example from the wiring tutorial.

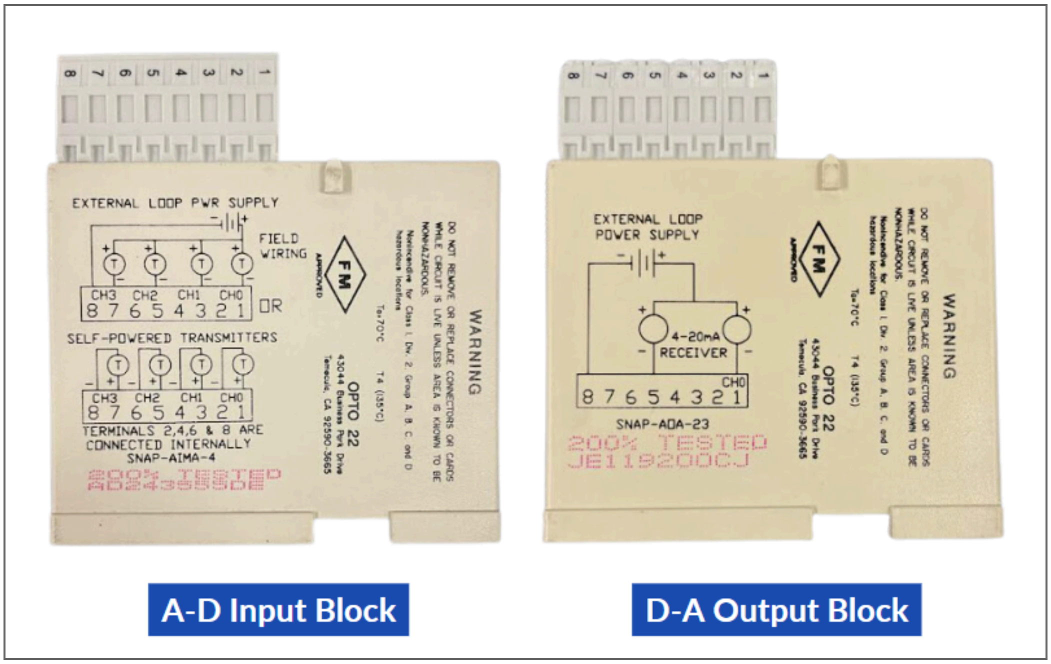


Figure 5: Wiring diagrams for the I/O blocks from the wiring tutorial.

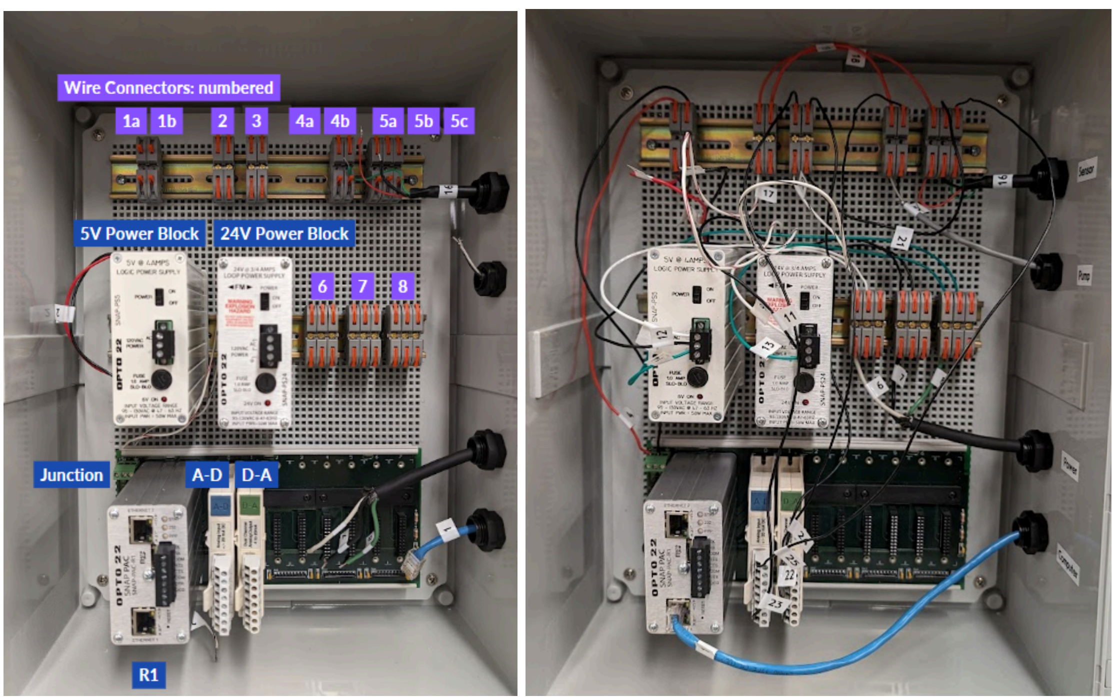
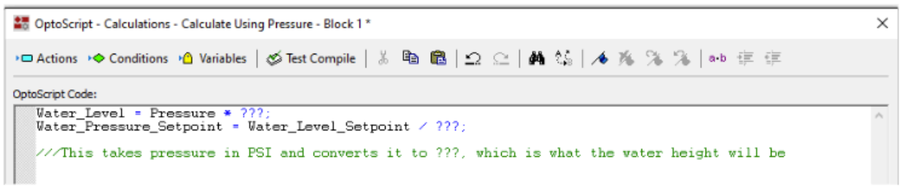


Figure 6: Electrical box before wiring (left) and after (right).

In the next tutorial, students are introduced to key Opto-22 tools and actions, including logic blocks and OptoScript code. This document guides students through the process of building the Opto-22 strategy by providing information about the tools in the software and helpful screenshots that show the process in making the strategy (Figure 7). At the start of the tutorial, the students are given very detailed step by step instructions, but as they progress through the tutorial, they are expected to use their prior knowledge to perform calculations and complete the activity.

13. Double-click the "Level Calculations" block.

This block will calculate the water level from the pressure value given by the sensor, then it will calculate the pressure needed to reach the water setpoint. Determine what you need to convert the measured pressure into a liquid height (mm, cm, in, etc.)!
You must end each line of code with a semicolon!
Tip: The variable names are case-sensitive and must be exactly how you made them. You can also search for them in the Variables ***"Variables" tab***



14. Click "Test Compile" to check for any errors in the code. If there are no errors or warnings click save.

Figure 7: Example from the strategy tutorial.

The last tutorial (Figure 8) helps visualize the system changes in real time and plot the PID controller response. Students will build their own display screen (Figure 9) and add interactive interface elements to change PID constants and setpoint. Students are given more creative freedoms to customize the display to their liking.

Step 4: Shutdown button

Choose the circle tool from the toolbox to draw a circle (or any other shape you want your button to be).
Right-click on the circle. Choose **fill**, then **color** -- Pick a color!

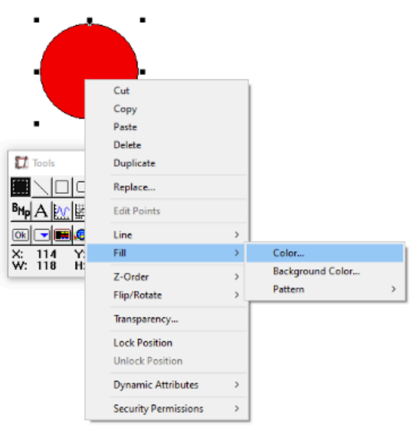


Figure 8: Example from the display tutorial.

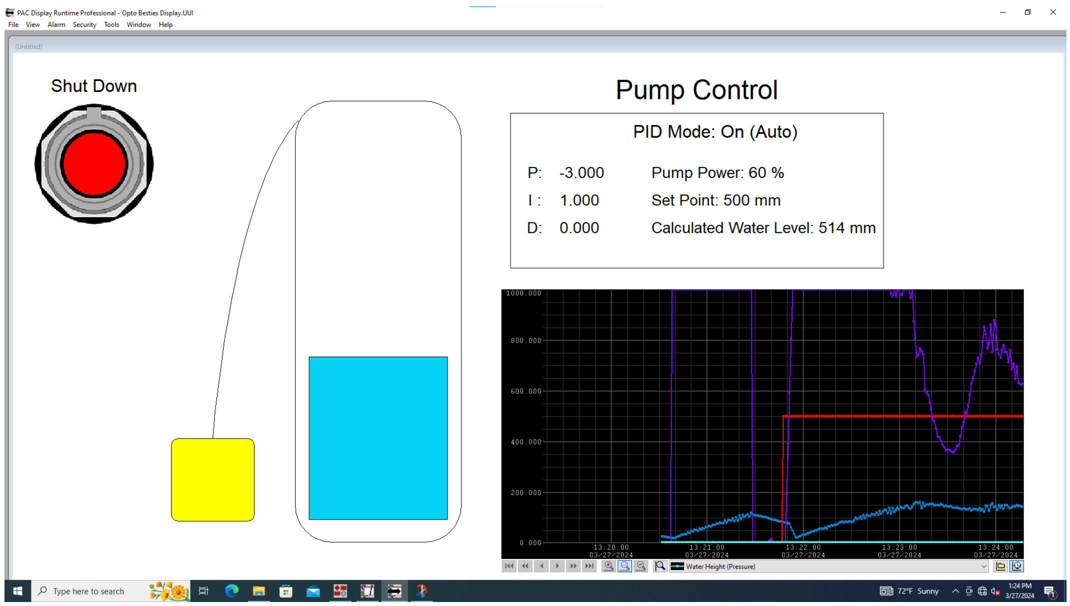


Figure 9: Opto display screen for liquid level.

Results and Analysis

Liquid Level Performance in Lab

The liquid level system functioned as expected, with no technical performance issues or leaks. At maximum pump power, the column took around 2 minutes to fill up to 15 L and drained in under 11 seconds when using the drain valve. The PID performed reasonably well and reached steady state in around 5 minutes when tuned to the following parameters: Ki = -2.0, Ti= 0.35, Td= 0.0. Optimal behavior was observed at water levels of 30-60 cm with typical noise around ±2 cm. The pump worked at the range of 3-100% power.

Student Learning Gains Survey Results

The results of the student survey on self-perceived learning gains indicated that students did not perceive their learning gains from the PAC configuration activity to be higher than those from the microcontroller or pilot-scale experiments. However, in several key areas, learning gains were still rated as at least good for the PAC configuration. Specifically, gains in understanding of sensor use and the PID algorithm had statistically significant lower ratings of learning gains, they were still rated as good (median score of 4). Similarly, curiosity about modeling also showed a statistically significant lower mean, but maintained a good median score. Learning gains in final control elements and overall curiosity about control did not differ significantly from other course activities.

Unexpectedly, confidence in engaging with real-world control applications was notably lower, with a median Likert score of 3 (moderate gain), compared to scores of 5 (great gain) for pilot scale and 4 (good gain) for microcontroller experiments. This may reflect the complexity of the PAC interface or its divergence from traditional chemical engineering applications.

Furthermore, gains in persistence in concept understanding and project completion were rated similarly to other experimental activities, indicating good learning gains. These findings suggest that, while students perceived more learning gains from the microcontroller and pilot scale experiments, they did still see the PAC configuration as beneficial in some areas and it did contribute to a well-rounded experience for learning about industrial control within the context of the lab course.

Student Reflection Results

The reflections written by students were read and analyzed for general themes of challenges and learning. Students faced challenges with the software in configuring the OptoScript, including variable definition, I/O unit labeling, and correct logic flow in the blocks. Many of the reports document mistakes in variable definition and I/O mapping as initial challenges, with the software requiring specific syntax and consistent variable definitions similar to any programming language. These are typical struggles students encounter within any programming environment.

Students learned to troubleshoot issues, including logic errors, syntax errors, and hardware connection problems. Many students mentioned the value of trial and error, re-walking the process to find mistakes, and consulting more experienced individuals, e.g. instructional staff and lab personnel.

Students reported a significant increase in understanding of process control principles and the application of theoretical knowledge to real-world systems. As one student stated, "This lab was a solid opportunity to get out of the books and into a real-world application of what we've been studying." Many students noted the importance of going beyond the books and experiencing these control systems to really grasp their impact. Students also mentioned appreciation of skill development in the areas of:

- Hands-on experience with wiring, programming, and configuring control systems using Opto-22 hardware and software.
- Improved troubleshooting and problem-solving skills when encountering errors.
- Enhanced understanding of PID control, transfer functions, block flow diagrams, and the importance of accuracy and precision in industrial control.

Students also found the exercises valuable in preparing for future careers in the chemical engineering field, particularly in process control and automation. As another student wrote, "this experience has given me an appreciation for chemical engineers, but more specifically it has shown me how important controls engineers are in industry." Students also expressed new appreciation for the complexity of real-world control systems, as opposed to the more simplified view of such control systems that might occur in academic settings. Some students mentioned a growing sense of confidence in their ability to make an impact in industry, particularly regarding process optimization.

Instructor Reflection

The Opto-22 configuration training modules fit well within the course progression. All student teams, with one exception, were able to complete the configuration activity within the 3-hour lab period allotted. The experience provided students with practical, hands-on experience in designing and implementing control systems. Through the challenges encountered and successes achieved, students gained a better understanding of PID control within the practicalities of industrial automation. The reflections show that this experience has helped students develop skills critical for their future careers in chemical engineering and related fields. The students made valuable connections between the theory that they have learned throughout their courses to practical applications in their control modules. As one student stated, he had "built a stronger understanding of control systems and how they operate because of this lab. This will help me in designing and troubleshooting control systems that I will encounter in an oil refining setting that I am planning to enter into after graduating." This module and these exercises have prepared the students for their future work in the field.

Conclusions

In this paper, we showcased a series of new hands-on PLC modules for chemical engineering undergraduate students, which were implemented in the Process Control Lab course. The first module utilized ready-to-work-with Learning Center Opto-22 hardware. For the second module we designed and built a portable cart with a Liquid Level column, powered by the SNAP PAC Opto-22 architecture. Comprehensive tutorials to guide students through wiring, programming, and system operation were created for both assignments. The main goal of these activities is to address the long-expressed concern about the theory vs. practice "gap" in process control education [12], by providing direct training with PLC systems similar to those in industry. Based on the surveys and reflections, the addition of the configuration tasks has created a more well-rounded process control education, bringing in a more industrial angle to the classroom, in balance with theoretical learning.

Conflicts of Interest Statement

The authors declare no conflicts of interest. The Opto-22 Snap PAC modules were donated to the University of Utah Chemical Engineering Department by Opto-22 many years ago for use in the unit operations lab, not for this particular project. The Opto-22 EPIC GROOV hardware was purchased by the department.

References

[1] H. Chestnut, “Bridging the gap in control - Status 1965,” IEEE Transactions on Automatic Control, vol. 10, no. 2, pp. 125–126, Apr. 1965, doi: https://doi.org/10.1109/tac.1965.1098125.

[2] T. F. Edgar, “Process Control Education in the Year 2000,” Chemical Engineering Education, vol. 24, no. 2, pp. 72–77, Jan. 1990.

[3] T. F. Edgar, B. A. Ogunnaike, J. J. Downs, K. R. Muske, and B. W. Bequette, “Renovating the undergraduate process control course,” Computers & Chemical Engineering, vol. 30, no. 10–12, pp. 1749–1762, Sep. 2006, doi: https://doi.org/10.1016/j.compchemeng.2006.05.012.

[4] F. Khan, P. Amyotte, and S. Adedigba, “Process safety concerns in process system digitalization,” Education for Chemical Engineers, vol. 34, pp. 33–46, Jan. 2021, doi: https://doi.org/10.1016/j.ece.2020.11.002.

[5] Y. Luo et al., “Chemical Engineering Academia-Industry Alignment: Expectations about New Graduates,” 2015. Available: https://www.aiche.org/sites/default/files/docs/conferences/2015che_academicindustryalignmentstudy.pdf

[6] H. Jack, “Teaching Controls With PLCs,” 2000 ASEE Annual Conference Proceedings, Session 1566. Available: https://peer.asee.org/teaching-controls-with-pl-cs.pdf

[7] S. C. Rowe, C. I. Samson, and D. E. Clough, “A Framework to Guide the Instruction of Industrial Programmable Logic Controllers in Undergraduate Engineering Education,” Education for Chemical Engineers, vol. 31, pp. 76–84, Apr. 2020, doi: https://doi.org/10.1016/j.ece.2020.03.001.

[8] D. Clough, “The Missing Link In Process Control Education Incorporating PLC’s Into The ChE’s Control Course,” ASEE Annual Conference, pp. 7–1166, doi: https://doi.org/10.18260/1-2--10746.

[9] K. Moodley, “Improvement of the learning and assessment of the practical component of a Process Dynamics and Control course for fourth year chemical engineering students,” Education for Chemical Engineers, vol. 31, pp. 1–10, Apr. 2020, doi: https://doi.org/10.1016/j.ece.2020.02.002.

[10] S. R. White and G. M. Bodner, “Evaluation of Computer Simulation Experiments in a Senior-Level Capstone ChE Course,” Chemical Engineering Education, vol. 33, no. 1, pp. 34–39. Available: https://journals.flvc.org/cee/article/view/123201.

[11] S. Firth, A. Butterfield, and M. John, “Development and Use of an Adaptable Arduino-Based Control System for Bench-Top Process Control Experiments,” ASEE Annual Conference, Feb. 2024, doi: https://doi.org/10.18260/1-2--43103.

[12] B. W. Bequette, “Process control practice and education: Past, present and future,” Computers & Chemical Engineering, vol. 128, pp. 538–556, Sep. 2019, doi: https://doi.org/10.1016/j.compchemeng.2019.06.011.

Appendix A: Liquid Level Cart Component Prices in U.S. Dollars

Parts which were already owned by the lab and did not contribute to the creation cost of the system are shown in gray. In instances where legacy equipment such as the MasterFlex Pump was used, a comparable alternative is provided. Prices are listed as of October 2023 when parts were ordered.

Part Description	**Source**	**Part #**	**Quantity**	**Price per**	**Cost**
Profile 1010	80/20 Inc.	1010	400	$0	$136
Corner bracket	McMaster-Carr	47065T239	12	$8	$96
Corner cubes	McMaster-Carr	47065T244	8	$12	$97
Wheel 2318	80/20 Inc.	2318	4	$14	$56
Bolts	80/20 Inc.	3061	100	$0.34	$34
Aluminum sheet	McMaster-Carr	89155K11	1	$200	$200
Plywood sheet	McMaster-Carr	1125T524	1	$17	$17
Cylinder 6in, 6ft	Grainger	BULK-PT-CAC-32	1	$551	$551
Pump	Avantor by VWR	MFLX77916-42	1	$5,030	$5,030
NPT fittings	McMaster-Carr	5372K121	4	$6	$25
Bucket	EZOWare	885157012447	1	$33	$33
Tubing	MasterFlex	96410-73	1	$148	$148
3D printer filament	Amazon	P-SUNLU-PLA-Black	1	$13	$13
Clear ruler decal	Amazon	B0C6NNLZQ5	1	$13	$13
Computer tower	Lenovo	7D8JA00XNA	1	$497	$497
Monitor	Dell	SE2422H	1	$99	$99
Mouse	Dell	15VVH	1	$20	$20
Keyboard	Dell	739P7	1	$20	$20
Mouse pad	Amazon	B07JQSVZ81	1	$13	$13
Opto Analog output	Opto22	SNAP-AOA-23	1	$429	$429
Opto Analog input	Opto22	SNAP-AIMA-4	1	$388	$388
24V power supply	Opto22	SNAP-PS24	1	$347	$347
5V power supply	Opto22	SNAP-PS5	1	$347	$347
SNAP-PAC	Opto22	SNAP-PAC-R1	1	$1,215	$1,215
Wires	Amazon	SW20G008F25C2	1	$11	$11
Wiring box	Amazon	B0BZR3M8PK	1	$99	$99
Pressure transducer	McMaster-Carr	396N11	1	$360	$360
				Total value	**$10,293**
				Total new purchases	**$1,679**

Appendix B: Opto-22 System Configuration Reflection Memo

DATE:

TO: Control Engineers In Training

FROM: Engineering Training Supervisor

SUBJECT: **Opto-22 Tutorial Reflection**

Now that you've had the experience of setting up instrumentation and configuring the control software for an industrial level control system, this reflection assignment aims to help you connect your practical skills with theoretical knowledge and real-world applications. Please answer the following questions thoughtfully, drawing on both your recent lab work and what you've learned in your process control theory course. Submit your work in a memo format.

1. **Understanding the Setup:**
   - Describe the process and the specific control system you worked with. What are the key components of this system, and how do they interact?
   - Which instruments did you set up, and what variables do they measure or control? Explain the significance of each instrument in the context of the overall process.
2. **Challenges and Solutions:**
   - What were the most challenging aspects of setting up the instrumentation and configuring the control software? How did you address these challenges?
   - Reflect on any troubleshooting or problem-solving techniques you employed. How do these techniques relate to what you've learned in your theoretical coursework?
3. **Theory in Practice:**
   - Discuss how the principles of process control theory applied in your lab task. Can you identify any specific theories or models that helped you understand or predict the system's behavior?
   - How did the practical experience of configuring the control software enhance your understanding of control algorithms and their implementation?
4. **Real-World Connections:**
   - Consider the industrial applications of the control systems you worked with. In what types of industries or processes would this system be essential, and why?
   - Reflect on the importance of accuracy and reliability in process control. Provide examples from your lab work where precision was crucial.
5. **Personal and Professional Growth:**
   - How has this experience influenced your perspective on the role of a chemical engineer in industry?
   - What skills have you developed or improved upon through this lab exercise that you think will be beneficial in your future career?

Please submit your reflections in a format that best allows you to express your thoughts clearly and thoroughly. This could be a written report, a video presentation, or a slide deck, as per the course guidelines.

Appendix C - Learning Gains Survey and Response Data

Table C.1 shows the questions presented to students in the learning gains survey. These questions were asked in reference to each experience: microcontroller experiments, pilot scale experiments, and Opto-22 PAC configuration.

Table C.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						

Plots in Figures C.1 - C.6 show response distributions for the surveys taken utilizing the questions above. Questions are listed by question number and a short description. An “A” is used to indicate data for that question as applied to the microcontroller experiments, a “B” represents responses for the question regarding the pilot scale experiments, and a “C” is used to indicate data from responses to the question about the Opto-22 PAC configuration. For all figures asterisks indicate means, targets indicate medians.

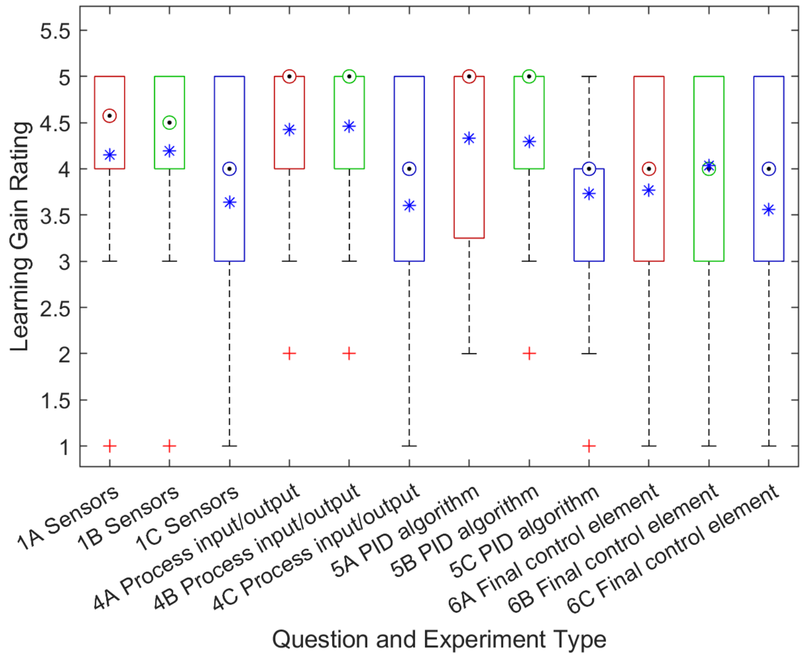


Figure C.1: Self-perceived learning gains in understanding of theory relating to control loop elements.

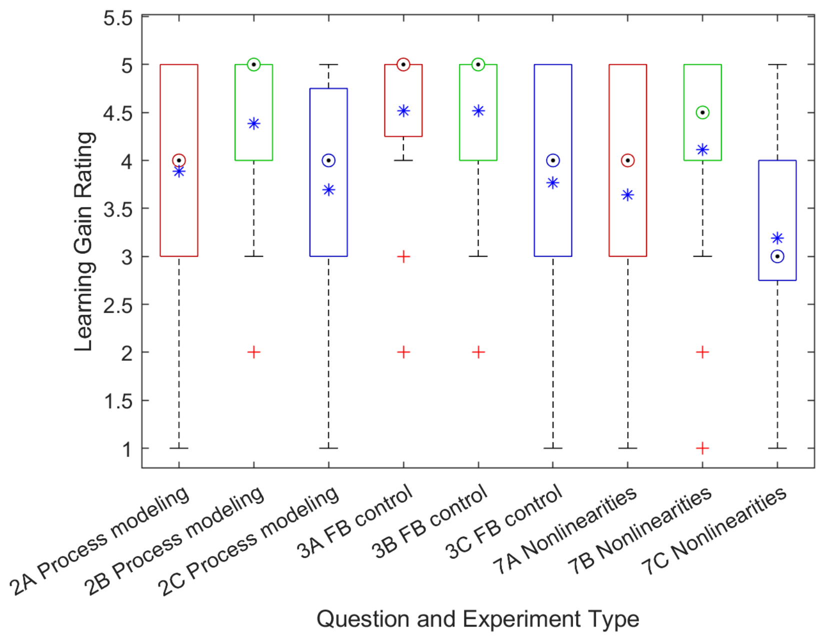


Figure C.2: Self-perceived learning gains in understanding of theory relating to control loop dynamics.

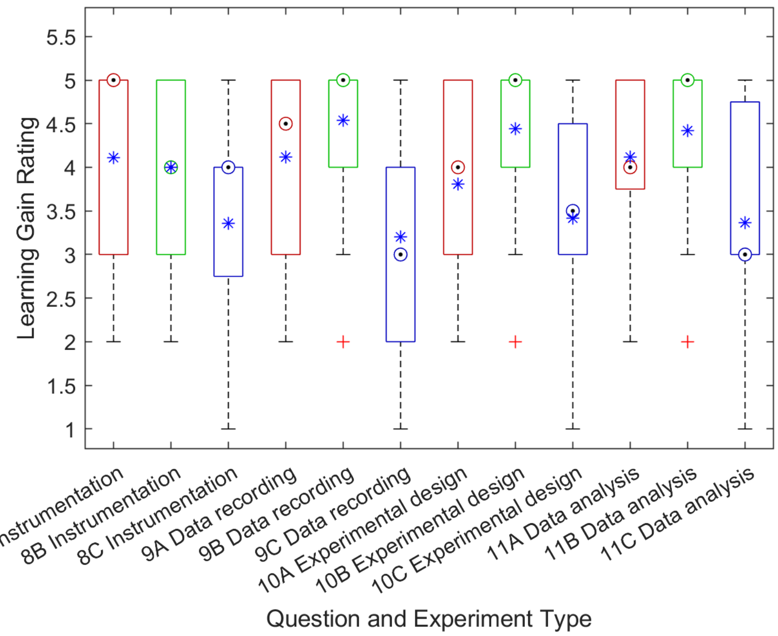


Figure C.3: Self-perceived learning gains in practical aspects of control relating to control loop instrumentation and experimentation.

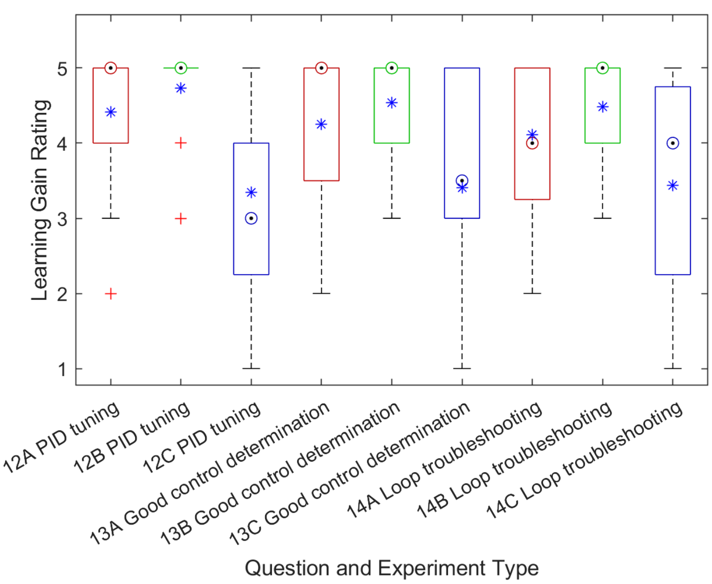


Figure C.4: Self-perceived learning gains in practical aspects of control relating to controller performance.

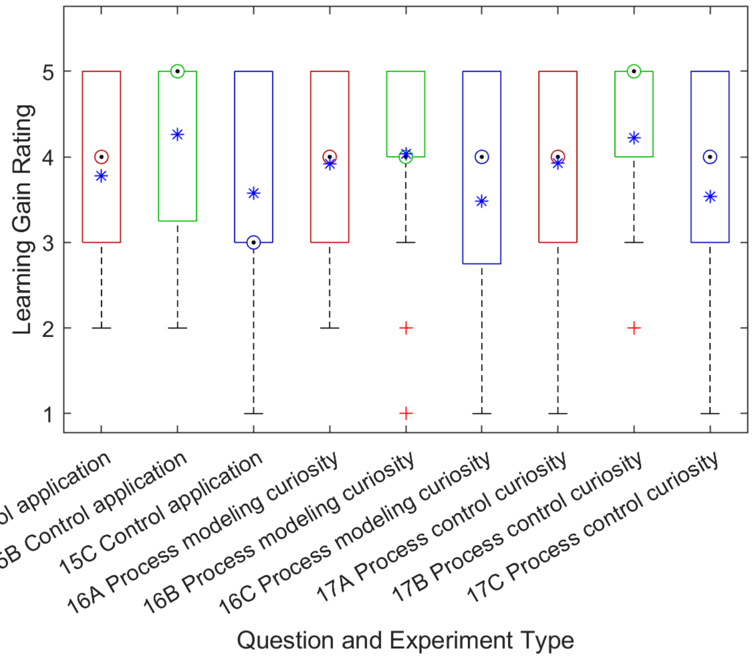


Figure C.5: Self-perceived learning gains in behaviors and attitudes about control relating to confidence in applying control and curiosity about aspects of control.

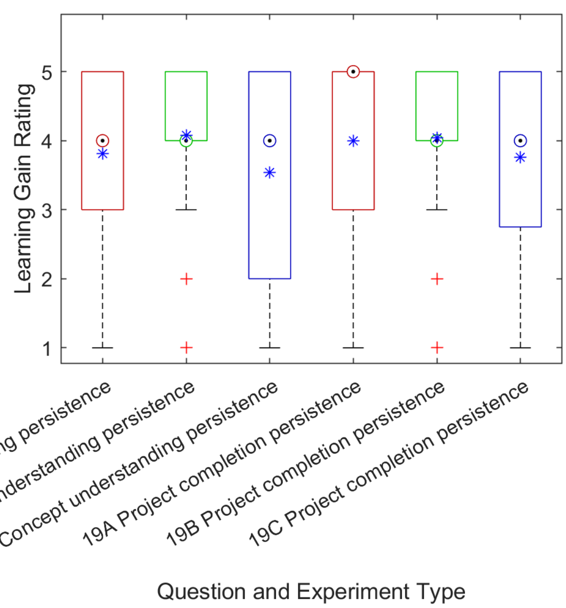


Figure C.6: Self-perceived learning gains in behaviors and attitudes about control relating to persistence in theoretical understanding and project completion.