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Lessons Learned From Microcontroller-Based Liquid Level Control

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Abstract

In chemical engineering education, connecting theoretical knowledge and practical application is crucial to helping students bridge the gap between engineering principles and how they are used, and preparing them to enter the workforce. Important in this process are the laboratory classes in the undergraduate curriculum. However, barriers of cost, equipment, and space availability exist, making implementation of lab experiences in a wide variety of typical industrial equipment challenging for undergraduate programs. This is especially true of the topic of process dynamics and control, typically taken by students in their final year. This course is a key class in the curriculum where students integrate the knowledge they have accumulated over their education with new topics of dynamic process operation and feedback control. Because these topics are generally challenging to students and significant to industry, laboratory experience is especially important. Unfortunately, the cost of industrial control systems, on top of the cost of laboratory-scale unit operations equipment, may be prohibitive for programs. In addition, instructors may not have the experience or time to set up these systems. In this paper, we present a bench-top liquid-level process identification and control project, designed to help transition theoretical understanding to hands-on application, giving students a chance to develop real-world problem-solving skills in engineering.

Using a low-cost Seeed Studio XIAO microcontroller, students interact with sensors, pumps, and pulse width modulation (PWM), reinforcing their understanding of feedback loops with process dynamics. There are several benefits to this type of experiment. For the student, the project provides the opportunity to learn about process instrumentation, utilize more complex control algorithms, and investigate process nonlinearities. Students also gain valuable experience with microcontrollers, PWM control, troubleshooting, and programming digital control algorithms. For the department, benefits include the low cost of the components and scalability to many other inexpensive and easily available sensors and actuators. In addition, the XIAO is natively programmed in CircuitPython, a microcontroller language based on Python, which many departments already utilize for scientific computing. Using a microcontroller programmed in language with which students are already familiar allows instructors to spend limited instructional time more efficiently, avoiding having to teach another programming language.

Introduction

Despite developments in more complex feedback control algorithms, Proportional-Integral-Derivative (PID) control forms the backbone of industrial process control, due to its simplicity and robustness, and is, therefore, a cornerstone topic in undergraduate engineering curricula. A recent survey by the Chemical Engineering Division of the American Association for Engineering Education (ASEE) indicated that nearly all institutions include PID controllers in their process control curriculum and survey respondents indicated that the need for more connections to the “real world” was a particular challenge [1]. There has long been a perceived gap between approaches to teaching PID control that often rely heavily on theoretical derivations and simulations, and the industrial practice of process control [2]. Integrating hands-on projects into the curriculum allows students to explore PID concepts through direct application, enhancing comprehension of theory [3] and student motivation in their own learning process [4].

Process dynamics and control introduces students to new topics of dynamics process operation and feedback control, topics which are crucial for industrial application. Students are expected to integrate this new knowledge with their accumulated education. Many students struggle to understand these topics and integrate them with their prior education, making hands-on laboratory experiences invaluable to reinforce their knowledge of these subjects. Programs often rely on unit operations labs to provide hands-on experience for students, yet only 56% of unit operations labs include process control experiments [5]. Of these, a higher fraction of the lab experiences are virtual, and a lower fraction is pilot scale, as compared to other topic areas such as fluids, heat transfer, and mass transfer. This is possibly due to the high cost of pilot-scale equipment and industrial control instrumentation and software.

The learning that comes from experiences with pilot scale equipment is important and includes the use of instrumentation, collection and analysis of real data, and experience with equipment and software like that found in industry [6]. However, physical labs can be time-consuming to set up and operate [3]. As an alternative, simulations are often utilized in process control education. Benefits of simulations include reduced cost without the need for physical equipment or consumables [7], and immediate feedback to students, helping them understand the consequences of their choices and how to adjust their approach [8]. Drawbacks to utilizing simulations include model simplifications that do not incorporate real-world complexities [8] and the elimination of the need for troubleshooting [6].

Smaller bench-scale control experiments, utilizing microcontrollers, have started to become more prevalent in teaching laboratories [5]. Their smaller scale and low-cost sensors and actuators can alleviate some of the problems experienced with pilot-scale equipment, while still providing students with experience on a real process. In addition, students gain experience programming their own feedback control algorithms. A menu of these small process control experiments using the Arduino microcontroller platform has been previously presented [9]. Arduino microcontrollers must be programmed in Arduino C, and if this is not the language used within the curriculum, it may be new to students. This new language can increase the cognitive load of experiment operation and reduce cognitive resources available for other learning [10] of concepts more germane to the study of process control.

To address the need for and the difficulties in implementing laboratory experiences, this paper introduces a bench-top liquid-level process identification and control project using a low-cost Seeed Studio XIAO microcontroller. The approach described provides an affordable, scalable, and practical solution that equips students with essential skills in process control. This project gives students the opportunity to have hands-on experience with sensors, pumps, and control algorithms while reinforcing their understanding of dynamic systems and feedback loops. Through the use of affordable, practical components and the leveraging of existing programming skills, this approach provides a practical solution to the need for student engagement and technical skill development.

Experimental Setup

This lab allows students to develop and analyze a level controller. The setup consists of a liquid-level vessel, a liquid source, a pump with tubing, a LIDAR sensor, and a microcontroller along with supporting electronic components. A diagram of how this setup is given in Figure 1. A more in-depth look at the controller parts and wiring will be given in the Practical Considerations and Implementation section.

In addition to the physical setup, students are provided with three sets of code. The first set of code is the library for communication between the microcontroller and sensor. This library will be added to the microcontroller’s storage, allowing the microcontroller to communicate with a sensor that does not simply rely on a single voltage reading (such as an I2C protocol).

The second set of code is a simple Python script that sets the pump power and outputs the liquid level reading. The code will control the pump power by modulating a PWM pin on the microcontroller. This code will be the controller code that is running in the microcontroller and provides students with a baseline code to work with. Students will add to this code to control the liquid level either through step changes in the pump power or by making it a PID controller.

The third set of code is a script that reads the output from the microcontroller and records the data for future analysis. This code will run on a computer that is connected to the microcontroller. Students will make minor adjustments to this code to ensure that the computer is reading from the port that is connected to the microcontroller and is reading data at an appropriate rate.

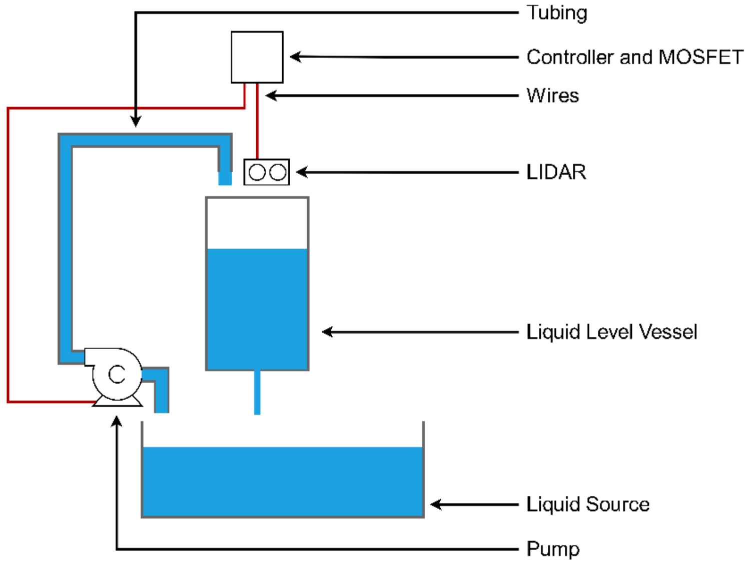

Figure 1. Liquid Level Lab Setup

The lab consists of two parts: examining the relationship between pump power and liquid level, followed by designing the controller and evaluating its performance. Basic source code for this project is available at: https://github.com/barkdullm99/Seeeduino-Liquid-Level.git (commit 9f23015).

Lab Part 1

In the first part of the lab, students will examine the relationship between the input and output of the system. Students can do this by having a list of pump powers to use and then cycling between these at a set interval. For example, students could have a list of 40, 20, and 50 they could then have the controller set the pump power to each value for 17 minutes before switching to the next value. The step changes and time at each step will need to be adjusted by the students so that they have an acceptable signal-to-noise ratio and see the liquid level reach a new steady state.

By changing the power of the pump, students can change the liquid level. Figure 2 shows part of a dataset that a student received from manipulating the pump power and recording the resulting liquid level. By varying the pump power at different initial pump powers and different increments of change, students can verify that the system is nonlinear. This can be further shown by estimating gain, time, and dead time constants for each step change in pump power and comparing them for various step changes.

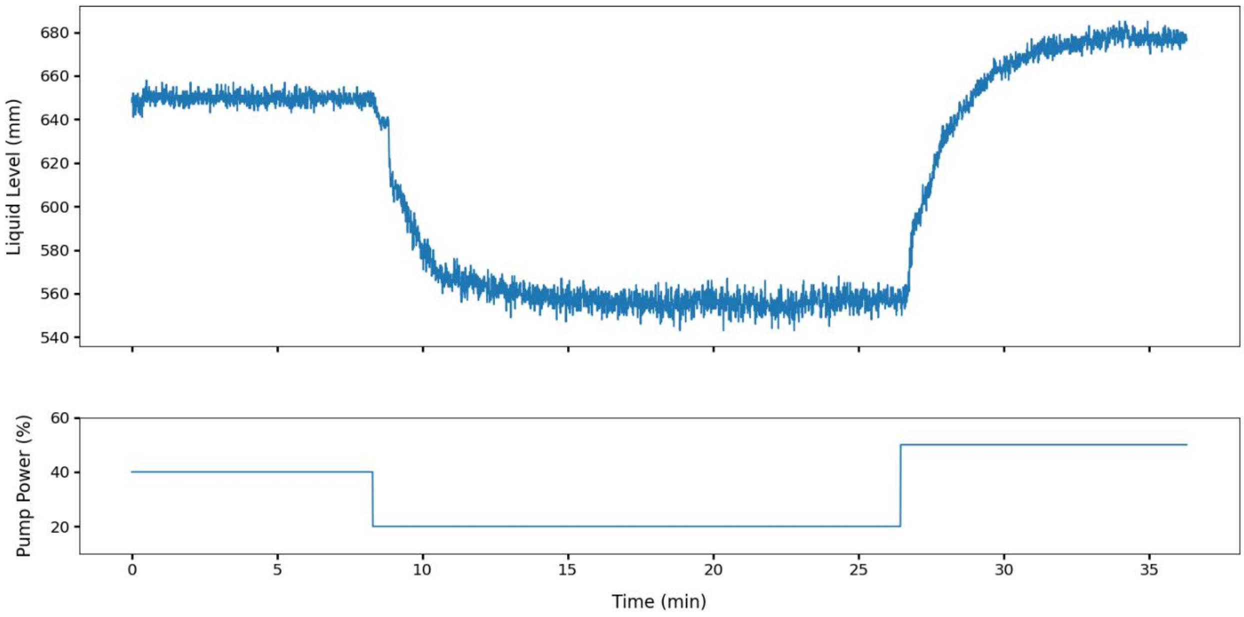

Figure 2. Lab Part 1 Student Data

Once students have collected their data, they use this data to suggest process parameters for tuning the controller. One method the students can use is to model the system as a first-order plus dead-time model. Since the system is nonlinear, this model will have inaccuracies. To account for this, in addition to a gain, time, and dead time constant, students would recommend a range of setpoint values and report a margin of error for the constants. Students can take alternative approaches for process parameter suggesting, but they must be able to justify their method. Whatever method students use, by the end of the lab they submit a report that includes the suggested process parameters and justification.

Lab Part 2

The second part of the lab can be completed by the same group of students or by another group of students. Should a new group of students complete this part of the lab, they will be given access to the previous group's report, with personal identifying information redacted or removed.

With the suggested process parameters from the previous part, students will tune a PID controller. Students may choose whatever tuning method they prefer to use based on the suggested process parameters.

Once initial tuning parameters are found, students will record the performance of the controller in response to a step change in the setpoint and to a disturbance. The performance will be analyzed and based on the controller's performance; students will then adjust the controller's tuning parameters. Students will then need to show that the new tuning parameters perform better than the initial tuning parameters. By the end of the lab, students should be able to generate several plots like Figure 3 that show the setpoint, actual liquid level, and the manipulated variable (pump power). Once completed, students submit a report that includes both sets of tuning parameters and the comparison of their performance.

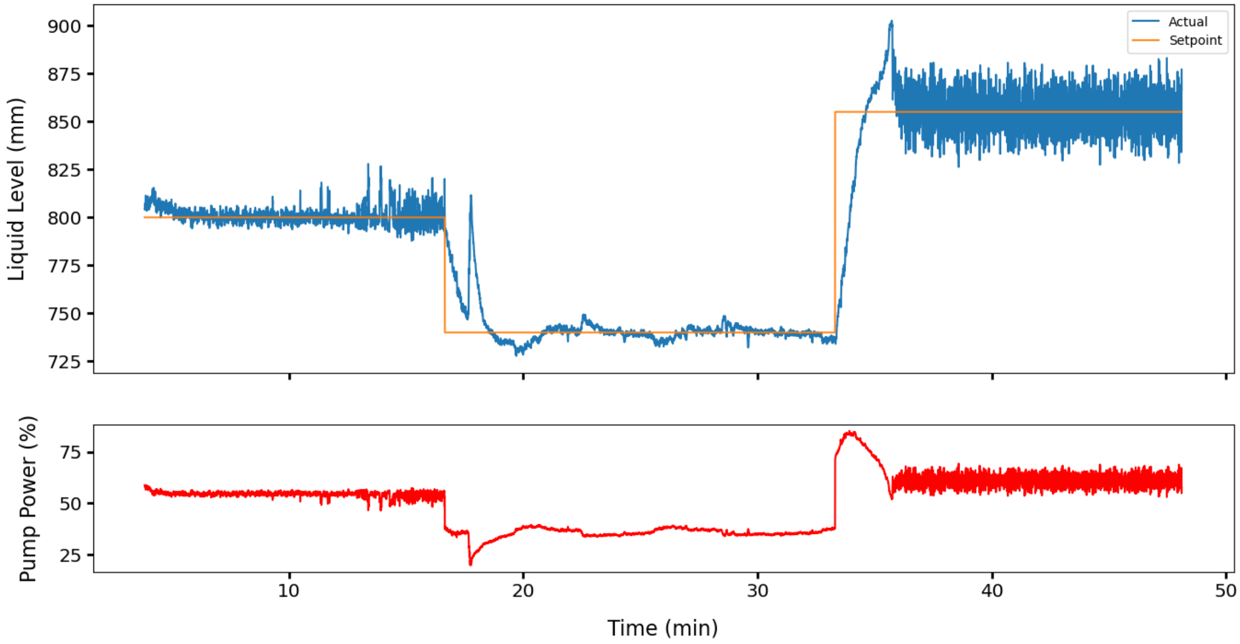

Figure 3. Lab Part 2 Student Data

Educational Benefits

Two cohorts of students in the Process Control Lab course were surveyed to ascertain their perceived learning gains from the various types of experiments conducted in the lab. Students who took the course during the Fall semester of 2022 performed microcontroller experiments using the Arduino platform, which is programmed using Arduino C. Students who took the course during the Fall of 2024 used the Seeed Studio XIAO microcontroller, programmed using CircuitPython. The survey questions used were from Firth et al. [9] and are repeated in Appendix A. Students were asked to assess their learning gains using a scale where 1 indicated no gains, 2 indicated minimal gains, 3 represented moderate gains, 4 indicated significant gains, and 5 represented excellent gains, with an option for NA (not applicable). Broadly, the survey questions were categorized into three areas: comprehension of control theory, practical application of control systems, and attitudes and behaviors related to the learning process within the context of process dynamics and control. There were 20 survey respondents in the 2022 cohort, and 27 respondents in the 2024 cohort.

The instructional design of the two years of lab was somewhat different. The 2022 cohort was given short and simple system identification and PID control implementation experiments on a small breadboard-contained process intended to introduce them to the microcontroller platform and the digital implementation of the PID algorithm. In addition, they also did a full-length lab project using a microcontroller for system identification or PID control implementation on a bench-top process. The 2024 cohort only did the small microcontroller experiments and performed the full-length experiments using the industrial-grade control software installed on the lab equipment. While the instructional design of the two years of the lab was somewhat different, with the microcontroller projects in 2024 being simpler and shorter in duration, there are some differences in the survey data that bear examination. The questions with a statistically significant difference, as measured by the two-sample t-test with $\alpha = 0.05$ were the following:

- Q3 Understanding of closed loop feedback control
- Q16 Curiosity about the topics of process modeling
- Q17 Curiosity about the topics of process control

Q3 showed a change in perceived gain in learning from 4 (good) in 2022 with the Arduino platform to 5 (great) in 2024 with the Seeed Studio XIAO. Q16 and Q17 each showed a change from 3 (moderate) to 4 (good). Other questions showed improvement in perceived learning gain but were not statistically significant. Box plots for all questions are shown in Appendix B.

The data indicates that perceived learning was at least as good, and in some critical areas higher with the microcontroller programmed in CircuitPython over that programmed in Arduino. This result would support the theory that utilizing a platform that employs a language with which the students are already familiar allows for cognitive resources to be devoted to learning topics aligned with the course objectives.

Anecdotally, students who used CircuitPython were more enthusiastic about the microcontroller projects and seemed to enjoy those experiments much more than the Arduino group did.

Practical Considerations and Implementation

The build for this lab can be split into two parts: the vessels (non-electrical components) and the controller (electrical components). The controller components are more specific and will take up most of the budget.

The non-electrical components consist of two vessels and tubing. One vessel will be used for measuring and controlling a liquid level. This vessel does not need to be clear but is recommended so students can see the actual liquid level. A 3-foot-long acrylic tube with a nominal diameter of 3 inches may be an appropriate vessel. This vessel will be almost completely sealed at the bottom except for a small opening on the bottom which will allow liquid to flow out of the vessel. The diameter of this hole will depend on the flow rate the pump can achieve and the desired range of operation for level height. Alternatively, a valve could be used and manually adjusted to optimize the flow out.

The vessel also requires a lid or stand that can be placed on top to position the LIDAR sensor. The sensor must be secure and point parallel to the height of the vessel. This could be an end cap that has holes cut out for the sensor and tubing. This vessel may also require a stand to hold the liquid-level vessel itself over the second vessel.

The second vessel is used as a storage for water. It is the source that the pump uses to fill the first vessel and is where the first vessel empties. The vessel should be large enough that at maximum pump power, there is enough water for the pump to not run dry yet when the pump is off, the vessel does not overflow.

The tubing's diameter should match the pump for a snug fit to prevent leakage. The tubing should also be long enough to deliver the water to the first vessel. In the setup used for this paper, the tubing went into the first vessel from the top and thus required a longer length of tubing. This allowed for a simpler vessel with reduced chances of leakage, but a vessel could be designed that would have a port towards the bottom to which the tubing could be attached. This would help reduce noise by preventing the tubing from getting in the way of the lidar sensor and reduce noise due to the splashing of water. These two approaches are shown in Figure 4.

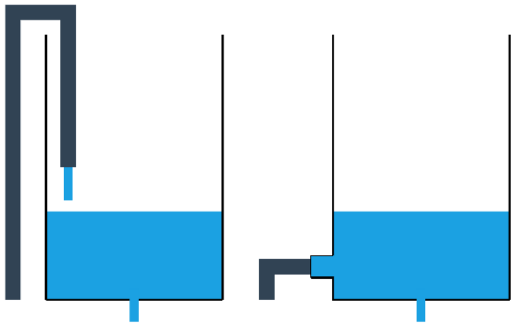

Figure 4. Liquid Level Vessel Design Used (left) Alternative Vessel Design (right)

Figure 5 shows how the controller is wired. This controller has four major components: the microcontroller, the LIDAR sensor, the pump, and a MOSFET module.

This lab used a Seeed Studio XIAO. Though limited in its pinout, the XIAO has the pins needed for this lab: SDA, SCL, 5V supply, ground, and a pin capable of PWM. The XIAO also natively works with CircuitPython. With many academic programs switching to using Python, using the XIAO will allow students to program in a language with which they are comfortable. This allows students and instructors to focus on the process control element of the lab rather than learning a new programming language.

In addition to being more practical, the XIAO is more affordable than its alternatives such as an Arduino or Raspberry Pi. The developers of the XIAO list an individual unit for $5.40, though cheaper listings can be found in bulk purchases or alternative distributors.

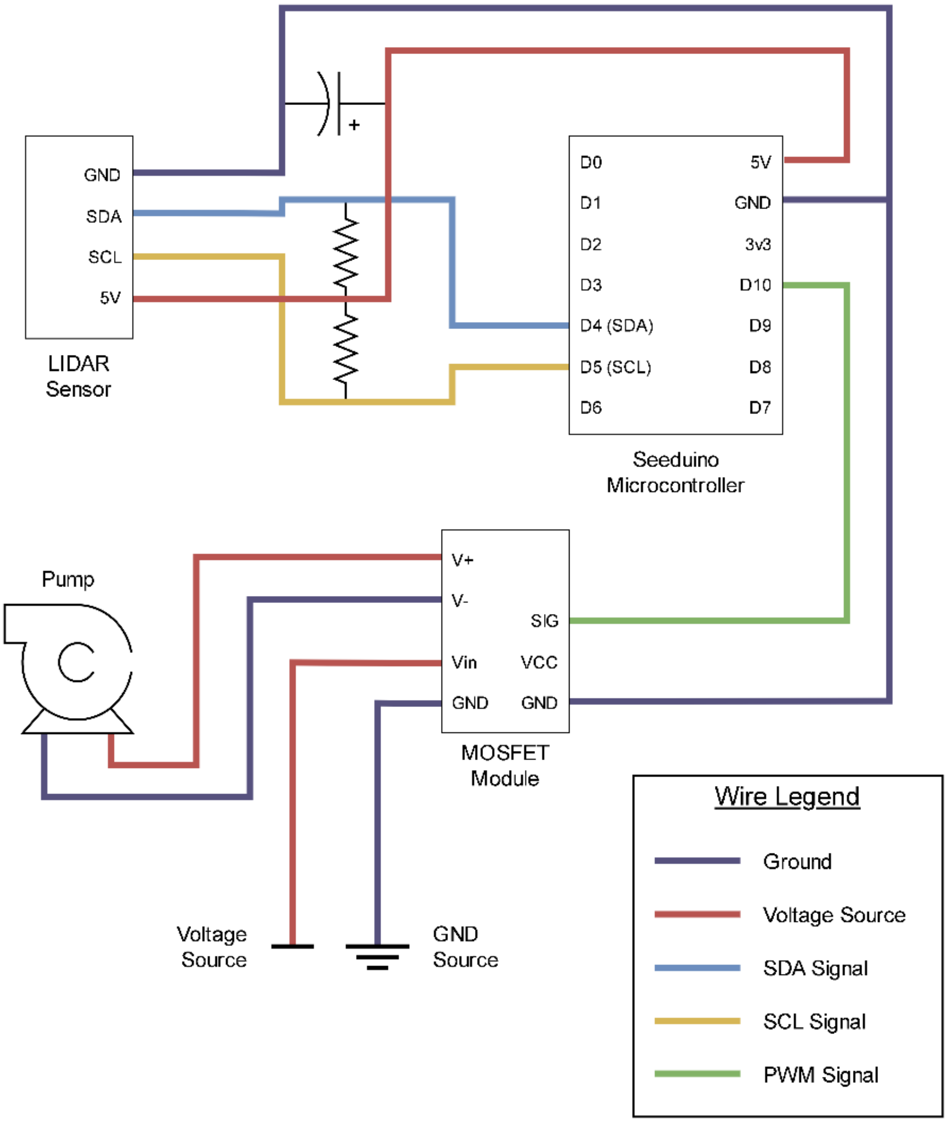

Figure 5. Controller Wiring

A LIDAR sensor was used to sense the height of the liquid in the liquid-level vessel. This component is potentially the costliest component. It is recommended that sufficient time is taken to research LIDAR options. For the purpose of this lab, the sensor does not need to be extremely accurate or new. LIDAR sensors for this lab can be acquired for about $5 each, though more expensive versions exist that may be more reliable and accurate.

The pump used for this lab was a DC 12V mini submersible pump. This pump only has two wires: a ground wire and a voltage supply wire. This simplicity allows for the pump power to be controlled using a PWM signal sent to a transistor that is connected to the pump. A submersible pump allows for fewer sections for tubing and does not require additional space to place the pump. These pumps can be found on Amazon for less than $15. The specs of the chosen pump should be considered when deciding on the height of the liquid-level vessel and the exit hole diameter.

A MOSFET driver module was used to allow the microcontroller to control the pump power through a PWM signal. Though this part could be replaced with just a transistor, the module is recommended as it reduces the chance of making a mistake in the wiring, which could lead to accidentally sending 12V to the microcontroller and computer, damaging both.

In addition to these parts, generic jumper cables, solderless breadboards, a DC barrel jack adapter, and a 12V barrel power supply are used.

One important design consideration is the length of jumper cables between components. The I2C communication protocol tends to degrade when used over longer wire lengths, so it is recommended to have the microcontroller close to the sensor to reduce the needed length of wiring. In designing this lab, it was found that longer lengths of wire would cause the controller to crash without throwing any errors.

To power the pump, a 12V power source is required. The method used in designing this lab was to connect a 12V parrel power supply to a wall plug and then to a DC barrel jack adapter. These adapters can take a barrel plug and allow for easy connection to a ground and positive wire which would connect to the MOSFET driver module.

The capacitor and resistors shown in the diagram may or may not be required. These components help to stabilize the signal, so adding them is a good place to start if a user is having issues with signal integrity and a crashing microcontroller, especially if longer wires are used between the sensor and microcontroller.

The resistors that connect the SDA and SCL lines to the supply voltage are referred to as pull-up resistors. They help ensure the SDA and SCL lines increase in voltage when there is not an active drain on them. The resistors used in the development of this project had a resistance of 4.7 kΩ. In addition to the resistors, a capacitor with a capacitance of 680 µF was used. These values can be a good starting place, but the user should refer to the manual of their LIDAR sensor to determine the appropriate values to use.

A breakdown of the estimated cost to make this lab is given in Table 1. The maximum cost required to make this lab is expected to be around $114 per setup. This cost can be reduced by reusing existing parts, buying in bulk, and seeking out alternative distributors.

Table 1. Estimate Cost Breakdown

Part	Cost	Distributor
Liquid Level Vessel	$26	Amazon, Hardware Store
End Caps	$2.80	Amazon, Hardware Store
Liquid Storage Vessel	$10	Amazon, Hardware Store, Walmart
Tubing	$6.00	Amazon, Hardware Store, Walmart
Seeed Studio Xia	$5.40	Seeed Technology Co. Ltd
LIDAR sensor	$5	Amazon, eBay
Pump	$12	Amazon
MOSFET driver module (IRF520)	$6.50	Amazon, Walmart
Jumper Cables and Breadboard	<$15	Amazon, Walmart, eBay
DC Barrel Jack Adapter	$3.00	Amazon, eBay
12V power supply	$15	Amazon, eBay, Walmart
2 Resistors	$6.00	Amazon, eBay
Capacitor	$1.00	Amazon, eBay
Total	$140-$160	

Conclusion

This paper presents a practical and cost-effective approach to enhancing chemical engineering education in process dynamics and control. Utilizing this Seeed Studio XIAO microcontroller-based bench-top liquid-level process identification and control project, students gain invaluable hands-on experience with dynamics systems and feedback control. This project addresses the financial and logistical barriers faced by many undergraduate programs in developing laboratory classes. This project utilizes accessible and easy-to-use equipment that allows students to focus on the goals of the project.

Through the integration of familiar programming languages, like Python, this approach ensures efficient use of instructional time, allowing for a focus on core concepts of process control. This gives students a more educational and enjoyable experience with the lab. The results from this scalable and adaptable solution demonstrate the potential for low-cost technologies to bridge the gap between theoretical knowledge and practical application, better preparing students for real-world engineering challenges.

Future work could expand this approach to incorporate additional control strategies, including process design and more complex systems. Additionally, this design could be adapted to provide hands-on experience as an introduction to chemical engineering for learners at varying levels of education.

Acknowledgment

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Appendix A – Learning Gains Survey

Table A.1: Self-Assessment Survey Questions for Learning Gains in a Process Control Lab Course [9]

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 and 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
Q15 Confidence to engage in real-world control application
Q16 Curiosity about the topics of process modeling
Q17 Curiosity about the topics of process control
Q18 Persistence in pursuit of concept understanding
Q19 Persistence in pursuit of project completion

Self-Assessed Learning Scale

no gains	a little gain	moderate gain	good gain	great gain	not applicable
1	2	3	4	5	NA

Appendix B – Survey response data

The plots in this appendix show response distributions for the surveys taken utilizing the questions in Appendix A. Questions are listed by question number and a short description. An “A” is used to indicate data taken from the cohort who used the Arduino platform for their microcontroller experiments in the lab, and an “S” is used to indicate data taken from the cohort using the Seeed Studio XIAO microcontroller.

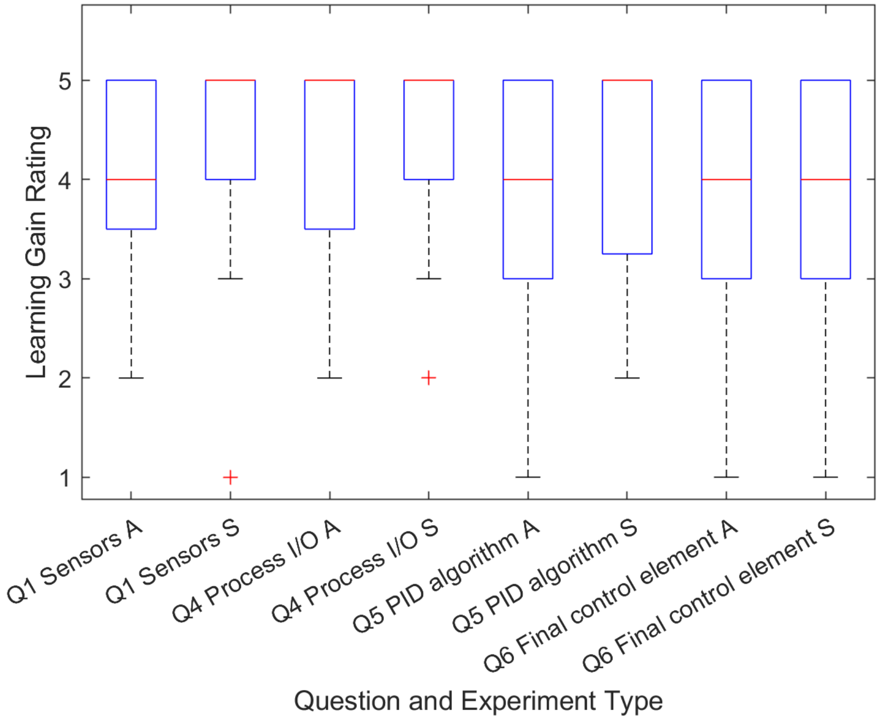

Figure B.1: Self-perceived learning gains in understanding of theory relating to control loop elements.

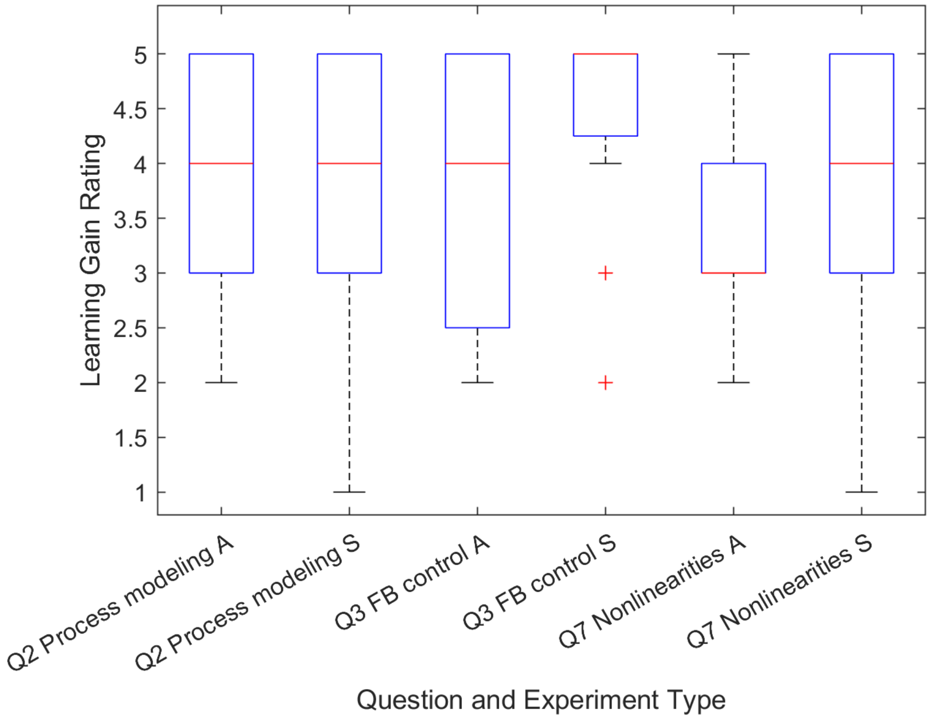

Figure B.2: Self-perceived learning gains in understanding of theory relating to control loop dynamics.

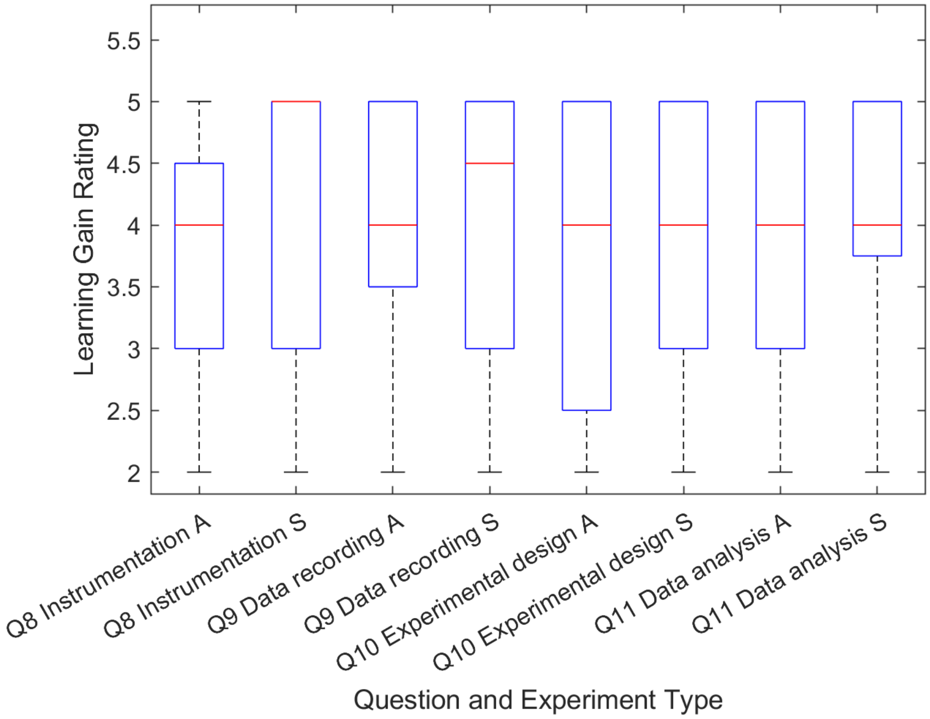

Figure B.3: Self-perceived learning gains in practical aspects of control relating to control loop instrumentation and experimentation.

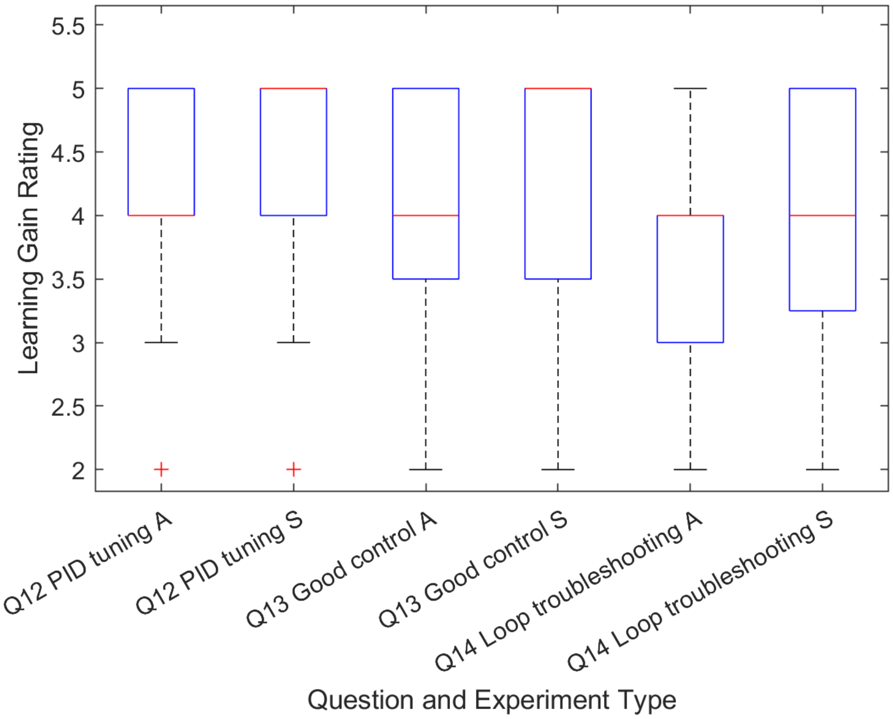

Figure B.4: Self-perceived learning gains in practical aspects of control relating to controller performance.

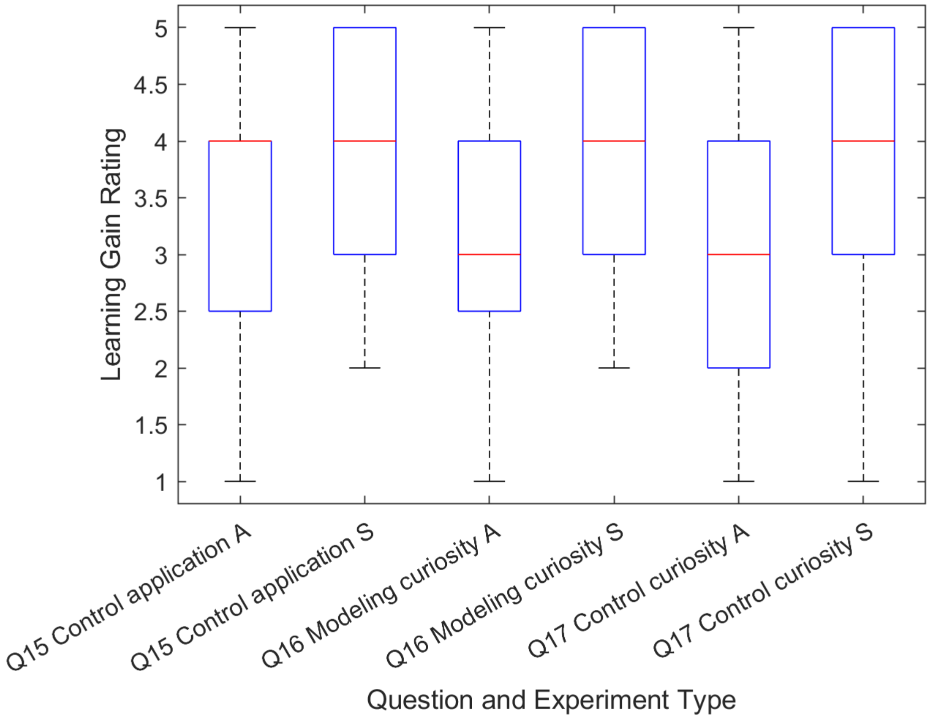

Figure B.5: Self-perceived learning gains in behaviors and attitudes about control relating to confidence in applying control and curiosity about aspects of control.

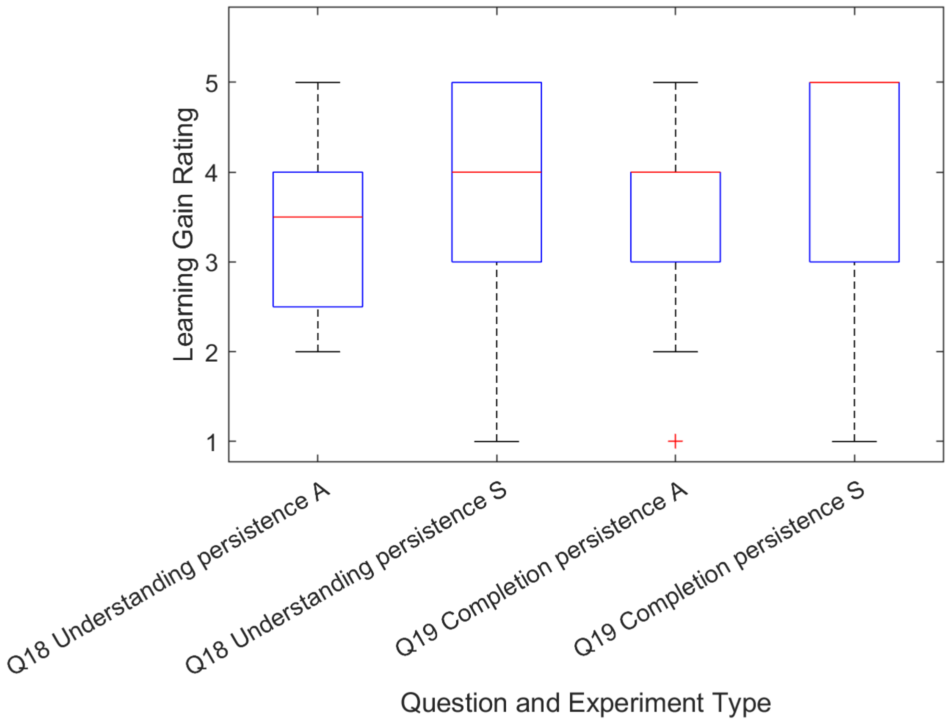

Figure B.6: Self-perceived learning gains in behaviors and attitudes about control relating to persistence in theoretical understanding and project completion.