2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #53290

Process Control's impact on Industry 4.0 Manufacturing Technical Workforce Preparation

Dr. Marilyn Barger, FLATE (Florida Advanced Technological Education Center of Excellence)

Dr. Marilyn Barger is the Senior Education Advisor for FLATE part of the FloridaMakes Network, a Manufacturing Extension Partnership Center. She was the P.I. and Executive Director of FLATE, an ATE Center focused on manufacturing technology education in Florida for over 18 years. Today FLATE is part of the FloridaMakes Network (www.floridamakes.com), the NIST Manufacturing Extension Partnership Center in Florida which is continuing its NSF mission supporting manufacturing technician education. Dr. Barger serves on several national and regional workforce education boards and has developed award-winning curricula for STEM programs at all educational levels. She taught Environmental Engineering at Hofstra and FAMU-FSU College of Engineering, authored many engineering education papers, is a registered Professional Engineer in Florida, and a Fellow of both the American Society of Engineering Education (ASEE) and the American Institute of Medical and Biochemical Engineers (AIMBE).

Dr. Richard Gilbert, University of South Florida

Richard Gilbert is a Professor of Chemical and Biomedical Engineering at the University of South Florida's College of Engineering . Richard is the Co-PI for the grant that supports the NSF designated Center of Excellence for Advanced Technological Educat

Andres M Cardenas-Valencia, Admiral Farragut Academy

Industry 4.0 Manufacturing Operations Impact on Process Control Technical Workforce Preparation

Abstract: A successful manufacturing operation requires focused perspectives from all personnel involved in the enterprise. Effortless interaction among technical manufacturing floor specialists, including comfortable communication with factory management, characterizes these perspectives. Management's concern that "time means money" (lag) and continued practice of Industry 3.0 (I3.0) based skills; equipment troubleshooting, preventive maintenance, repair, and replacement, are the essential characteristics of managers, technicians, and engineers responsible for accomplishments in today's Industry 4.0 manufacturing environments. However, additional challenges in the Industry 4.0 work environment include the shift in process control strategy for product production and the near-universal application of the Proportional, Integral, Differential (PID) control model for equipment operations. The preparation of new technical professionals for the I4.0 factory workforce requires augmenting skills-teaching approaches to include the expanded process control reality in their future workspace. In addition to content adjustments with I4.0 emphasis, additional student hands-on experiences are needed. A student hands-on learning station has also been developed, with its details and applications discussed in this paper. Additionally, recommendations on the use of simulated results that illustrate the dynamics of the controlled variable in a control loop as a function of the PID model constants are included. The simulation option is essentially free of user costs and a supportive tool for remote teaching.

Keywords: Lag, I3.0. I4.0, Process Control, Setpoint, Process Tuning, Disturbance, Gain, Bias, Offset, Error

Introduction. The preparation of new technical personnel to reduce production lag, the interruptions in normal manufacturing operations, is an expected responsibility of faculty in the ASEE's 2-year Division as well as its member 4-year engineering colleges. To adjust to this expectation by addressing I4.0 demands, faculty preparing a future manufacturing technician (MT) may have to expand their process control knowledge base as well as develop methods to present the impact of mathematics operators that drive the Proportional, Integral, Differential (PID) model without adding burden to the existing 2-year degree course loads [1], [2]. Engineering college faculty may need to increase their familiarity with the skills required of an MT and expand their appreciation of the additional process input conditions and output expectations in an I4.0 manufacturing facility [3], [4].

Manufacturing, as categorized during the Industrial Revolution, reached a well-established I3.0 phase in the 20th century and is now developing and/or expanding the 21st century requirements [5]. Today, the in-plant equipment needed to produce the product, as well as the manufactured product, is built to I3.0 standards that assure the equipment's construction materials meet high standards and that the equipment and the product produced meet precisely stated tolerances. As a result, 21st-century I4.0 guidance includes continued I3.0 best practices with additional incentives to meet modern factory production demands.

Figure 1 presents subsets of sensors, actuators, and final control elements used in I4.0 manufacturing scenarios. There are many strategies and options for these well-crafted Industry 3.0-standard devices for input signal detection, output signal preparation, and control signal delivery to final control elements. For simplicity of presentation, the figure illustrates four sensors, three actuators, and three final control elements [6]. In most manufacturing environments, there are many choices available to design engineers that depend on cost, size, and other production-specific factors. Floor technical personnel must know how to perform timely, appropriately target troubleshooting, maintenance, repair, and replacement duties for processes that employ any or all those device options.

Fig. 1. Manufacturing Supportive Sensors, Actuators, and Final Control Element Examples

It is well known that the sensor element detects, monitors, and/or measures the controlled variable, and constitutes the "eyes and ears" of the control loop. The actuator moves, propels, starts or stops the final control elements that influence the process, so that a manipulated variable attempts to keep the controlled variable within specifications. The controller makes decisions on how to affect the actuator. Figure 2 (top) visualizes the high-level relationship between the sensor, controller, actuator, and the control process. Figure 2 (bottom) shows a block diagram of a feedback control loop. Block diagrams facilitate the understanding of the control scheme's expected sequence of events. A block diagram indicates controller options when the measured variable is not equal to its setpoint expected value. The arrangement and

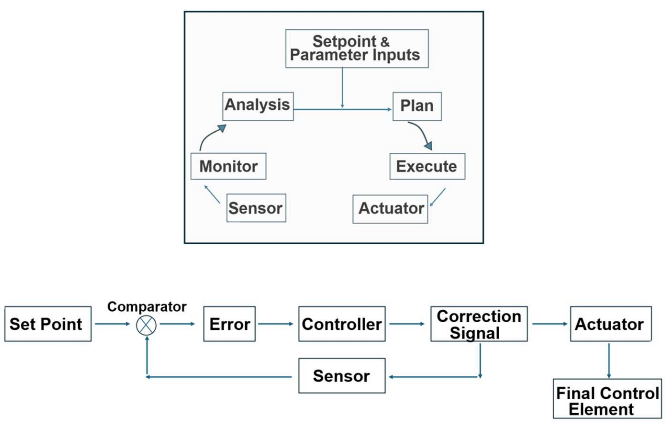


Fig. 2. Universal general representation of process control and box style diagram showing specific process control sequence concepts.

vocabular in box diagrams is influenced to some extent by the engineer that designed the control scheme, however the MT is expected to understand that vocabular and the concept flow shown in a box diagram.

A simplified introductory control situation that reflects the information presented in Figure 2 could be the bioreactor fluid flow temperature control scenario suggested in Figure 3. This scenario involves a vernier flow meter including a valve actuator and a fluid flow valve. For flow scenarios, the MT, after the classic "power and ground" measurement, will use information obtained from the Human Machine Interface (HMI) as the investigative guidelines. Working technicians will, if needed, typically acquire that skill as an "on-the-job" training experience. Students in 2-year technical degree programs acquire the skills to use the subsystem HMI as a troubleshooting tool during hand-on lab activities [7].

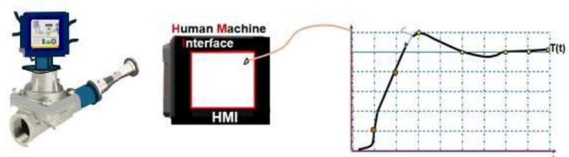


Fig. 3. Flowing Fluid Temperature Controller with HMI generated temperature verses time display.

One possible student learning experience is to examine HMI data to determine whether the bioreactor process reaches the expected setpoint temperature. The temperature sensor, not shown in the figure, as it is likely embedded the fluid conduits, delivers its data to the HMI. The HMI's ability to track temperature response also emphasizes the expectation that the MT will know how to interact with the HMI to facilitate the monitoring and troubleshooting of the bioreactor process. For example, if the expected setpoint is not observed, the MT will direct the HMI to selectively monitor signals from sensors, actuators, and final control elements to initiate troubleshooting procedures. The HMI can also be directed to monitor the process response to a PID controller. Most MT activities related to the PID output are attenuated; manufacturing floor engineers frequently use the HMI mode. Figure 4 illustrates three possible process-scenario reports, which are explored in the next section.

Discussion: A PID controller uses a calculus model, an integral-differential equation-based mathematical approach to generating signals directed to final control elements for process control. The B.S. degree in

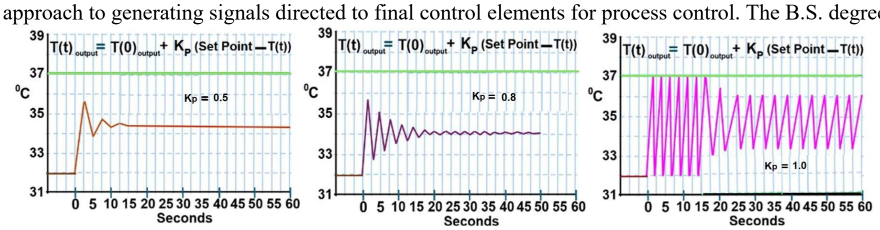


Fig. 4. Illustrations of Temperature Response to a Proportionally Controlled Bioreactor Scenario

engineering requires students to be familiar with all aspects of this model. The MT 2-year degree level student PID model interactions should be limited to hands-on learning experiences. They should be familiar with the "event-response" level needed to troubleshoot a process that is not running as expected [8]. Process control design engineers are responsible for the full range of PID control mathematics, including differential equations, linear algebra, and mathematical principles and manipulations. The manufacturing floor engineer determines the model-optimal coefficient and coefficient scalar values for a specific manufacturing situation and establishes HMI monitoring protocols for manufacturing process steps.

Referring to the temperature control situation in Figure 3, the succinct PID model statement is;

$$T(t)_{output} = T(0)_{output} + \mathbf{K_p}\,(\text{Set Point} - T(t)) + \mathbf{K_i} \int (\text{Set Point} - T(t))\,\mathbf{dt} + \mathbf{K_d}\,\frac{\mathbf{d}}{\mathbf{dt}}(\text{Set Point} - T(t))$$

and this model generates temperature corrective action as a function of time. It is initially explored as student output results as presented in Figure 4. The model includes, a constant value component, the first term, $T(0)_{output}$. This term is the model scalar coefficient that represents temperature when the time value is 0 seconds. The remaining three model elements have a zero value at t = 0 sec. and do not contribute to the $T(t)_{output}$ value. Although the value of each of these three model terms vary as a function of time, their model parameters respectively; the proportional, K_p, coefficient, the integral, K_i, scalar coefficient, and the differential scalar coefficient, K_d, are constant for a specific scenario. The critical role for these coefficients is to adjust the influence of the setpoint minus T(t) calculation i.e. adjust the offset or error.

Figure 4 presents three independent HMI data plots when the K_i and K_d values are equal to zero and the temperature value $T(0)_{output}$ in all three cases is 32 °C. The model operation distinction among the three plots is due to the difference in K_p values. These values increase from left to right in the presented graphics. The students assigned two of the model's scalar coefficients to zero; $\mathbf{K_i}$ = 0, $\mathbf{K_d}$ = 0, and set $\mathbf{K_p}$ values before operating the hands-on PID controller described below in the Results. All students who did this exercise quickly recognized the impact the $\mathbf{K_p}$ values had on the temperature of the flowing fluid. At this point in the learning process, the coefficient value selection activity was conducted through their individual trial-and-error procedure. "Tuning" protocols to stabilize the output temperature values are not introduced at this point [9]. However, students in 4-year programs do address the integral and differential terms in the model. The MT student's hands-on learning event that explores the integral term is presented in Figure 5.

The visualizations in Figure 5 indicate the impact of including the integration term. In both cases, the $\mathbf{K_p}$ coefficient value is 0.8 and the $\mathbf{K_d}$ value is 0 seconds and value $T(0)_{output}$ is 32 °C. Thus, the PID model's integration term value is inversely proportional the accumulated error. The steady state offset, 37 ºC minus 34 ºC, shown in the center graphic of Figure 4 is significantly greater than the 1.4 ºC offset (error) shown in the left side graphic. The offset when $\mathbf{K_i}$ was set to 0.2 seconds^{-1} (inverse seconds) allowed the PID controller to reduce the offset, as shown in the right side of figure 5, to 0.6 ºC. If the MT student holds $\mathbf{K_p}$ and $\mathbf{K_i}$ constant and then varies the $\mathbf{K_d}$ value, the differential model element will be observed as the instantaneous rate of error, ºC verses time, that, in turn, reduces the swing of the temperature of bioreactor example.

The MT students generating the HMI graphs in figures 4 and 5 will quickly visually appreciate the impact of the values assigned to $\mathbf{K_p}$, $\mathbf{K_i}$, and $\mathbf{K_d}$ on the performance of the PID model as it generates values that adjust the flowing fluid's temperature. It is easy for the 2-year program students to understand what and perhaps why the model altered the temperature but by showing the actual effects on the dynamics of temperature, it can now mathematically conceptualize how it happened. By contrast, the B.S. engineering degree program student must fully understand, the what, when, why, and how of the model's temperature adjustment task, as well as rigorous systematic tunning parameters procedures.

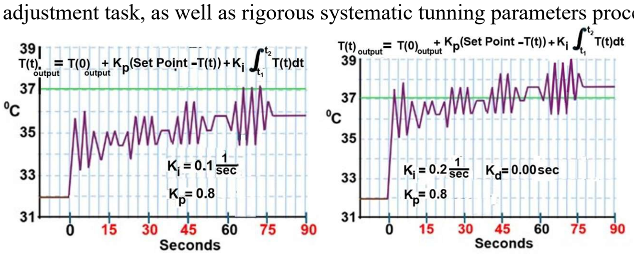


Fig. 5. HMI Display of $\mathbf{K_i}$ Values Impact for a PI Controlled Process Controller.

Results*:* The two photographs in Figure 6 provide a visual prelude for the discussion of the Hands-on Learning Tool the students used to simulate the control of an antenna via a PID driven process controller descriptively illustrated in Figure 8. The photo on the left shows the components of a hands-on learning tool that introduces, expands, and reinforces the PID concepts presented above. Details of the assembled components that include the items listed are available [10]. The photo on the right is the system as assembled by a Manufacturing Technician A.S. degree student. Faculty instruction was limited to reinforcement of safety expectation however; Figure 7 was available to each student and provided a circuit overview with key component identification. Although the B.S. degree student would be expected to complete this assembly from the input/output assignments of the Arduino being used, the two-year degree student will need the extra assistance provide in Figure 7. If class time usage is an issue, it is suggested that the circuit assemble activity be a separate hands-on lesson that will also reduce the attenuation of the PID learning experience. In either learning approach, the breadboard circuit that is given to the student preassembled has a 2nd order RC filter to smooth the signal interactions with the Arduino microcontroller.

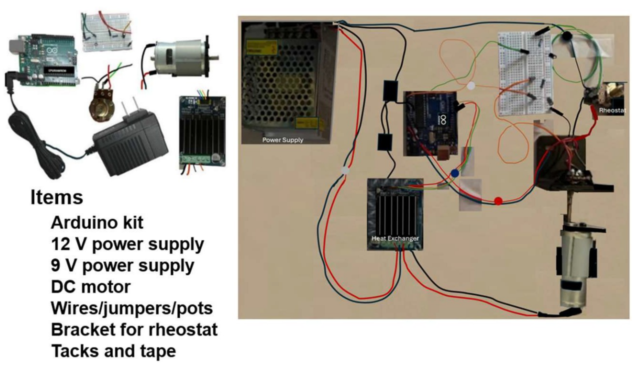


Fig. 6. Hands-on Experience System to Explore Operation of a PID-based Control.

Although the fluid temperature control discussion connected to Figure 3 was presented to students first, their hands-on experience is based on the antenna situation illustrated in Figure 8. The antenna azimuthal angle adjustment due to a wind generated rotation disturbance scenario was selected as the student's first hands-on experience because it does not require or expect any student pre-technical expertise. Details are

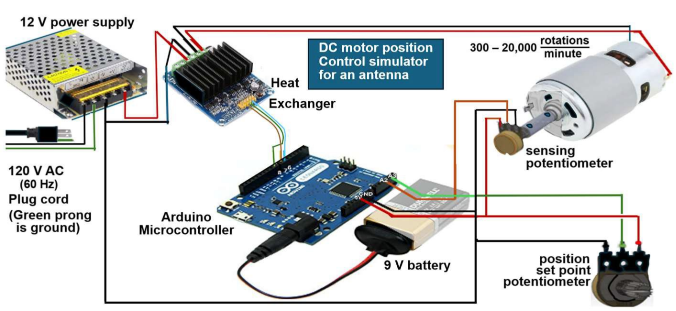


Fig. 7. Hands-on Experience System Circuit illustration to explore PID antenna disturbance simulation.

available [11]. Figure 8's drawing includes notations for the roles of the antenna components. Student appreciation of this bidirectional data transmission as a general knowledge principle can also be reinforced using the analogy of simple motor control. Such discussions will reduce possible student concerns that their current lack of knowledge will hinder their ability to develop a PID controller.

The significance of this project lies in the student's ability to execute PID-correctable control signal scenarios. In this specific case, the student must first be the wind disturbance signal and then the position sensor signal. These two requirements for demonstrating a PID controller's actions are easily met by inserting rheostats into the hands-on controller. Figure 9 shows these rheostats (also known as potentiometers or variable resistors) with abbreviated signal direction notations.

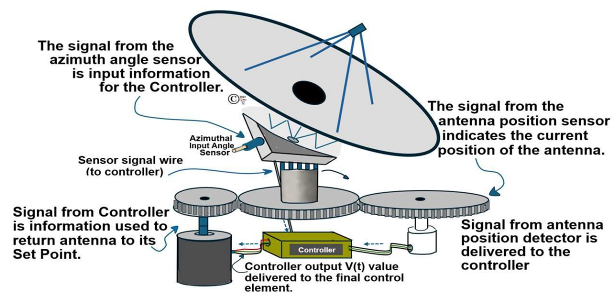


Fig. 8. Satellite Signal Reception Antenna Illustration with Function Details.

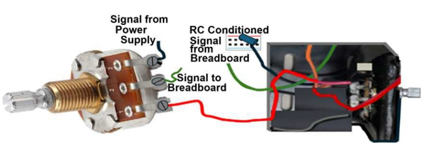
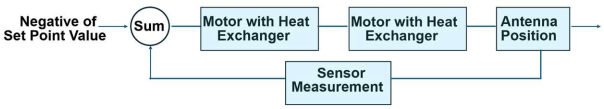


Fig. 9. Input and Output for the Simulation of Disturbance Input and Position Sensor Response

After the students have completed the "hardware" assembly, the PID simulation session can begin. The student turns the rheostat on the left in Figure 9 to simulate a gust of wind that is forcing the antenna to rotate counterclockwise. The rheostat on the right is adjusted by a different student to simulate the antenna's PID controlled position sensor's response to this latest disturbance. Both students should have a paper copy of a block diagram of the control scenario. A paper copy is recommended to avoid possible phone distractions that would be real disturbances in this learning experience.

Figure 10 includes the block style diagram used for the simulation exercise conducted at a recent NSF Advanced Technological Engineering sponsored conference for 2-year technical program faculty. The diagram shows the flow of information through the two rheostats shown on the right side of the circuit illustration in Figure 7. The arrow on the right side of this block diagram indicates the disturbance adjustment signal direction. The actual simulation circuit with its laptop computer display was easily assembled on the floor to adjust to the logistics of the conference workshop room assignment.

Engineering technology students must appreciate the importance of tuning-up a control loop. The hand-on controller activity using the PID control simulation tool provides a practical exposure student in-class experiential learning experience. A technician in a manufacturing environment is not responsible for controller design, but tunning skills are needed to appreciate the impact the PID model coefficients, $\mathbf{K_p}$, $\mathbf{K_i}$, and $\mathbf{K_d}$, have on the performance of process equipment they must maintain. A student HMI



Commented [AC1]: The block diagram above has the wrong labels. There is no heat exchanger that is worth mentioning in the labels. I believe the correct labels are in the figure below...

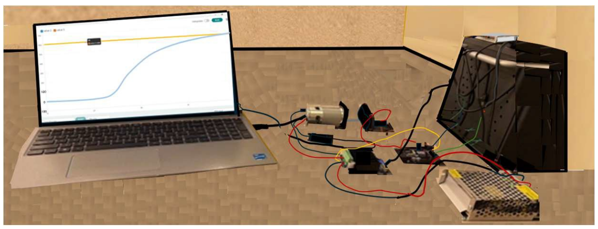


Fig. 10. H a n d s O n Setup including a Laptop to Monitor Simulation Activities.

monitored multimeter application is useful but at an addition cost ($100 amazon-acquired 2025 costs) per student station. A fully simulated result using computers and internet connectivity will make hands-on driven learning of control, automation, and tuning concepts a safe learning event when remote learning scenarios are required.

One of this manuscript's authors deployed and implemented two prototypes of the learning stations (like those in figures 6 and 7) for use in a classroom with about a dozen of students. The students were enrolled in an "Automation and Sensors" class (ETS1535C, according to SPC numbering system). The practical knowledge involving controllers, closed loop diagrams and PID components had already been covered.

Working in teams, the students were asked to turn the computer on, connect the Arduino microcontroller to the computers, and set the plotting serial interface. The system was tuned, e.g. PID time constants were set to provide adequate corrections in the motor position. The students were asked to adjust the controlling potentiometer (wind impact) and observe the respond of the system. The motor gyrates to the desired position, while the computer displays plots of the real monitored position and the set-point as a function of time. The position as displayed as a fraction a 5-volt signal (as demonstrated in Figure 10). Students were asked to change the set point (Arduino control program code change) and observe the system response. After the motor reaches this new set point location, the students were asked to introduce the "disturbance" by manually moving the motor position. Once, again the system makes the correction and adjusts the motor position to that of the setpoint. The students were asked to measure the voltage of the rheostat and verify that value matches the equivalency of the voltage values shown in the computer screen. Students were also asked to open the sketch (Arduino program) and identify the sections of the software that were related to; (1) the PID time constants, (2) the PID summation (as in equation for T output above), and (3) the comparison of the set point with the actual position voltages.

At the end of the activity, the students were asked to provide their impressions of the exercise. They were guided by the prompt "how learning about PID controllers would have been different if they didn't have the experience of using the prototypes described herein"? The comments of the students to this prompt were centered on how hands on an essential tool for effective learning is and transforming the abstract concepts into tangible things. They also commented on how they understand that the set point and the position are seen by the controller as voltage levels. Additional comments included the analog conversion to digital conversion performed by the Arduino in these voltage values as evidenced by the discretization of voltages. One student asked if he could build one of the prototypes (figure 6 and 7) instead of the Temperature PID controller which constitutes their final project. When asked the reason for that preference, the student said it is better to see the "movement" in the controller in this learning station rather than observing a temperature display changing as water is heated to a set point with an ohmic resistor.

These students' reflections demonstrate that moving the students from passive learners to active ones had benefits, as their knowledge became deeper and they noticed subtle details on PID controlling schemes, while definitely boosting engagement. Students demonstrated enthusiasm as the learning stations were working. It is the hope that the activity will also increase student retention as well.

Discussion on a simulated PID control loop: There are countless examples of algorithms for simulations online and in the literature which are readily accessible to students [12]. Microsoft, excel, and programmable logic controller applications are available [13,14, 15]. The simulation visualized in Figure 10 that utilizes, in this case, Arduino or other microcontroller integrated circuits, Microbits for example, can be implemented online [16-20].

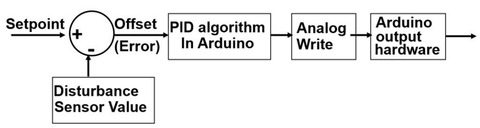


Fig. 11. Block diagram for Arduino based PID Control Loop Simulator.

A block diagram for a simulation of a PID control loop using an Arduino with signal filter components is shown in Figure 11. This controls approach was also originally implemented with an Arduino nano using a TinkerCad and code by Autodesk [21-24]. TinkerCard simulations also allow the use of digital multimeters and avoid faculty microcontroller programming mistakes and "simulated wire" connectivity issues [25]. Arduino platforms are easy to program and are open source [26].

Figure 12 presents a passive resistor capacitor input/output signal conditioning circuit for Arduino based online simulation scenarios [21]. In the original scenario, a variable zero volt through five-volt analog input signal was filtered. In that application 2 capacitors and 2 resistors are arraigned as a 2nd order passive filter. The image on the left side of Figure 12 shows, symbolically, the resistor capacitor arrangement for this filter. The image on the right shows the actual breadboard circuit used to implement this filter and its connection to the analog A0 input of the Arduino microcontroller for TinkerCad simulations. This approach still uses the rheostat, which is connected to the breadboard wire shown on the right side of the breadboard, to simulate the input sensor signal but removes the rest of the hardware shown in Figure 6.

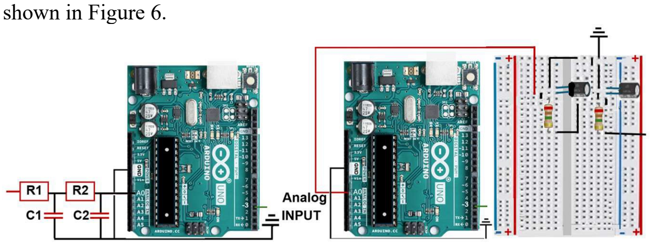


Fig. 12. RC Filter for I/O Signals for Arduino PID Driven Simulation.

The simulation can also be constructed so that there is no breadboard circuit or any other hardware. Figure 13 displays this total simulation results. The values for $\mathbf{K_p}$, $\mathbf{K_i}$, and $\mathbf{K_d}$ are simulator inputs typed in by the student. The simulation produced plots similar to those presented in Figure 5. The values for $\mathbf{K_p}$, $\mathbf{K_i}$, and $\mathbf{K_d}$ in Figure 13 were simulator inputs typed in by the student. Thus, a bioreactor scenario that could never be a hands-on experience in a 2-year MT preparation program of study can be explored at no expense to the program.

$$T(t)_{output} = T(0)_{output} + \mathbf{K_p}\,(\text{Set Point} - T(t)) + \mathbf{K_i}\int(\text{Set Point} - T(t))\,\mathbf{dt} + \mathbf{K_d}\,\frac{d}{dt}(\text{Set Point} - T(t))$$

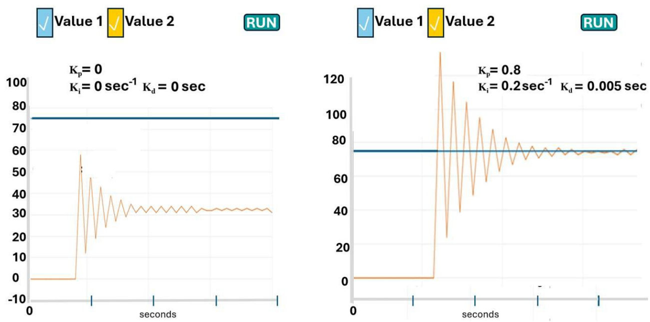


Fig. 13. Tinkercad Simulation; Scenario with Different PID Coefficient Values

Conclusions*:* The preparation of new technical professionals for the I4.0 factory workforce requires augmenting the skills-teaching approaches to incorporate the expanded process control reality in the manufacturing workspace. The student hands-on experiences needed can be provided with a hands-on PID controller or alternatively, and to a lesser degree, using TinkerCad simple algorithms. The hands-on student-focused controller shown in Figure 7 is being used in Engineering Technology A.S. programs in Florida. The controller, Arduino-driven with supportive parts, is inexpensive. State funding is being secured, via the "Chips" program grant being implemented at St. Petersburg State College, to assist the 20 state college manufacturing programs in acquiring this hands-on PID teaching tool.

Hands-on learning experiences to facilitate students' acquisition of the necessary troubleshooting, maintenance, and replacement skills using this PID simulator are in development and/or testing. All these exercises include best safety practices as well as the expected "check power and ground" activities. These lessons are not math class example situations. They are blended into "safety-first" hands-on activities to help refocus students' attention on the Industry 4.0 learning message at hand. These lessons are repetitively taught until student tedium assures student understanding. These lessons must also be delivered with intense detail and include conscious effort to avoid teaching "Cut to the Chase" steps.

Avoiding the "Cut to the Chase" practice that students always want to use is extremely important. PID-controlled scenarios beyond the simple proportional control mode do not have "Cut to the Chase" steps. Faculty familiar with PID can combine model concepts, but this skill should never be used in the classroom. This constraint acknowledges that although a successful teaching event is enjoyable, the necessary repetition to ensure student mastery of the skills being taught is the work part of that teaching event. Thus, repartition is a necessity and cannot be avoided.

Focused humor that repeats and strengthens the learning process is a useful repetitive tool. As an example, related to the repetition message presented in the previous paragraph, perhaps the repeated use of the word repetition and its various forms is generating a smile and twinkle in the reader's eye. If it did not accomplish that intent, perhaps the paragraph can be reread.

Acknowledgements: Work was supported by the National Science Foundation (NSF); Award 2148138.

Disclosures: The authors declare no conflict of interest.

References

[1] M. Barger, “Future of Work Issues for Florida’s Two-Year Engineering Technology Programs, ASEE 2022 Annual Conference Proceedings (2022), https://peer.asee.org/41296.

[2] W. Altmann, *Practical Process Control for Engineers and Technicians*, Newnes, 2005.

[3] M. Barger, R. Gilbert, “Future of Work Skills Integration with Florida Manufacturer’s Technician Skill Needs”, J. Adv. Technol. Educ. vol 2. no 1., pp. 14-19, 2023 doi 10.5281/zenodo.7776408.

[4] Splunk “Industry 4.0 Insights – Smart Manufacturing Guide”

[5] activeyouth.it>2024/01/31>understanding-industry 3.0-AY Institute

[6] M. Cossette, I. Fidan, G. Gailani, and A. Xiao, “Workforce development strategies in additive manufacturing”, J. Adv. Technol. Educ, vol. 1, no.1, pp.15-16 , 2022, doi 10.5281/zenodo.6506544.

[7] NIST “ https://csrc.nist.gov/glossary/term/human_machine_interface”

[8] B Grubb, L Smelser, D. Goodson, K. Short, M. Roberton, “Bridging the Gap: Identification of Critical Knowledge, Skills and Abilities (KSAs) to fill Entry-level Bioprocess Technician Positions”, J. Adv. Technol Educ. vol. 4, no. 3, pp. 14, doi: 10.5281/zenodo.10956883.

[9] M. L. Lipton, *Practical Process Control: Tuning and Troubleshooting*, Elsevier, 2005.

[10] URL at https://geekeeceebee.com/DCMotor%20Position%20Tracking.html, PID DC Motor Position Control, and also URL at https://electricdiylab.com/arduino-pid-dc-motor-position-control-close-loop-system/

[11] Norman S. Nise, Sistemas de Control para Inenieria, CECSA, 3rd edition (in English) 1st edition in Spanish, Mexico, 2005

[12] Thomas Cavicchi, “Integration of Programmable Logic Controller Programming Experience into Control System Courses,” AC2008-3, American Society for Engineering Education, 2008.

[13] Shiyoung Lee, “Application of the PID Control to the Programmable Logic Controller Course” Pennsylvania State University, Berks, AC 2009-955, American Society for Engineering Education, 2009

[14] Herbert M. Schaedel, Process Identification, Control Tuning and Control Circuit Simulation; 13th IFAC Symposium on System Identification, Paper SWR 14.

[15] Kevin Erickson, “Programmable Logic Controllers: An Emphasis on Design and Application,” Dogwood Valley Press, 2005.

[16] Gregory Stanton, “Proportional, Integral, and Derivative (PID) Controllers,” EMET410 Automated Control Systems Lecture Note, Penn State Berks, 2007.

[17] Dinesh Bista, Understanding and Design of an Arduino PID Controller, Master thesis, GWU, 2016

[18] PID temperature controller, Commercial product that is sold by Jameco (jameco.com). The description can be found at URL at https://www.jameco.com/jameco/products/prodds/2190178kitinstructions.pdf?srsltid=AfmBOooHSVHZvVxM4yLZt2yCfon07jQC198kXgi1OquJFx6pTjD-jXWP

[19] T. Uzunovi; E. Žuni; A. Badnjevi; I. Miokovi; and S. Konjicija, Implementation of digital PIC controller, MIPRO 2010, May 24-28, 2010, Opatija, Croatia. 1357-1361

[20] URL at GitHub - Hybricks/PID-for-microbit: Using a PID controller on a BBC Microbit to synchronise 2 motors, (http://github.com/Hybricks/PID-for-microbit),

[21] Ian Carey website; https: https://www.youtube.com/watch?v=RZW1PsfgVEL, PID control simulator

[22] URL at https://www.youtube.com/watch?v=RZW1PsfgVEI,

[23] Dashboard - Tinkercad, URL at tinkercad.com

[24] Radha Abburi1, Manne Praveena2, R.Priyakanth3, “TinkerCad - A Web Based Application for Virtual Labs to help Learners Think, Create and Make” Journal of Engineering Education Transformations, Volume 34, January 2021, Special issue, eISSN 2394-1707

[25] Branimir Pejcinovic, Jamie Lyn Kennedy, Melinda Holtzman, Using Tinkercad in introductory electrical and computer engineering courses, Paper ID 47974 2025 American Society of Engineering Education, Annual Conference and Exposition, Montreal, QC, Canada, 2025

[26] Richard Blum, Arduino Programming Sams Teach Yourself in 24 hour, SAMS Indianapolis Indiana, 2015 ISBN-13 978—672-33712-2