

Computer Programming and Process Control Take-Home Lab

John Hedengren, Brigham Young University
Jeffrey Kantor, University of Notre Dame

The Temperature Control Lab is a community-developed Arduino lab for process dynamics and control that has been adapted as a remote lab experience. Introductory programming modules are for students who need help getting started with computer programming in Matlab, Python, or Java. The lab provides each student with sensor data for dynamic modeling and a device to implement feedback control. It has evolved over 8 years of development to provide a plug-and-play experience for common operating systems and coding environments. Preliminary results suggest that the TCLab improves learning, but additional assessments are needed to quantify the education objective of improving practical understanding of system dynamics and process control.



Figure 1. Temperature Control Lab.

The survey on *Chemical Engineering Academia-Industry Alignment: Expectations about New Graduates* [1] emphasizes the industrial need for students to have a practical understanding of system dynamics and process control. Graduates should have experience translating process control theory into practice. Many universities have a process control lab to meet this need, but access to these labs is incompatible with new requirements for remote instruction or social distancing due to COVID-19. There are several strategies to provide a practical process control experience using simulators or home-based Arduino labs [2].

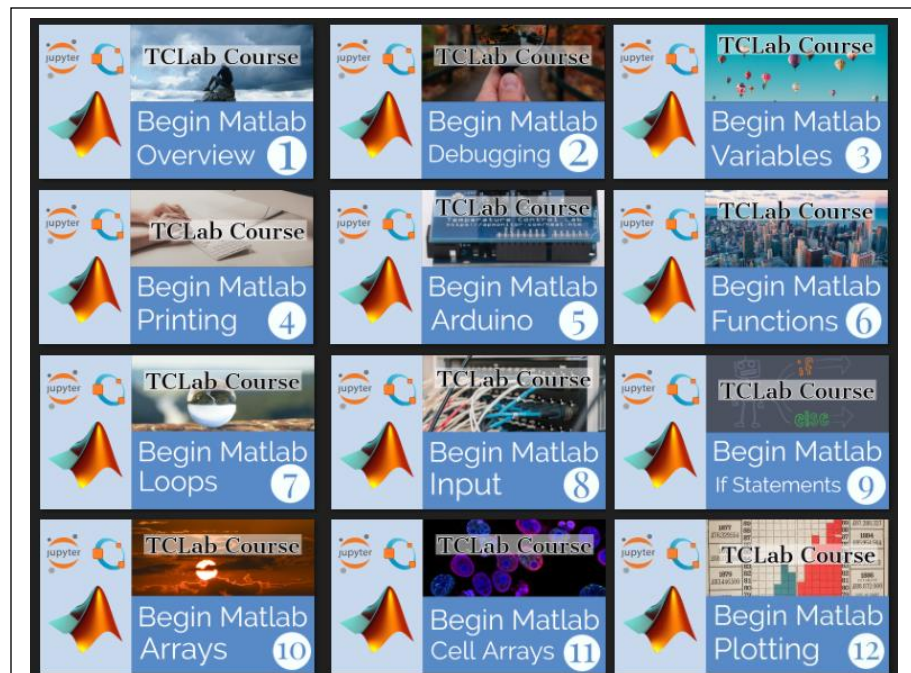


Figure 2. Begin Matlab Course

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The TCLab is a pocket-sized process control lab that reinforces process control theory and computer programming skills. The Temperature Control Lab (TCLab) as shown in Figure 1 is a small and inexpensive process control experiment. It is made available to students to reinforce concepts in dynamics and control theory. For students that need help getting started with programming, there are 12 introductory

modules (each 15-20 minutes) to introduce or refresh knowledge of programming. Although students may have had a programming or numerical methods course, many need a primer if it hasn't been used regularly throughout the engineering curriculum.

The course is designed to start from no programming experience and guide a self-paced learner through the basics of Matlab, Python, or Java. The 12 modules in the Matlab course are run from Matlab, Octave, or Jupyter Notebooks. Any of these serve as the Integrated Development Environment (IDE) but the Jupyter notebooks are used for all solution videos. The tutorials start with how to install the software and use the hands-on lab kit as shown in Figure 2.

Universities have adopted this lab for process control instruction and initial results show improvement in learning [3-7], although more instructional design and assessment work remains. Early participants on this community initiative are Chemical Engineering departments from Notre Dame, Iowa State, Oklahoma State, Georgia Tech, New York University, Louisiana Tech, McMaster University, Christian Brothers University, Villanova, University of Iowa, Brigham Young University, University of Pretoria, and Western Michigan University. Software interfaces have been developed in Python, MATLAB, Simulink, and Java. The software and problem statements have been modified by instructors to integrate with their teaching materials.

Desired characteristics of a take-home lab are safety, durability, small size, low cost, compatibility with all student computers, plug-and-play (minimal setup), open-source and community developed, and available templates for course integration. The Arduino-based TCLab meets these requirements and gives students access to a compact (5" x 3" x 2") boxed lab that has two actuators (TIP31 BJT transistors as heaters) and two temperature sensors (TMP36 thermistors). The TCLab is a shield for the Arduino Leonardo as a micro-controller to provide the Analog / Digital interface to the hardware and provide a USB connection to most PC operating systems.



Figure 3. Production of the TCLab.

When first implemented in 2013 at BYU, students were given the circuit components and instructed to breadboard the lab. Although the circuit design is not overly complicated, some students inadvertently mis-wired the circuit or damaged lab components. The result was a c. a. 50% success rate in running the lab exercises and a high degree of frustration from the students. For this reason,

the current versions of the lab is manufactured as a plug-and-play lab kit. Bulk PCB production and assembly of the TCLab has resolved these issues and over 7000 have been produced as of June 2020 with one batch shown in Figure 3.

At BYU, a lab-based exercise is included for every homework (23 modules) in Process Dynamics and Control starting in 2019. The 23 modules were developed for the course with the objective of reinforcing each of the theoretical or simulation exercises with data from a real system. From 2013-2018, the TCLab was a one-week lab component of the course but this has expanded to reinforce each concept as it is taught. A flowchart map of the new course is shown in Figure 4.

Next steps are improved assessment of learning outcomes, additional Arduino-based take-home modules such as liquid level control and refrigeration, microfluidics, language translation, and resources to support remote group learning with take-home labs. The COVID-19 pandemic has created both a challenge and an opportunity to deliver home-based instruction with practical process control exercises. Automation, computer programming, and computer control is increasingly important in many industries. Engineering students need a foundation in computer programming and practical experience with process control.

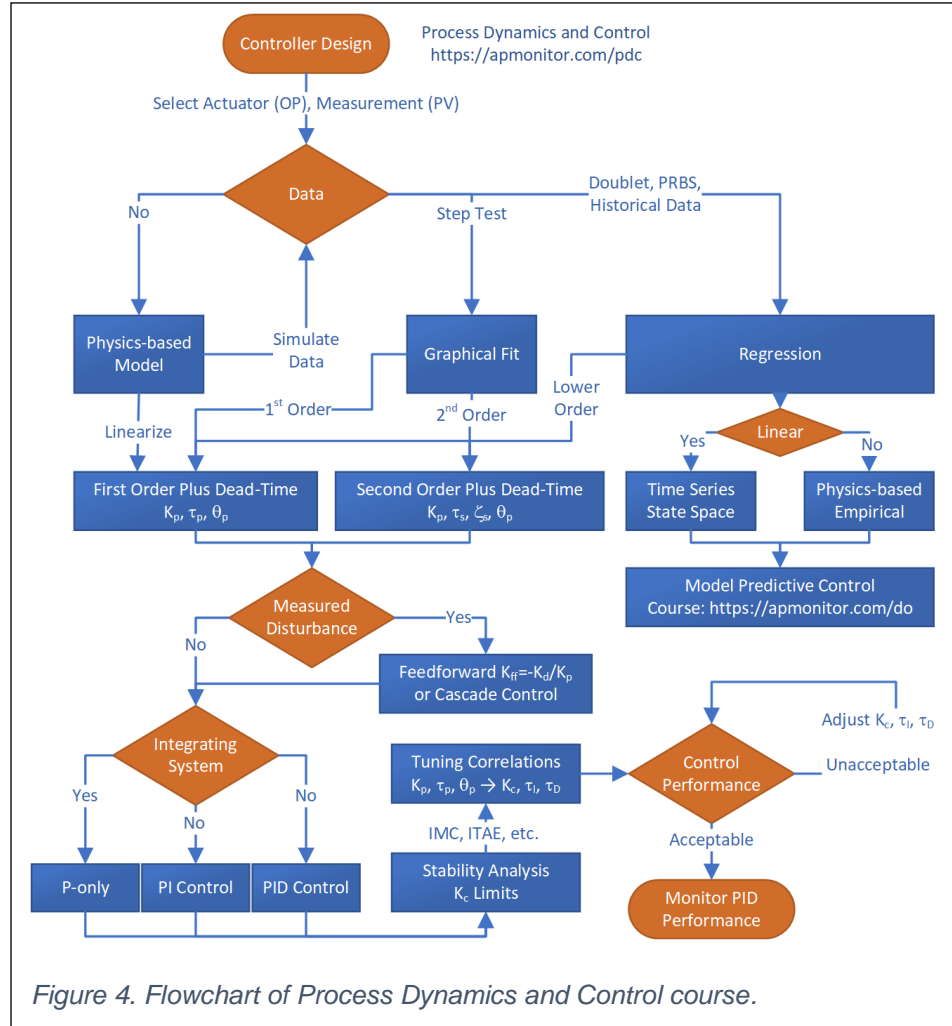


Figure 4. Flowchart of Process Dynamics and Control course.

Acknowledgements

The development of the TCLab is a community effort with contributions from R. Abraham Martin for developing the physical lab, Jeffrey Kantor and Carl Sandrock for the Python interface, Samvith Rao for the Simulink interface, Paulo Moura Oliveira, Junho Park, and John Anthony Rossiter for publishing classroom best-practices. Many others have contributed through curriculum development and instructional feedback.

Authors



Dr. John Hedengren is an Associate Professor at Brigham Young University in the Chemical Engineering Department. He leads the BYU Process Research and Intelligent Systems Modeling (PRISM) group with a focus on structured machine learning for optimization of energy systems, unmanned aircraft, and drilling. He leads the development of the Arduino-based Temperature Control Lab that is a community initiative used by 55 universities, primarily for process dynamics and control education.



Dr. Jeff Kantor is a Professor at University of Notre Dame where he was Vice President and Associate Provost from 1996-2001 and Vice President for Graduate Studies and Research and Dean of the Graduate School from 2001-2006. Dr. Kantor is interested in the analysis and optimization of integrated financial and process operations using methods of stochastic control, convex optimization, and quantitative finance.

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Appendix A

The following is a table the 23 lab modules that reinforce concepts in the Process Dynamics and Control curriculum. The first set of 10 modules is for process dynamics to generate data and evaluate the agreement with different modeling strategies including physics-based and empirical methods. It also includes exercises for model regression for controller design. The next set of 13 modules is for process control where the temperature sensor provides a measurement and the heater is adjusted to regulate to a desired set point. Each homework for the course has an associated lab exercise.

	Number	TCLab Module Description
Dynamics	1	Simulate Step Response
	2	Convective Heat Transfer
	3	Radiative Heat Transfer
	4	Linearize Energy Balance
	5	First Order Plus Dead Time (Graphical)
	6	First Order Plus Dead Time (Regression)
	7	Impulse Response (Analytic Solution)
	8	State Space Simulation
	9	Second Order Response
	10	Higher Order Response
Control	11	Controller Design
	12	P-Only Control
	13	PI Control
	14	PID Control
	15	PI Control Tuning
	16	PID Control Tuning
	17	PID with Feedforward
	18	Heater Actuator
	19	Temperature Sensor
	20	Block Diagram
	21	On/Off Control
	22	Stability Analysis
	23	Cascade Control

Appendix B

In addition to the Begin Matlab course, a Begin Java and Begin Python course are published on YouTube and GitHub with the Java course shown in Figure B6.



Figure B5. Begin Java Modules with Hands-On TCLab Exercises

Below is a list of courses that use the TCLab for teaching computer programming, data science, and process control:

- Begin Matlab: <https://apmonitor.com/che263/index.php/Main/BeginMatlab>
- Begin Python: <https://apmonitor.com/che263/index.php/Main/CourseProjects>
- Begin Java: <https://apmonitor.com/che263/index.php/Main/BeginJava>
- Data Science: <https://apmonitor.com/che263/index.php/Main/DataScience>
- Process Dynamics and Control: <https://apmonitor.com/pdc>
- The Process Control Laboratory (Notre Dame): <https://github.com/jckantor/CBE32338>