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Temperature Control Lab for Dynamics and Control

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The 2015 NSF-sponsored report “Chemical Engineering Academia-Industry Alignment: Expectations about New Graduates” [1] identified a strong industrial need for practical understanding of process control and system dynamics. Industry feedback also suggests more focus is needed on translating process control theory into practice [2]. At many universities, this need is met by integrating laboratory experiences into process control courses. However, increased enrollments in chemical engineering strain the available laboratory resources and make these labs difficult to schedule and manage. For these reasons, we have developed small, inexpensive, and portable process control lab designed to reinforce process dynamics and control theory. The Temperature Control Laboratory (TCLab) hardware consists of an Arduino shield that fits onto a standard Arduino UNO or Leonardo microcontroller, a 2A, 5V power supply, and a USB cable for communication with a PC. For reliability and safety, there are no moving parts and there is a safety shut-off to prevent temperatures above 100ºC. The TCLab software consists of firmware that can be preloaded on the Arduino microcontroller, an open-source Python library providing a laboratory interface, real-time plotting and data logging services, and a library of Jupyter notebooks demonstrating topics in process control.

From a modeling and identification perspective, TCLab is a simple multivariable system comprised of 2 heaters and 2 closely coupled temperature sensors. The step response of each heater/sensor pair can be approximated by a first order system with a time constant of 2 minutes. The interaction between the heater/sensor pairs is small enough that SISO control is effective, but sufficient to give an introduction to multivariable modeling and control. Thermal energy from the heater is transferred by conduction, convection, and radiation to the surroundings and to the temperature sensor. A detailed energy balance provides a high-fidelity model for each heater/sensor pair that can be extended to a linear state space model with four states, two inputs, and two measured outputs for the entire device. All model parameters can be identified with step test experiments.

The TCLab module can demonstrate many process control modalities. Basic single-input single-output control adjusts heater power output to maintain a temperature setpoint. Interacting two-input, two-output control can be demonstrated by simultaneously controlling both heaters. Cascade control is demonstrated by manipulating one heater and two sensor measurements to control the temperature of the other device. Students can implement the control modalities by coding control algorithms including relay, PID, and model predictive control.

The TCLab device is also a platform for demonstrating state estimation. A linear four-state model for the temperatures of the two heaters and two sensors provides excellent description of the observed dynamics. An observer can be implemented to estimate all states from either or both sensor measurements, and used to demonstrate state feedback, the use of soft sensors to control heater temperature, and sensor fault detection.

The small process control experiment is given to students to reinforce concepts in dynamics and control theory. The lab is integrated at various points to reinforce theory with a practical application for the process dynamics and control course. There are a number of potential pitfalls to avoid and effective strategies to adopt to maximize the learning potential of the lab experience. The lab kit is used to teach digital twin modeling, model identification, and dynamic parameter regression. The objective of this presentation is to give additional details on the learning objectives and discuss the educational outcomes.
Lab kits have been distributed to early-adopting universities that include 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, Western Michigan University, and Zaragoza University. Companies such as APCO, Inc. have developed commercial

software for the TCLab into SimTune for training on industrial controllers such as Allen Bradley and Honeywell PID control. Approximately 40 universities use the TCLab for the process dynamic and control course and several faculty have developed new learning modules in a variety of spoken and computer languages. The modules consist of several learning phases: (1) generate a step response, (2) estimate parameters to determine a model, (3) tune a PID controller, (4) reject disturbances and track setpoint, (5) develop SISO and MIMO control methods, and (6) advanced topics such as Model Predictive Control (MPC) [3] and machine learning [4]. This lab was also presented at the 2017 ASEE Summer School at NCSU as part of resources for teaching process transient analysis. Lab solutions for instructors are provided in Python and MATLAB.

See https://apmonitor.com/heat.htm for additional lab details.

References

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