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Automated Process Control Laboratory Experience: Simultaneous Temperature and Level Control in a Continuously Stirred Tank Reactor System

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Abstract

A process control laboratory experience has been developed using a continuously stirred tank reactor system that permits simultaneous level and temperature control using water as the process medium. This work was originally completed as a senior honors thesis project, and the resulting system has been successfully incorporated into the process control block of a junior-level unit operations laboratory course. Use of the apparatus over multiple laboratory sessions provides students with a hands-on experience that illustrates the concepts of system characterization (e.g., calibration, determining operating ranges, understanding electromechanical component specifications, etc.), open-loop process response measurements, and closed-loop response and PID tuning. A controller program to interface with the valves and sensors and to perform data logging was constructed in LabView, employing a graphical user interface. As part of the experience, all sensors and valves of the system are to be characterized and calibrated. The two system processes—i.e., temperature and height—are run in an open loop manner, with data collection providing a means to determine appropriate process models. Process parameters from these models permit the estimation of controller tuning values (i.e., controller gain and time constants) through formula- or software-driven means (e.g., Control Station Loop-Pro). SISO configurations are then employed to test various control settings for tuning purposes, with the use of hand-tuning techniques to refine these values. The system can ultimately be operated in a MIMO configuration without and with decoupling gains; the typical oscillatory behavior without decoupling is demonstrated due to the inherent process interactions. Students who use this system are thereby given a hands-on opportunity to practice a variety of essential process control techniques and concepts, providing important context for this material. Student assessments conducted prior to and after using this and other hands-on systems indicate marked improvement in understanding and comfort-level for process control applications.

Introduction

The theory and application of process control concepts is a challenging area of instruction within the chemical engineering curriculum. This is often the result of students perceiving the material as being conceptually difficult, abstract, and disconnected from the rest of their coursework[1]. Classroom strategies have been developed to permit students to form a more definitive connection to this important area of professional practice, including the use of computer simulation[2], case-studies[3], in-class control kits[4-7], and more integrated hands-on process control systems[8]. Such enhancements have been successful, as indicated in associated student feedback and assessment metrics.

Hands-on experiences are particularly useful to students to help in the understanding of process control concepts and application. When constructed with sufficient complexity—including physical materials, electromechanical elements, control algorithm parameter selection via computer interface, and data-logging for subsequent analysis—the student can make an immediate link between what was learned in the classroom with process control practice, as they get to directly experience the "cause-and-effect". A laboratory setting offers a high-quality venue within which to work with such hands-on systems, as students can spend several hours at a time moving through the various familiarization, characterization, and open and closed loop testing steps required to gain a complete picture of process control application. It also has the added benefit of expanding a student's troubleshooting skills.

At Lafayette College, the integration of more sophisticated, hands-on process control laboratory experiences into the curriculum has been taking place for several years as a means of providing enhanced synergy between the lecture-driven process control course and the junior-level unit operations laboratory course. Examples include Lego NXT computer brick driven systems for level control in a tank or continuously stirred tank reactor (CSTR) and vapor rate control in a steam-driven tray distillation column. While illustrative, additional experiences are being developed so as to increase complexity and to permit smaller groups of students to work on any one given apparatus. As such, the focus of this paper is on the development of another robust system for use in learning process control.

Learning Objectives

The primary objectives for creating this system were as follows:

- To create a hands-on, user-friendly, laboratory experience for students to study process control concepts and its related implementation and tuning procedures under single-input, single-output (SISO) and multiple-input, multiple-output (MIMO) modes of operation
- To incorporate the system into the process control block of a junior-level laboratory course in experimental design and to assess its effectiveness in teaching process control

The platform for developing this system was an Honors Thesis project, involving a senior undergraduate who accomplished the related design, procurement, assembly, programming, characterization, and testing under the close direction of a faculty advisor. The following sections provide the details of this system and demonstrate fulfillment of the above objectives.

System Description

Apparatus

The operating objective of the apparatus was to separately or simultaneously control the level and/or temperature of water fed into a CSTR using feedback-based control. The concept was based on a prototype system previously constructed from less sophisticated components and software control, with the new system being fabricated using components already on-hand or ordered per specification. The assembled MIMO system is shown in Figure 1, with the accompanying process and instrumentation diagram appearing in Figure 2.

Briefly, the apparatus incorporates a two-liter Chemglass jacketed CSTR, equipped with a variable speed impeller. Water was supplied from the city water line and was regulated to lower pressures using separate in-line regulators and hand-valves for the hot and cold water feed lines. Hot water was generated with an in-line water heater tank with a 2.5-gallon capacity. Separate solenoid-based control valves (0-5 VDC) were used to control the cold (level) and hot (temperature) water flow rates. A three-way valve was placed on each feed line after the control valve so as to permit flow rate calibration. A small capacity centrifugal pump and hand valve were placed at the effluent of the CSTR to better modulate the liquid flow rate draining from the tank and to therefore set the corresponding dynamics. A pressure sensor (Omega Engineering PX40 Series) was placed at the base of the CSTR to measure level. Temperature was measured using a low-noise temperature sensor (TC 9701A) embedded in heat-transfer epoxy and was placed in the effluent line between the pump and hand-valve. All liquid leaving the system was sent to the drain.

User Interface

The apparatus was controlled and monitored using a custom-built graphical user interface programmed using LabView. The feedback control scheme was based on the control block diagram depicted in Figure 3, which directs all potential modes of operation for the system—including both SISO mode and MIMO mode (with and without decoupling). The user interface screen appears in Figure 4. The screen includes real-time plots of the height and temperature measurements, along with the controller output for each control valve. Set points and proportional-integral-derivative (PID) parameters may be entered for both height and level control loops, with each control loop individually turned ‘on’ or ‘off’ and set to ‘direct’ or ‘indirect’. When operated in MIMO control mode, process interaction decoupling parameters may be entered for each variable so as to help dampen typical sinusoidal behavior and to improve process dynamics. Prior to open- or closed-loop operation, calibration experiments may be performed so as to compute the slope and intercept values for the sensor output signals, and the screen permits entry of these values for use in controlling the system. The final section of the screen defines where final control element (FCE) minimum and maximum voltages may be entered to define the system bounds, in addition to providing a means for the user to manually set the height or level controller output at a specified value (which is useful for calibration and characterization studies).

It should be noted that the input and output signals between the system components and computer were interfaced using a National Instruments data acquisition board (NI-DAQ USB 6009). Data entered and displayed on the user interface are tied to the underlying programs that process and deliver these signals (i.e., pressure sensor, temperature sensor, final control element, controller, and overall process control programs). Time-dependent output data for multiple parameters are collected and written to a delimited text file, which can be uploaded into a spreadsheet (or other software) for analysis.

Operation

Calibration and Component Characterization

To successfully operate the system in either SISO or MIMO modes of control, the sensors and control elements needed to be calibrated and characterized. These results ultimately were used to derive an initial set of control parameters and to set the control variable operating ranges.

Both the pressure and temperature sensors possessed a linear voltage response to changes in the measured variable, which permitted a straight-forward calibration using the programs contained within the user interface screen. For height, pressure sensor readings were collected for liquid heights between 10 and 20 cm above the sensor, which avoided readings within the curved bottom of the CSTR. A typical pressure calibration curve and linear regression appears in Figure 5, denoting a nominal sensor output on the order of 30 mV/cm tank height. For temperature, temperature sensor readings were collected in the range of 20 to 50 ºC, which is below the maximum allowable temperature of 70 ºC. A typical temperature calibration curve and linear regression appears in Figure 6, denoting a nominal sensor output on the order of 20 mV/ºC. The slope and intercept for each variable would then be entered into the appropriate cell in the 'Sensor Calibration' area.

For reference purposes, the hot and cold water flow control valves can be characterized to aid in understanding the system dynamics and control behavior. To accomplish this, flow rates were measured by collecting fluid at the calibration ports as a function of the valve excitation. These results are shown in Figures 7 and 8, where both valves demonstrate hysteresis as the valve is switched from an opening vs. closing direction. In addition, it is observed that the flow rate operating ranges are within 0-1000 mL/min for the hot and cold water lines, where the maximum flow is a function of the degree of source flow regulation prior to the control valve.

Open Loop Characterization

With system components characterized, information about the height and temperature dynamics of the system and a basis to determine proper control tuning parameters can be obtained through open loop testing. Such information is instrumental for users to understand process dynamics and to create an initial set of tuning parameters for the controllers used.

A common test procedure for an individual variable loop follows a standard duplet form, where a unit step change is made in one direction of the set point, followed by a double unit step change in the opposite direction of the set point, and finally stepping the set point back to the original value. This provides equal weighting to both directions of the process dynamics and provides a large amount of information from one set of tests. Note that the loop that was not being tested was set at a constant nominal value corresponding to what might be typically seen in a MIMO configuration, and tests were all started at approximately half the total tank height in an attempt to characterize the mean process parameters. All time-dependent data collected from these tests were analyzed using Control Station Loop-Pro, where data were fit with the model resulting in the greatest R^2 fitness parameter. From this process model fit, the Loop-Pro process parameters could be used to determine aggressive and conservative controller tuning parameters to initiate tests in closed loop process characterization (via the built-in tuning algorithms within Loop-Pro or via standard formulas—e.g., Ziegler-Nichols). Suggested values for proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) may be obtained.

A typical height open loop duplet test is shown in Figure 9 and also shows the fitted process model (i.e., a first-order plus dead time model). To perform this test for height, an unsteady state duplet test was utilized in an attempt to relate the gain of the system to the rate of the height change in the tank, rather than to a steady state height value; a fixed effluent flow rate was used.

A typical temperature open loop duplet test is shown in Figure 10 and also shows the fitted process model (i.e., a first-order plus dead time model). For the temperature open loop characterization, a steady state duplet test was used, as the temperature of the system reaches a steady state value for any combination of steady incoming flow rates. This was accomplished through manual manipulation of the respective control valves in the absence of feedback control, employing the drain valve and exit pump as a means to keep the level nearly constant inside the CSTR. (Note that the dip/sinusoidal behavior observed in this experiment is a result of the temperature controller already in place on the point-of-use water heater, which cannot be avoided without bypassing installed safety mechanisms.) In viewing these results, the first-order plus dead time best-fit models are not unexpected, as the system dynamics do not promote overshoot and slow responses create appreciable dead-time.

SISO and MIMO Operation and Tuning

After system characterization in the open loop, the information obtained permits students to proceed to operating the system in the closed loop and assessing the related dynamics. This data can then be used to determine the best P/PI/PID control scheme and corresponding set of parameters using an appropriate set of metrics (e.g., integral squared error, overshoot, offset, controller response activity, oscillations, etc.). The following discussion presents typical experimental results that one may obtain through operation of the apparatus in various closed loop control configurations.

For SISO control of either CSTR liquid height or temperature, the same duplet test method as the open loop method was followed for a variety of control parameter schemes. The variable that was not being tested was held at a constant value in the same manner as in the open loop characterization. Typical results for PI- and PID-based level control appear in Figure 11 for both the Loop-Pro and hand-tuned sets of control parameters. It is readily noted that the overshoot and response times vary as a function of the control settings, along with the activity of the controller response (or valve position). The controller response using the algorithm-based values appeared to be much more active compared to the results obtained for hand-tuning. For temperature control, a typical PID hand-tuning result for a closed loop duplet test is shown in Figure 12. As with the SISO height study, typical control results may be observed, including offset, response times, oscillations, associated controller response activity, and system limitations (e.g., hot water supply temperature). Controller gains and time constants may be compared for each variable, affording an opportunity for the student to compare the respective process dynamics. Note that the hand-tuning results in Figures 11 and 12 do not correspond to any specific tuning objective, using settings determined solely through operator judgment. As such, they are not meant to represent an optimally-tuned controller, where more rigorous tuning schemes may be employed—e.g., quarter-decay ratio, minimum rise time, etc.

With SISO control parameters as a starting point, MIMO operation for simultaneous level and temperature control can be implemented and tuned to generate good control behavior. Results for PID control without and with decoupling appear in Figure 13. For each coupling mode, a duplet test was first performed for one variable while the other was held constant, followed by the opposite combination afterward. It is readily apparent that decoupling vastly improved MIMO-based control, reducing the oscillatory behavior of each control variable and overall activity of the controller response. The decoupling parameter values used can be tuned using either rule of thumb or systematic trial and error methods.

In all cases, the integral squared error may be used to assess control effectiveness, paying attention to the data interval being used in the time-sequence. The data-logging provided by the user interface makes this quantitative assessment much easier to implement, with low values of squared error typically signifying better control. In addition, the use of direct observation on the quality of control with respect to the metrics listed above may be used. Specifically, attention can be paid to the controller response activity, in which frequent and large excursions in the position of the valve are not ideal due to increased wear over time; such analysis may suggest a trade-off, where a scenario with higher squared error but less valve motion is preferred. Clearly, operation of this MIMO system creates opportunities for students to test, interpret, and assess a wide array of process control scenarios.

Laboratory Implementation and Student Assessment

The MIMO system has been implemented as part of the process control block of CHE 322 Experimental Design II. This is a junior-level laboratory class focused on experimental design using various unit operations and is taught concurrently with the process control course, CHE 324 Process Control. This process control block occurs in the last four weeks of the semester, offering the students the opportunity to utilize the content learned in the lecture-based course and to apply it to this (and the other aforementioned) hands-on laboratory experiences.

Students typically work in groups of three to four to accomplish a set of generally-defined tasks. For this MIMO apparatus, these tasks are as follows:

- Week One – System Familiarization: Students become familiar with the apparatus, establishing operating ranges, refining standard operating procedures, and calibrating and characterizing system components.
- Week Two – Open Loop Studies: Set-up and analysis of open loop experiments to determine process model parameters for both height and temperature control loops. Loop-Pro/Control Station software is employed to facilitate analysis, permitting the estimation of an initial set of tuning parameters for use in closed-loop control.
- Week Three – Closed Loop Studies: Set-up and analysis of closed loop experiments for temperature-only and level-only SISO control and for simultaneous temperature and level MIMO control, with and without decoupling. Various P/PI/PID control schemes are evaluated for control quality.
- Week Four – Reporting: Presentation of results and analysis in both oral presentation and written report formats.

Note that the students develop written memos before and after Week One and after Week Two to assist in understanding their experimental plans, observations, and analysis, along with helping them to prepare their final oral presentation and written report. An example of the laboratory description that can be employed when administering this system as part of this process control block is shown in Figure 14. It includes the milestones described above, along with a preliminary standard operating procedure that the students can use to assist in their familiarization with the apparatus and which they must adapt and modify to reflect their knowledge and experience with the MIMO apparatus.

The use of this hands-on experience is an important tool for students to better understand process control concepts and to improve their general troubleshooting skills. The benefits are numerous and relate and to the fact that the student performs a complete study and tuning of a process system, in addition to using “state-of-the-art” software tools to assist in the analysis (e.g., Loop-Pro, Excel, LabView, etc.). Specifically, the student is engaged in familiarization, calibration, characterization, and the set-up of both open and closed loop experiments. Various approaches to experimental set-up may be pursued, and the student can see the impact of algorithmic and manual tuning strategies for both SISO and MIMO modes of operation. The impact of decoupling is also readily visible, in addition to assessing the overall quality of the regulation provided by the control scheme implemented. Within the context of this institution’s curriculum, the added experience of group-driven project work and both oral and written communication are also important educational experiences.

To assess the impact of the use of this and the other hands-on process control related experiments, pre- and post-experience surveys were employed with two different groups of students in successive offerings, examining multiple aspects of the process control course, in-class exercises, and the concurrent laboratory course. The surveys were administered in the Spring 2010 and Spring 2011 semesters, with a high participation rate from the 27 and 32 total students enrolled, respectively. Specific results from these assessments—which are relevant to the process control apparatus described—are shown in Figures 15 and 16, providing assessment data on students’ comfort and ability to understand simple feedback and multiple-input/multiple-output control systems. Students rated each item on a Likert Scale (1-7). When viewing the data presented in both figures, it should be noted that the absolute magnitude of the rating data is inherent to the group of students being assessed.

The assessment data presented in Figures 15 and 16 clearly indicate the positive influence that hands-on lab experiences have on the students’ familiarity and comfort-level with the material and its application, with overall scores significantly improving in each category. In terms of understanding simple feedback control systems (i.e., Figure 15), the pre- to post-assessment averages improved from 2.8 to 5.9 and 5.0 to 6.3 in each successive year. For concepts and practice related to MIMO (i.e., Figure 16), the pre- to post-assessment averages dipped for the first year (5.3 to 4.3) and markedly improved for the second year (2.8 to 4.8). On this point, it is important to note that the lack of demonstrated improvement observed in the Spring 2010 assessment for MIMO can be attributed to the fact that a ‘beta’ version of the MIMO system was used for this offering, with only a subset of students directly exposed to this system. The assessment data from Spring 2011 strongly demonstrate the desired pre- to post-assessment improvement, which is a result of implementing the enhanced and complete apparatus detailed in this article, along with an improved, more broadly-based delivery of the related content to the full group of students enrolled in the class.

Further qualitative evidence of the impact of using this hands-on experience on student performance can be drawn from an examination of the assignments completed as part of this laboratory. The quality of the written assignments was found to steadily improve, with students demonstrating increased depth of knowledge and greater command of their descriptions of the mechanical elements and functionalities of the system. In addition, observations related to how students executed the laboratory tasks showed increased comfort level and familiarity with the equipment. Note that quantitative analysis of student performance on these assignments and other self-assessment survey data are outside the scope of this work and will be discussed elsewhere.

Conclusions

Process control is an important part of the chemical engineering curriculum, and laboratory experiences in process control provide valuable hands-on opportunities to reinforce and to expand upon theoretical and abstract classroom concepts. In this study, a water-based CSTR system with simultaneous temperature and level control has been successfully constructed, employing a graphical user interface and extensive data-logging capabilities. A coherent laboratory experience with this and other hands-on process control systems has been incorporated into a junior-level laboratory course in experimental design that is taught concurrently to the lecture-based process control course and offers students extensive opportunities to practice familiarization, characterization, and open and closed loop experimental tasks. Pre- and post-experience assessment data that measured the impact of these hands-on process control experiences has been collected and indicate a positive influence on students' understanding of and comfort-level with process control. As such, this MIMO system appears to have great value in its use as a robust teaching tool for process control related content.

Acknowledgments

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Bibliography

1. Lant, P. and Newell, R.B., "Problem-Centered Teaching of Process Control and Dynamics", *Chemical Engineering Education*, **30**(3), pp. 228-31 (Summer 1996).
2. Woo, W.W., "A Motivational Introduction to Process Control", *Chemical Engineering Education*, **31**(1), pp. 58-9, 63 (Winter 1997).
3. Bequette, B.W., Schott, K.D., Prasad, V., Natarajan, V., and Rao, R.R., "Case Study Projects in an Undergraduate Process Control Course", *Chemical Engineering Education*, **32**(3), pp. 214-9 (Summer 1998).
4. Moor, S.S., Piergiovanni, P.R., Metzger, M., "Process control kits: a hardware and software resource," *Frontiers in Education, 2005. FIE '05. Proceedings 35th Annual Conference* , pp.T2G-27, 19-22 Oct. 2005.
5. Moor, S.S., Piergiovanni, P.R., and Metzger, M., "Learning Process Control with LEGOs," 2004 ASEE Annual Conference (June 2004).
6. Moor, S.S., Piergiovanni, P.R., "Inductive Learning in Process Control", Proceedings of the 2004 American Society for Engineering Education Annual Conference and Exposition, Salt Lake City, UT., June 2004.
7. Moor, S., Keyser, D., and Piergiovanni, P., "Design-Build-Test: Flexible Process Control Kits for the Classroom," ASEE Conference Proceedings (2003).

8. Bequette, B.W., Aufderheide, B., Prasad, V., and Puerta, F., “A Process Control Experiment Designed for a Studio Course”, AIChE Annual Meeting, Los Angeles, CA, November 2000.
9. Smith, C.A., Corripio, A.B., *Principles and Practice of Automatic Process Control, Second Edition*, p. 566 (1997).

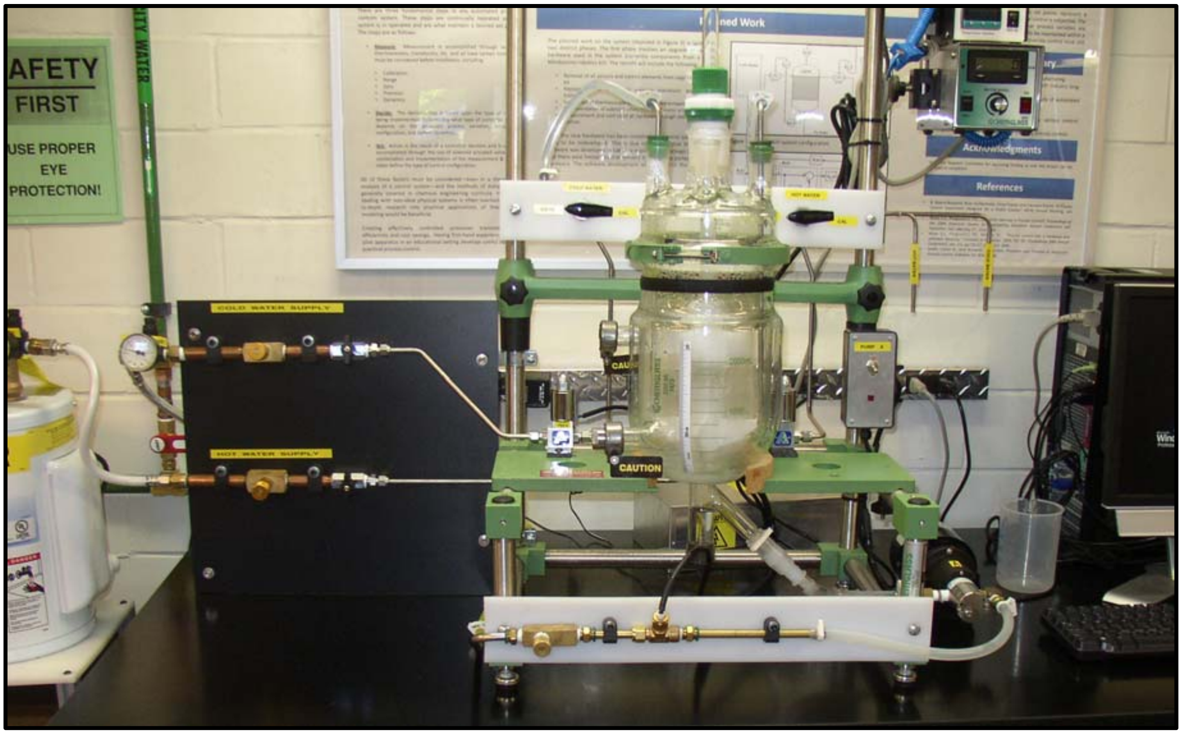


Figure 1: Fully-assembled MIMO continuously-stirred tank reactor process control apparatus.

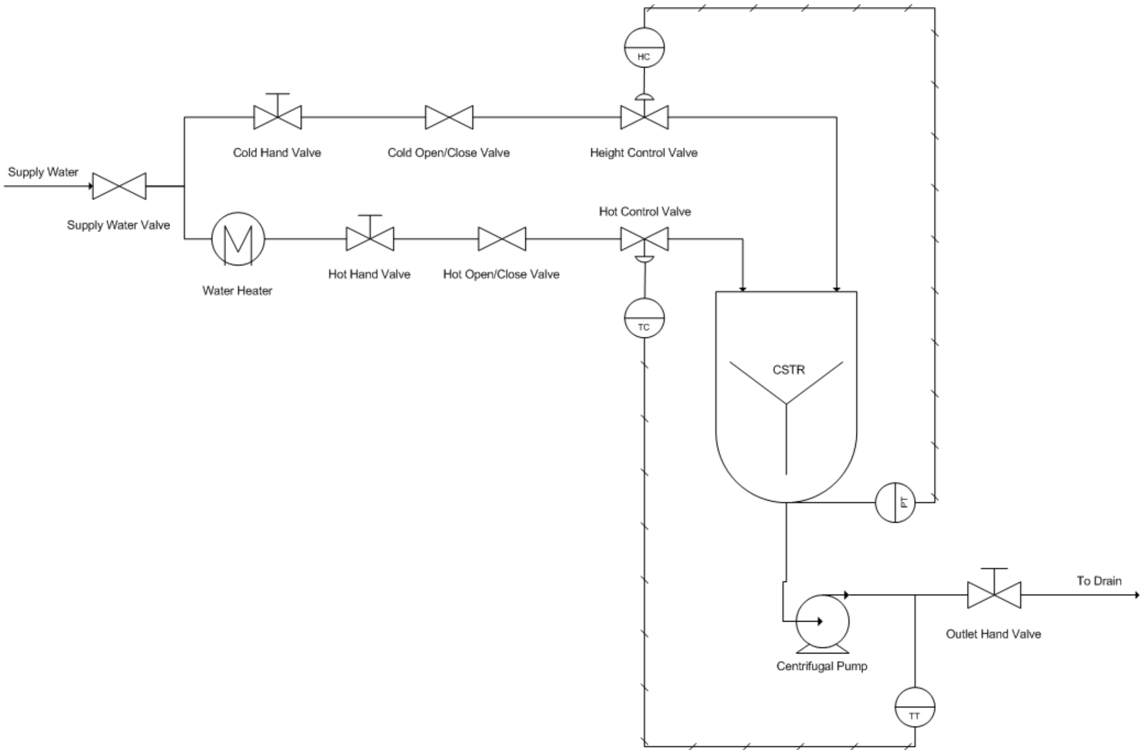


Figure 2: Process and instrumentation diagram for the core elements of the MIMO continuously-stirred tank reactor process control apparatus.

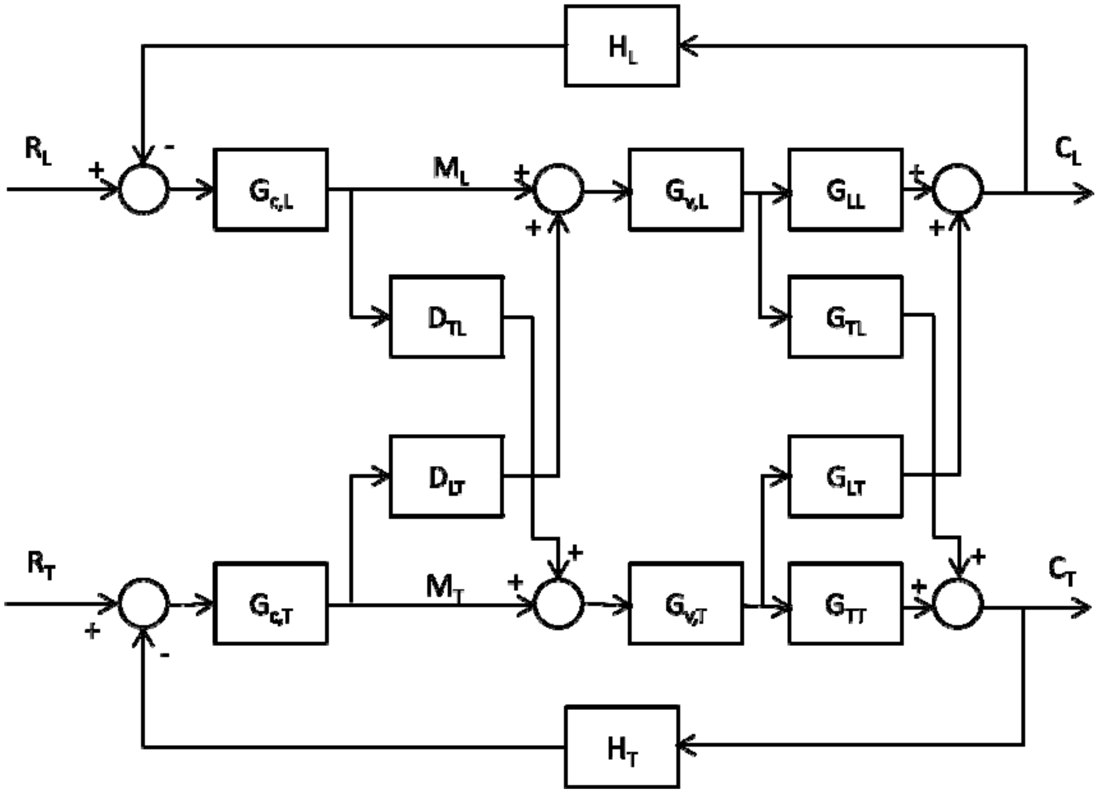
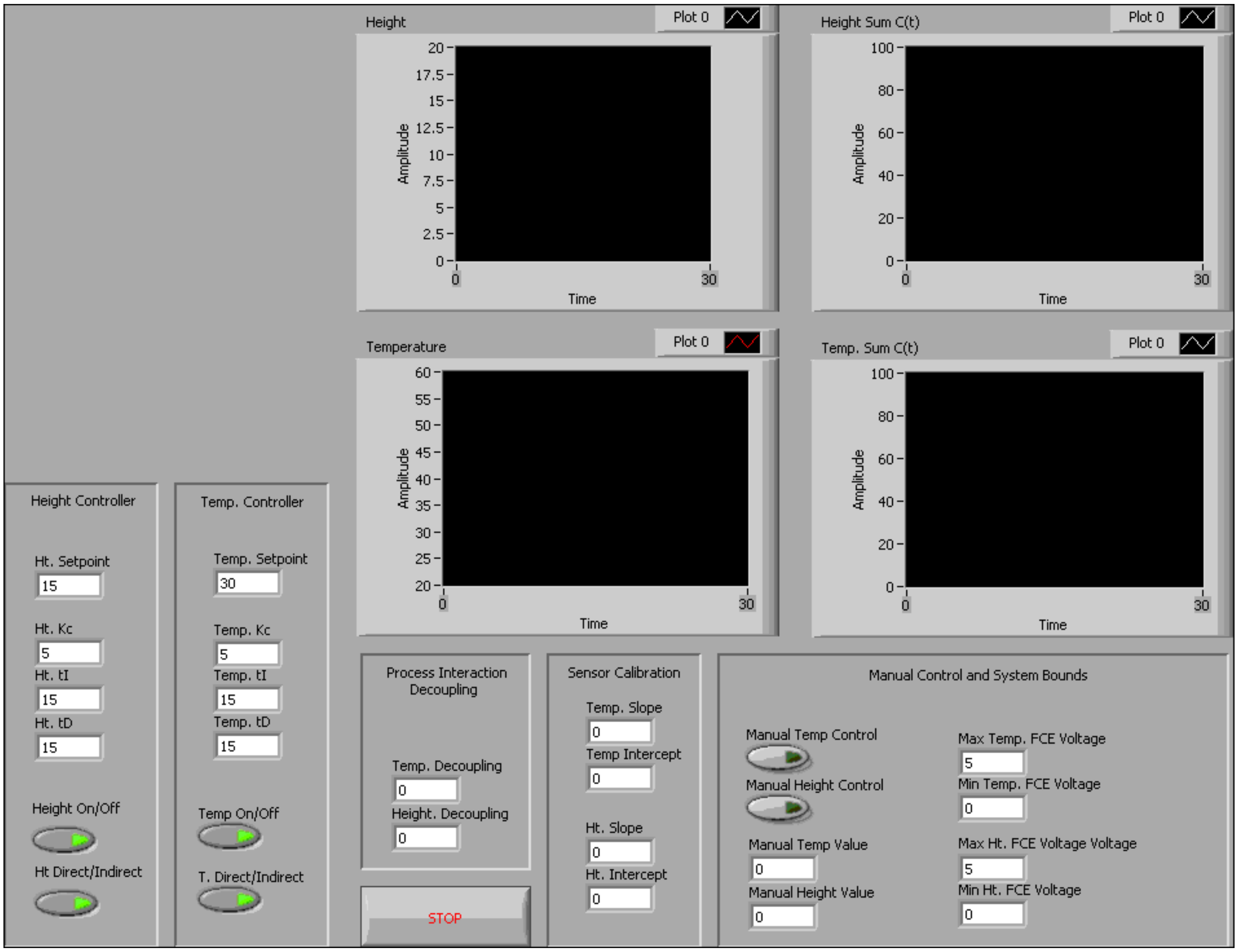


Figure 3: Control block diagram depicting the feedback control scheme incorporated into the LabView program, permitting both SISO and MIMO modes of operation. Key: L = Level, T = Temperature; R = set point; M = manipulated variable; G_c = controller; D = decoupler; G_v = control valve; G = process interaction; H = sensor; C = controller response. Diagram is adapted from Smith and Corripio[9].



Height Controller

Ht. Setpoint
15
Ht. Kc
5
Ht. tI
15
Ht. tD
15

Temp. Controller

Temp. Setpoint
30
Temp. Kc
5
Temp. tI
15
Temp. tD
15

Process Interaction Decoupling

Temp. Decoupling
0
Height. Decoupling
0

Sensor Calibration

Temp. Slope
0
Temp Intercept
0
Ht. Slope
0
Ht. Intercept
0

Manual Control and System Bounds

Manual Temp Value
0
Manual Height Value
0
Max Temp. FCE Voltage
5
Min Temp. FCE Voltage
0
Max Ht. FCE Voltage Voltage
5
Min Ht. FCE Voltage
0

Figure 4: User interface screen, programmed in LabView.

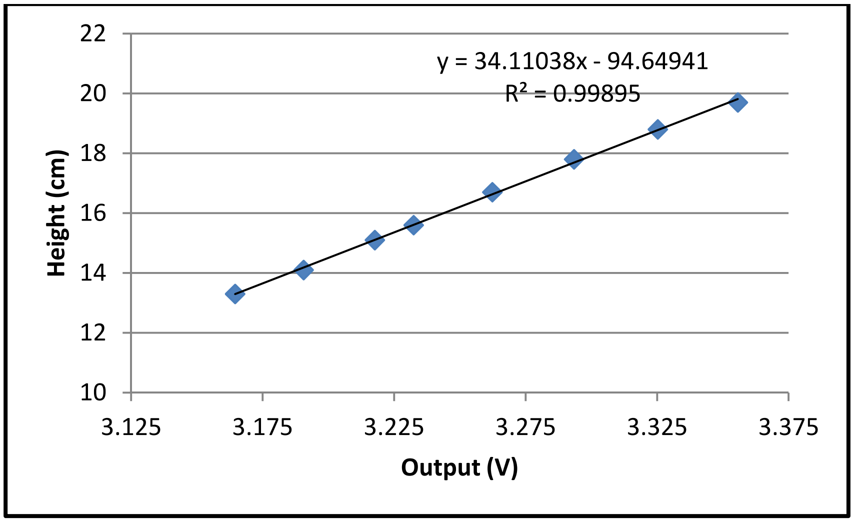


Figure 5: Typical pressure sensor calibration plot.

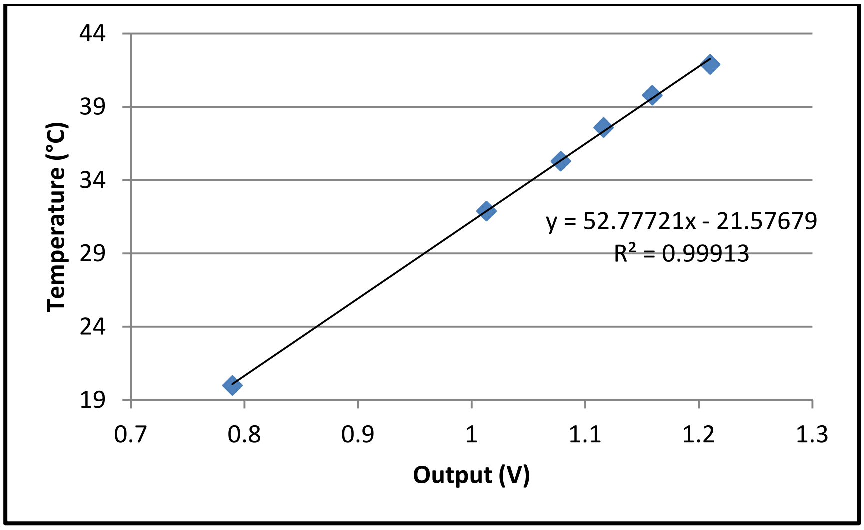


Figure 6: Typical temperature sensor calibration plot.

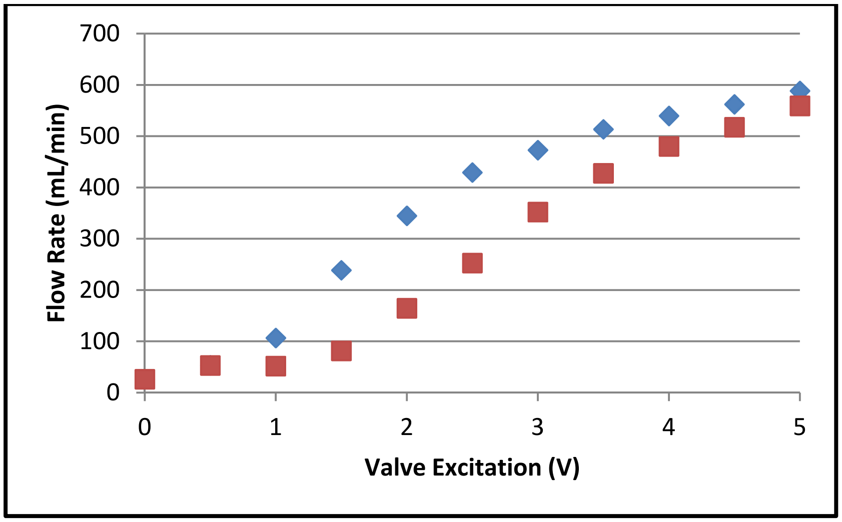


Figure 7: Temperature control valve (hot water) characterization. Squares represent increasing calibration, while diamonds represent decreasing calibration.

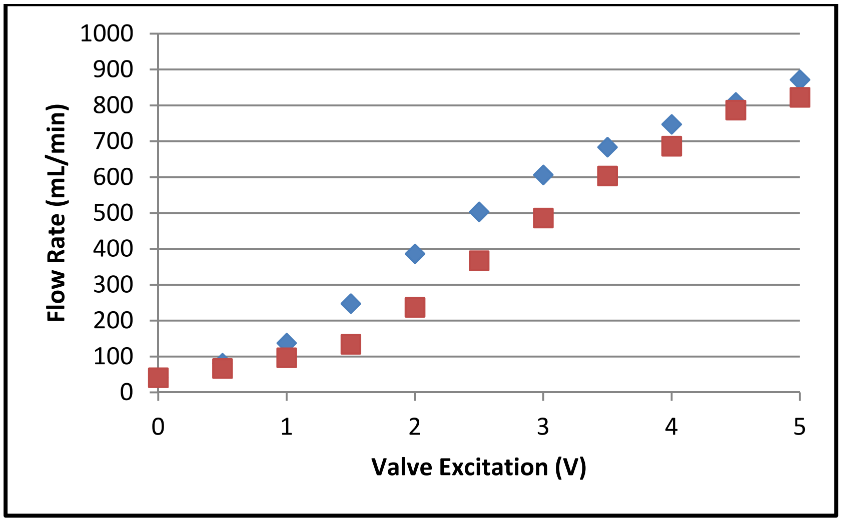


Figure 8: Level control valve (cold water) characterization. Squares represent increasing calibration, while diamonds represent decreasing calibration.

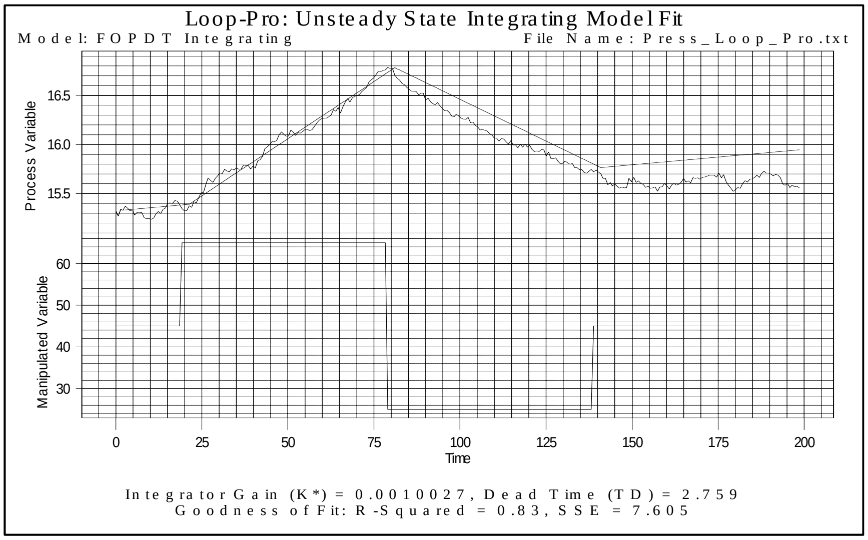


Figure 9: Typical open loop unsteady-state duplet test for height; first order plus dead time model used. Note that the response and model fit data appear in the upper portion of the plot, while the set point appears in the lower portion of the plot.

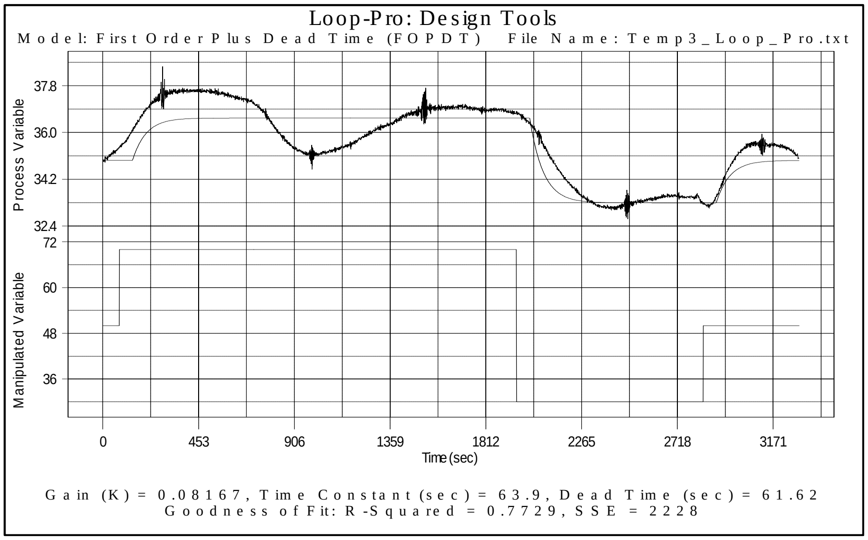


Figure 10: Typical open loop steady-state duplet test for temperature; first order plus dead time model used. Note that the response and model fit data appear in the upper portion of the plot, while the set point appears in the lower portion of the plot.

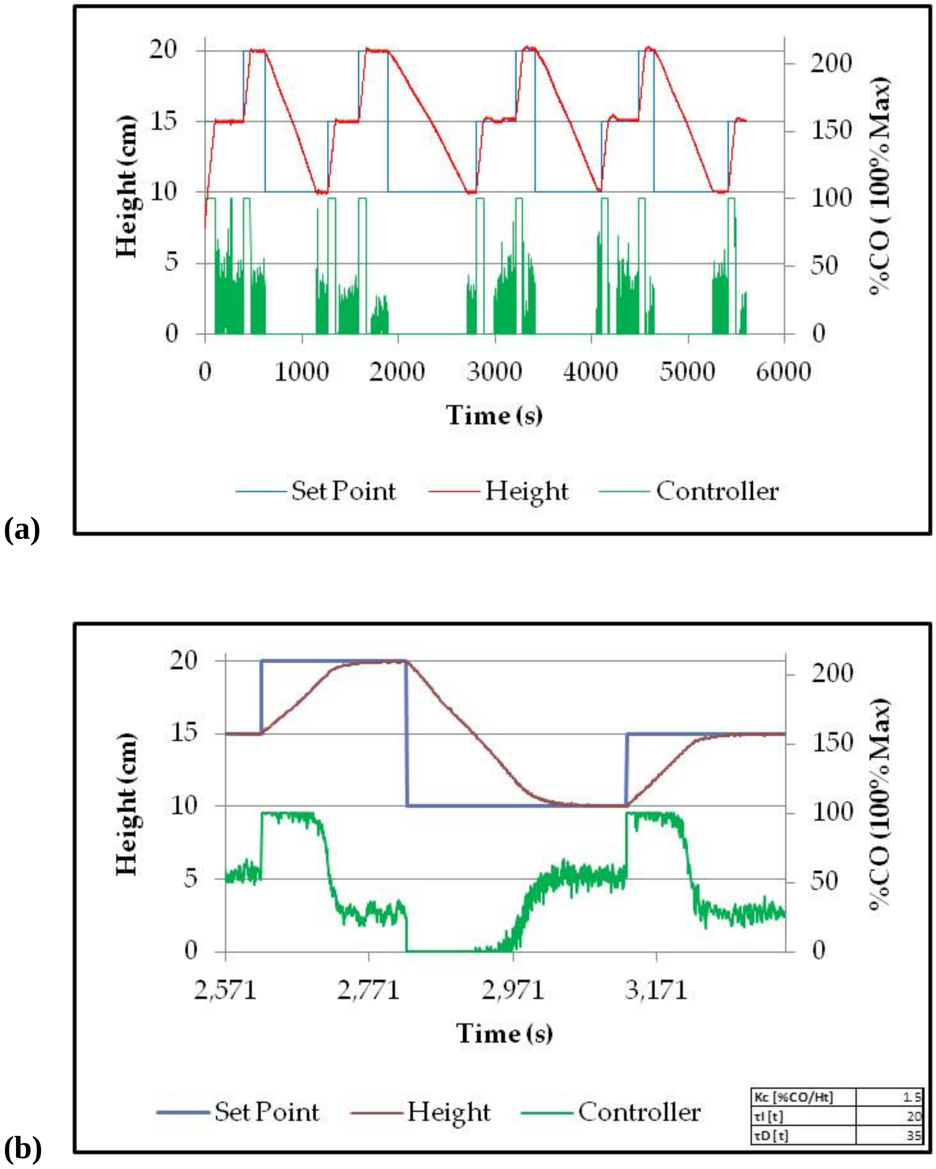
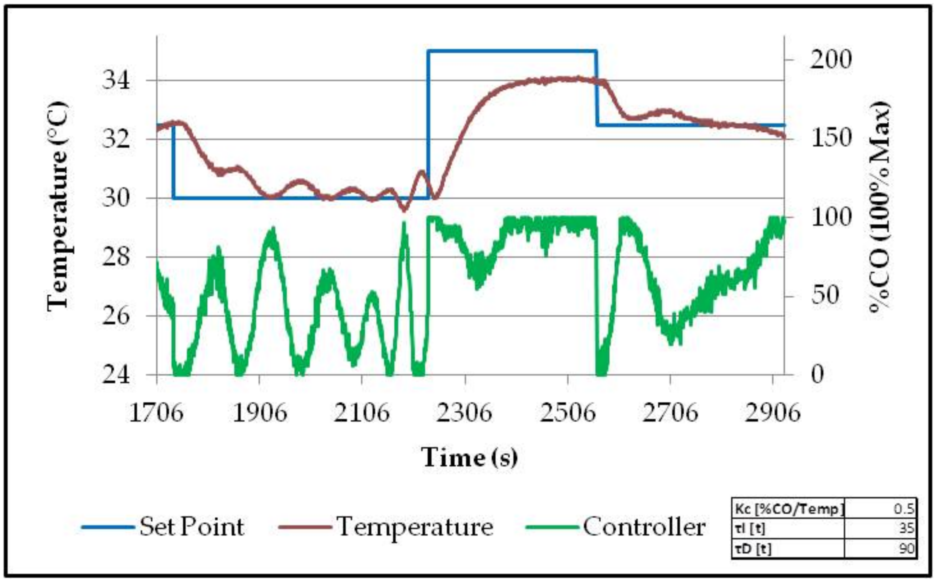
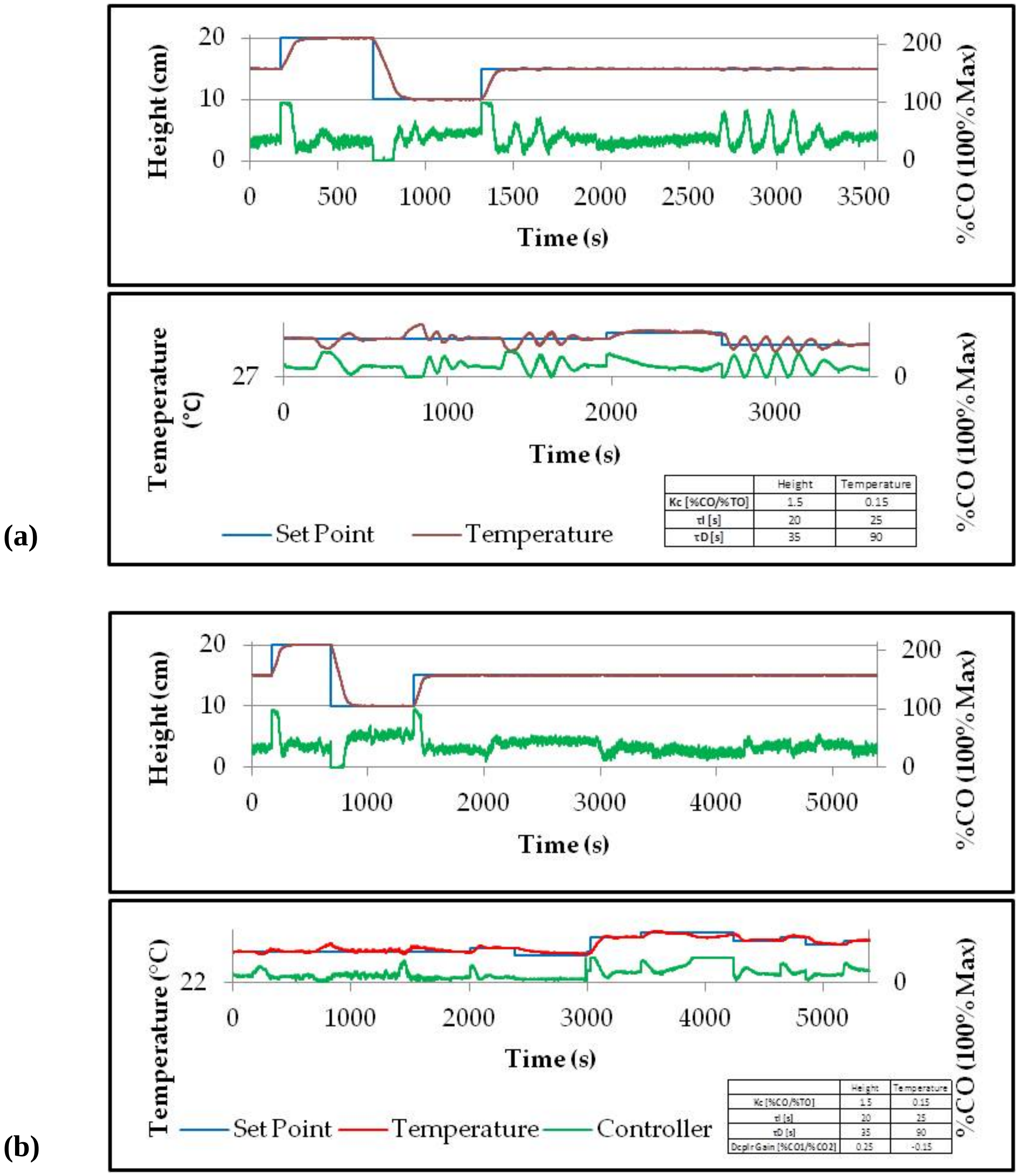


Figure 11: (a) Closed loop SISO height control testing using various PI and PID control modes; the order of the duplet tests is aggressive PI, conservative PI, aggressive PID, and conservative PID. (b) Closed loop SISO height control test using PID hand-tuning. Note that the Set Point and Height value appears in the upper portion of each plot (left-axis), and the Controller value appears in the lower portion of each plot (right-axis).



Kc [%CO/Temp]	0.5
τI [t]	35
τD [t]	90

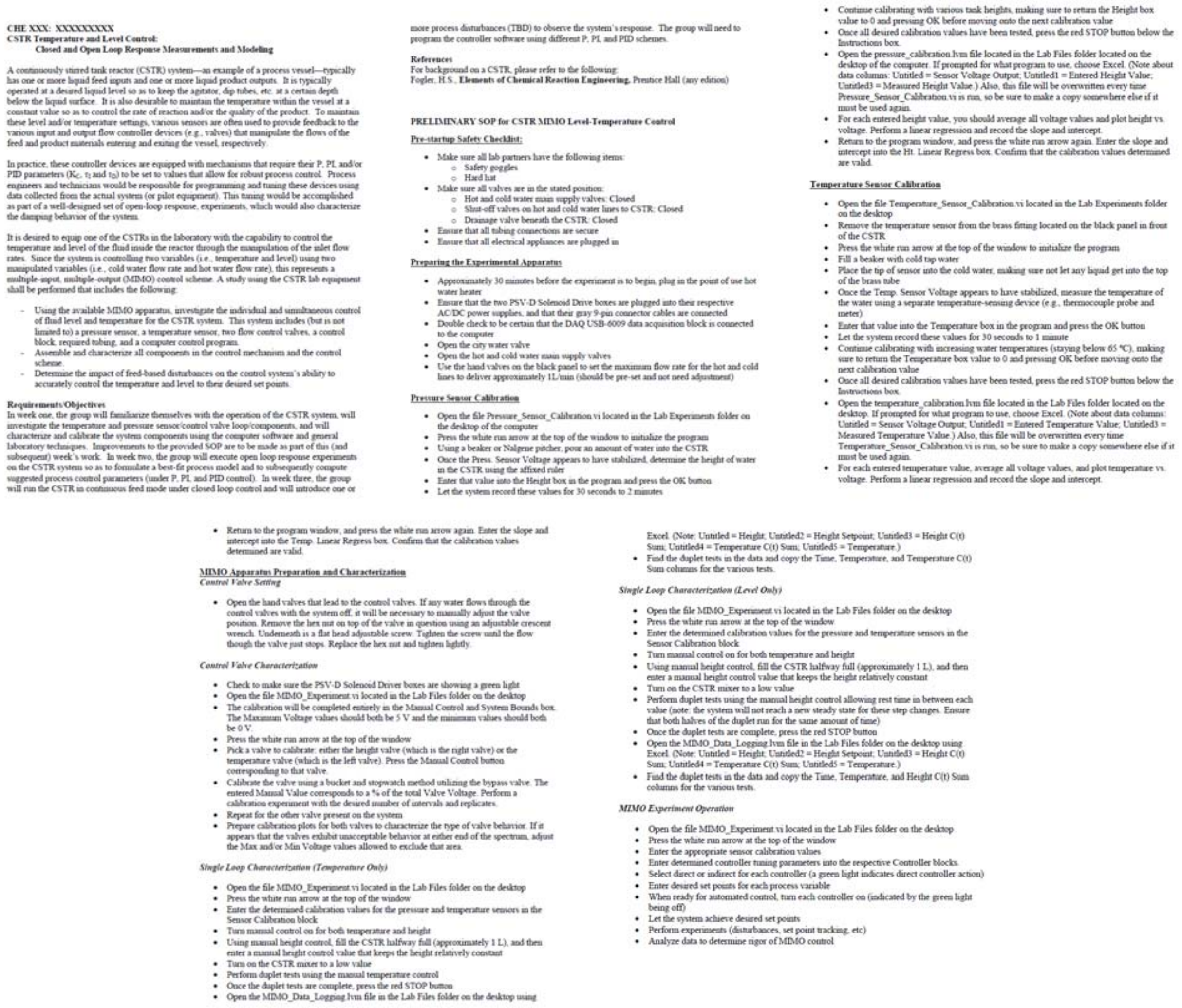
Figure 12: Closed loop SISO temperature test using PID hand-tuning. Note that the Set Point and Height value appears in the upper portion of each plot (left-axis), and the Controller value appears in the lower portion of each plot (right-axis).



	Height	Temperature
Kc [%CO/%TO]	1.5	0.15
τI [s]	20	25
τD [s]	35	90

	Height	Temperature
Kc [%CO/%TO]	1.5	0.15
τI [s]	20	25
τD [s]	35	90
Dcplr Gain [%CO1/%CO2]	0.25	-0.15

Figure 13: (a) Closed loop MIMO height and temperature control without decoupling using PID control mode; oscillations are readily observed. (b) Closed loop MIMO height and temperature control with decoupling using PID control mode; oscillations are suppressed. Note that the Set Point and Height value appears in the upper portion of each plot (left-axis), and the Controller value appears in the lower portion of each plot (right-axis).



CHE XXX: XXXXXXXXXX
CSTR Temperature and Level Control:
Closed and Open Loop Response Measurements and Modeling

A continuously stirred tank reactor (CSTR) system—an example of a process vessel—typically has one or more liquid feed inputs and one or more liquid product outputs. It is typically operated at a desired liquid level so as to keep the agitator, dip tubes, etc. at a certain depth below the liquid surface. It is also desirable to maintain the temperature within the vessel at a constant value so as to control the rate of reaction and/or the quality of the product. To maintain these level and/or temperature settings, various sensors are often used to provide feedback to the various input and output flow controller devices (e.g., valves) that manipulate the flows of the feed and product materials entering and exiting the vessel, respectively.

In practice, these controller devices are equipped with mechanisms that require their P, PI, and/or PID parameters (K_C, τ_I and τ_D) to be set to values that allow for robust process control. Process engineers and technicians would be responsible for programming and tuning these devices using data collected from the actual system (or pilot equipment). This tuning would be accomplished as part of a well-designed set of open-loop response, experiments, which would also characterize the damping behavior of the system.

It is desired to equip one of the CSTRs in the laboratory with the capability to control the temperature and level of the fluid inside the reactor through the manipulation of the inlet flow rates. Since the system is controlling two variables (i.e., temperature and level) using two manipulated variables (i.e., cold water flow rate and hot water flow rate), this represents a multiple-input, multiple-output (MIMO) control scheme. A study using the CSTR lab equipment shall be performed that includes the following:

- Using the available MIMO apparatus, investigate the individual and simultaneous control of fluid level and temperature for the CSTR system. This system includes (but is not limited to) a pressure sensor, a temperature sensor, two flow control valves, a control block, required tubing, and a computer control program.
- Assemble and characterize all components in the control mechanism and the control scheme.
- Determine the impact of feed-based disturbances on the control system's ability to accurately control the temperature and level to their desired set points.

Requirements/Objectives
In week one, the group will familiarize themselves with the operation of the CSTR system, will investigate the temperature and pressure sensor/control valve loop/components, and will characterize and calibrate the system components using the computer software and general laboratory techniques. Improvements to the provided SOP are to be made as part of this (and subsequent) week's work. In week two, the group will execute open loop response experiments on the CSTR system so as to formulate a best-fit process model and to subsequently compute suggested process control parameters (under P, PI, and PID control). In week three, the group will run the CSTR in continuous feed mode under closed loop control and will introduce one or more process disturbances (TBD) to observe the system's response. The group will need to program the controller software using different P, PI, and PID schemes.

References
For background on a CSTR, please refer to the following:
Fogler, H.S., **Elements of Chemical Reaction Engineering**, Prentice Hall (any edition)

PRELIMINARY SOP for CSTR MIMO Level-Temperature Control

Pre-startup Safety Checklist:

- Make sure all lab partners have the following items:
  - Safety goggles
  - Hard hat
- Make sure all valves are in the stated position:
  - Hot and cold water main supply valves: Closed
  - Shut-off valves on hot and cold water lines to CSTR: Closed
  - Drainage valve beneath the CSTR: Closed
- Ensure that all tubing connections are secure
- Ensure that all electrical appliances are plugged in

Preparing the Experimental Apparatus

- Approximately 30 minutes before the experiment is to begin, plug in the point of use hot water heater
- Ensure that the two PSV-D Solenoid Drive boxes are plugged into their respective AC/DC power supplies, and that their gray 9-pin connector cables are connected
- Double check to be certain that the DAQ USB-6009 data acquisition block is connected to the computer
- Open the city water valve
- Open the hot and cold water main supply valves
- Use the hand valves on the black panel to set the maximum flow rate for the hot and cold lines to deliver approximately 1L/min (should be pre-set and not need adjustment)

Pressure Sensor Calibration

- Open the file Pressure_Sensor_Calibration.vi located in the Lab Experiments folder on the desktop of the computer
- Press the white run arrow at the top of the window to initialize the program
- Using a beaker or Nalgene pitcher, pour an amount of water into the CSTR
- Once the Press. Sensor Voltage appears to have stabilized, determine the height of water in the CSTR using the affixed ruler
- Enter that value into the Height box in the program and press the OK button
- Let the system record these values for 30 seconds to 2 minutes
- Continue calibrating with various tank heights, making sure to return the Height box value to 0 and pressing OK before moving onto the next calibration value
- Once all desired calibration values have been tested, press the red STOP button below the Instructions box.
- Open the pressure_calibration.lvm file located in the Lab Files folder located on the desktop of the computer. If prompted for what program to use, choose Excel. (Note about data columns: Untitled = Sensor Voltage Output; Untitled1 = Entered Height Value; Untitled3 = Measured Height Value.) Also, this file will be overwritten every time Pressure_Sensor_Calibration.vi is run, so be sure to make a copy somewhere else if it must be used again.
- For each entered height value, you should average all voltage values and plot height vs. voltage. Perform a linear regression and record the slope and intercept.
- Return to the program window, and press the white run arrow again. Enter the slope and intercept into the Ht. Linear Regress box. Confirm that the calibration values determined are valid.

Temperature Sensor Calibration

- Open the file Temperature_Sensor_Calibration.vi located in the Lab Experiments folder on the desktop
- Remove the temperature sensor from the brass fitting located on the black panel in front of the CSTR
- Press the white run arrow at the top of the window to initialize the program
- Fill a beaker with cold tap water
- Place the tip of sensor into the cold water, making sure not let any liquid get into the top of the brass tube
- Once the Temp. Sensor Voltage appears to have stabilized, measure the temperature of the water using a separate temperature-sensing device (e.g., thermocouple probe and meter)
- Enter that value into the Temperature box in the program and press the OK button
- Let the system record these values for 30 seconds to 1 minute
- Continue calibrating with increasing water temperatures (staying below 65 °C), making sure to return the Temperature box value to 0 and pressing OK before moving onto the next calibration value
- Once all desired calibration values have been tested, press the red STOP button below the Instructions box.
- Open the temperature_calibration.lvm file located in the Lab Files folder located on the desktop. If prompted for what program to use, choose Excel. (Note about data columns: Untitled = Sensor Voltage Output; Untitled1 = Entered Temperature Value; Untitled3 = Measured Temperature Value.) Also, this file will be overwritten every time Temperature_Sensor_Calibration.vi is run, so be sure to make a copy somewhere else if it must be used again.
- For each entered temperature value, average all voltage values, and plot temperature vs. voltage. Perform a linear regression and record the slope and intercept.
- Return to the program window, and press the white run arrow again. Enter the slope and intercept into the Temp. Linear Regress box. Confirm that the calibration values determined are valid.

MIMO Apparatus Preparation and Characterization
Control Valve Setting

- Open the hand valves that lead to the control valves. If any water flows through the control valves with the system off, it will be necessary to manually adjust the valve position. Remove the hex nut on top of the valve in question using an adjustable crescent wrench. Underneath is a flat head adjustable screw. Tighten the screw until the flow though the valve just stops. Replace the hex nut and tighten lightly.

Control Valve Characterization

- Check to make sure the PSV-D Solenoid Driver boxes are showing a green light
- Open the file MIMO_Experiment.vi located in the Lab Files folder on the desktop
- The calibration will be completed entirely in the Manual Control and System Bounds box. The Maximum Voltage values should both be 5 V and the minimum values should both be 0 V.
- Press the white run arrow at the top of the window
- Pick a valve to calibrate: either the height valve (which is the right valve) or the temperature valve (which is the left valve). Press the Manual Control button corresponding to that valve.
- Calibrate the valve using a bucket and stopwatch method utilizing the bypass valve. The entered Manual Value corresponds to a % of the total Valve Voltage. Perform a calibration experiment with the desired number of intervals and replicates.
- Repeat for the other valve present on the system
- Prepare calibration plots for both valves to characterize the type of valve behavior. If it appears that the valves exhibit unacceptable behavior at either end of the spectrum, adjust the Max and/or Min Voltage values allowed to exclude that area.

Single Loop Characterization (Temperature Only)

- Open the file MIMO_Experiment.vi located in the Lab Files folder on the desktop
- Press the white run arrow at the top of the window
- Enter the determined calibration values for the pressure and temperature sensors in the Sensor Calibration block
- Turn manual control on for both temperature and height
- Using manual height control, fill the CSTR halfway full (approximately 1 L), and then enter a manual height control value that keeps the height relatively constant
- Turn on the CSTR mixer to a low value
- Perform duplet tests using the manual temperature control
- Once the duplet tests are complete, press the red STOP button
- Open the MIMO_Data_Logging.lvm file in the Lab Files folder on the desktop using Excel. (Note: Untitled = Height; Untitled2 = Height Setpoint; Untitled3 = Height C(t) Sum; Untitled4 = Temperature C(t) Sum; Untitled5 = Temperature.)
- Find the duplet tests in the data and copy the Time, Temperature, and Temperature C(t) Sum columns for the various tests.

Single Loop Characterization (Level Only)

- Open the file MIMO_Experiment.vi located in the Lab Files folder on the desktop
- Press the white run arrow at the top of the window
- Enter the determined calibration values for the pressure and temperature sensors in the Sensor Calibration block
- Turn manual control on for both temperature and height
- Using manual height control, fill the CSTR halfway full (approximately 1 L), and then enter a manual height control value that keeps the height relatively constant
- Turn on the CSTR mixer to a low value
- Perform duplet tests using the manual height control allowing rest time in between each value (note: the system will not reach a new steady state for these step changes. Ensure that both halves of the duplet run for the same amount of time)
- Once the duplet tests are complete, press the red STOP button
- Open the MIMO_Data_Logging.lvm file in the Lab Files folder on the desktop using Excel. (Note: Untitled = Height; Untitled2 = Height Setpoint; Untitled3 = Height C(t) Sum; Untitled4 = Temperature C(t) Sum; Untitled5 = Temperature.)
- Find the duplet tests in the data and copy the Time, Temperature, and Height C(t) Sum columns for the various tests.

MIMO Experiment Operation

- Open the file MIMO_Experiment.vi located in the Lab Files folder on the desktop
- Press the white run arrow at the top of the window
- Enter the appropriate sensor calibration values
- Enter determined controller tuning parameters into the respective Controller blocks.
- Select direct or indirect for each controller (a green light indicates direct controller action)
- Enter desired set points for each process variable
- When ready for automated control, turn each controller on (indicated by the green light being off)
- Let the system achieve desired set points
- Perform experiments (disturbances, set point tracking, etc)
- Analyze data to determine rigor of MIMO control

Figure 14: A sample laboratory handout to be provided to students working on the MIMO system during the process control block of the course.

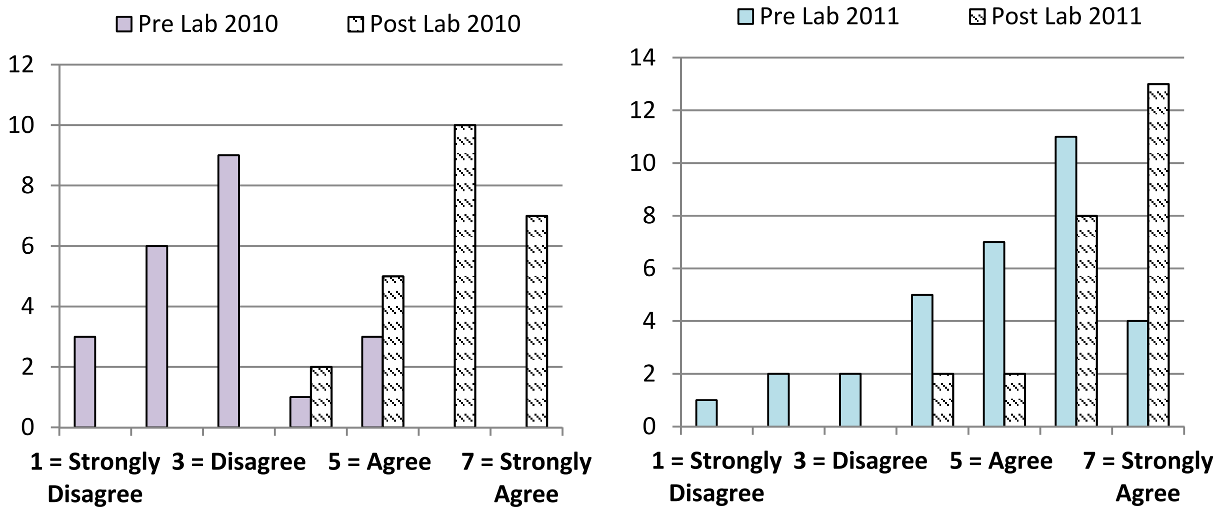


Figure 15: Student Responses: "I am comfortable, understand and am able to design a simple feedback control system.”

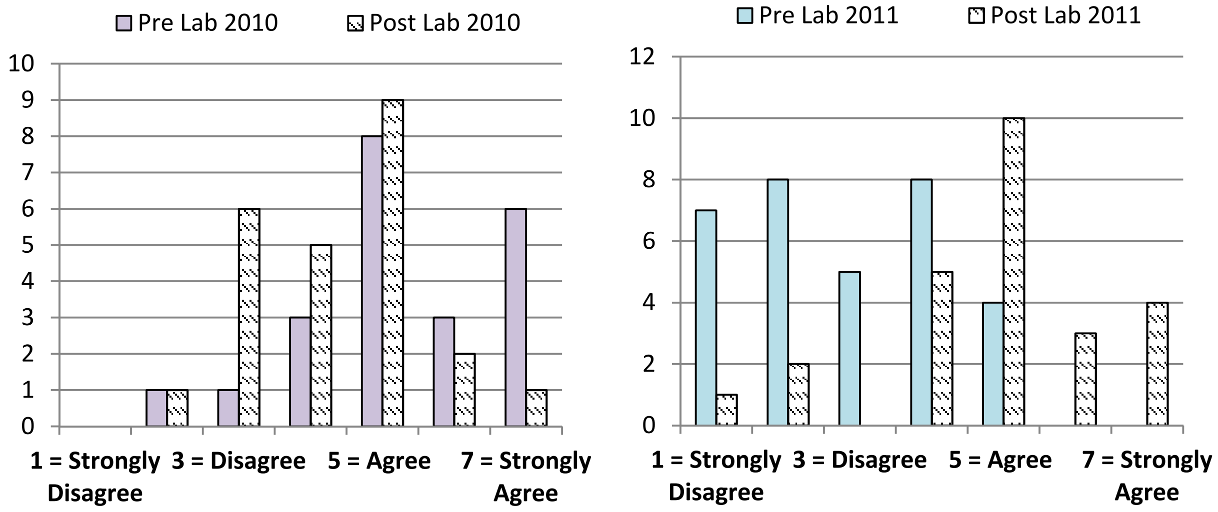


Figure 16: Student Responses: “I am comfortable, understand and am able to design a simple (2 controller) MIMO (multiple input, multiple output) control system.”