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# Process Control Final Projects Inspired By Real Unit Operations Laboratory Modules


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# Process Control Final Projects Inspired By Real Unit Operations Laboratory Modules

**Abstract:**
Northeastern University specializes in opportunities for experiential learning, both through a co-op program as well as through direct coursework. The style of experiential and inquiry-based learning have been particularly reinforced through two intermediate-level Unit Operations courses, in which students have been tasked with developing experiments, selecting measurement parameters, and designing analysis. Students' previous experiences have been utilized in the development of final projects for their Process Control course.

In order to provide a culmination of the entire Process Control course and to challenge students to design a complete controls system relying on some combination of feedback, feedforward, and/or cascade control, a final project was designed to connect the concept of Control to a real-world system. Student teams were given the option of selecting from six different modules they had observed and analyzed in a previous laboratory course, including distillation, liquid-liquid extraction, heat exchangers, reverse osmosis, and water remediation. These modules had required complete manual control, and had a range of parameters that could be adjusted during operation. For their final project, students were challenged to design a complete control system that required them to select control variables, handle multiple disturbances, and operate within acceptable limits. Students derived overall balances, designed block diagrams, calculated tuning parameters both by hand and through simulation software, and analyzed their proposed control system for stability and economic viability.

The project culminated in both a technical written report and a presentation. Across three semesters and multiple sections, every team has designed a different system resulting in different quality of control. Requiring the students to defend their design decisions and forcing them to account for a range of disturbances has helped students develop a much more complete grasp of Process Control and given them greater confidence exiting the course.

This presentation will provide examples of the modules and assessment of the project.

**Background:**
The development of interactive modules and course projects for Process Control has been a component of chemical engineering instruction for many years, with a range of different formats being presented. These methods include Lego kits to control liquid level in a tank by modifying fluid flow,[1,2] and Arduino kits for a range of applications,[3] both for smaller, in-class approaches. On a larger scale, other techniques have focused on temperature control in a pilot polymerization reactor,[4] and through direct integration into Unit Operations laboratory components.[5-8] Similarly, there has been a desire for Process Control projects that involve a more open-ended focus, potentially providing students the opportunity to design an original control system and evaluate its performance.[9] In this paper, we describe efforts to connect students' familiarity with hands-on laboratory experiments with more theoretical open-ended control design.

In order to develop an approach at Northeastern University that would allow students to design a control system and evaluate its performance, a component of the students' Capstone design project in their Capstone course was originally required to contain a process control system. Students were taking both Capstone and Process Control in their final semester of their senior year, so the concepts lined up well for students to be able to apply their understanding from one course to another. This plan became complicated by several factors, both structural and conceptual. First, an increase in enrollment, including a number of students with advanced credit, drove a need for Process Control to be taught in all semesters for students in both their junior and senior years. The structural change to the academic plan made the crossover between Process Control and Capstone no longer a viable option. This was compounded by several Capstone projects being developed along more theoretical approaches for some systems that could not incorporate a proper control system. As such, a different approach within the Process Control course by itself was necessary; design-related process control that had been associated with the course for many years through association with other courses now instead needed to be established solely within the Process Control course itself.

Despite some initial desire to connect Process Control with the equipment in the Unit Operations laboratory, the expanding enrollment quickly made that a challenge in itself, with the graduating class growing from around 50 to nearly 150 within just a few years. Space limitations and access to the equipment was simply not possible while ensuring the upkeep of the equipment for lab course experimentation. Similarly, developing hands-on components was a challenge, given the unpredictable growth and what would be the consistent need to develop more devices to accommodate all the students. However, all students had some familiarity with the equipment in the lab courses, which provided a possible solution.

Given their experimentation and understanding of how the devices worked, students could potentially be challenged to design a control system that could theoretically automate the operation of the large-scale equipment they had previously used. Students already had access to experimental data, process flow diagrams, and equipment measurements; they could now propose a theoretical redesign of the system with alarms, controller, and new sensors and valves as necessary, and use this theoretical design to simulate and analyze the new system's performance. Thus, the design would focus a practical approach to process control concepts, reinforce skills and understanding gained from unit operations experimentation, and provide an opportunity for an open-ended design-based project that would be effective within the Process Control course by itself.

**The Project**

Near the beginning of each semester, students were provided with a list of six different Unit Operations Laboratory systems, most of which were focused on heat transfer or separations experiments. A simple diagrammed depiction of the system was provided, with certain valves noted on the piping and more superfluous components neglected. Any systems which operated on a batch-design in actuality were instead presented as continuous for the purposes of the project. Included among these systems were a distillation column, a liquid-liquid extraction column, a reverse osmosis membrane, a heat exchanger with hot water tank, and a set of heat exchangers in series. An additional system based on a water remediation project[10] particular to the laboratory course was also included, although this was known to be a challenging system to work with and was already the result of open-ended design. Diagrams of these six systems are presented in Figure 1.

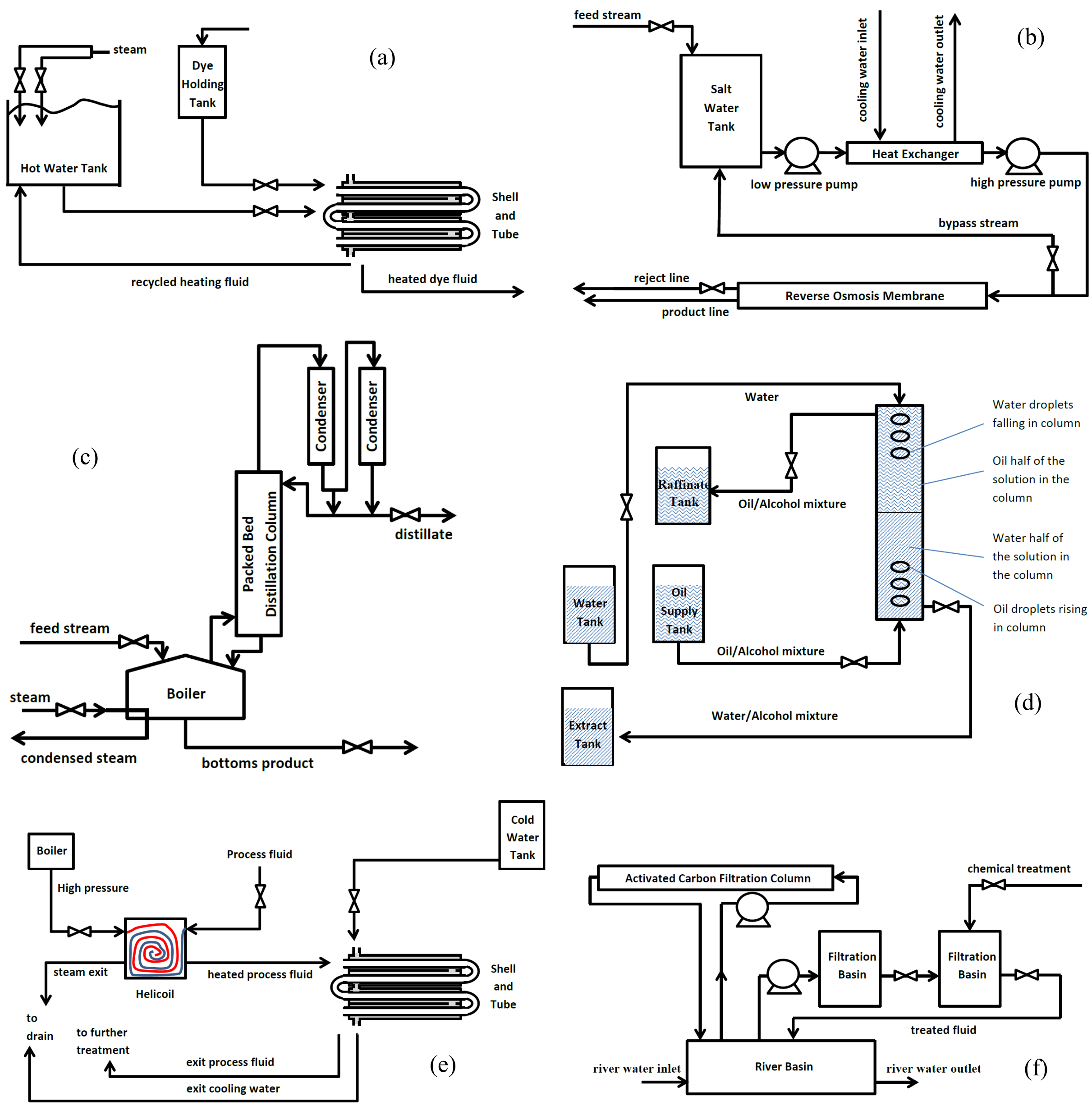



**Figure 1a-f.** Diagrams of the Unit Operations modules that students were provided to design control systems for, including (a) a heat exchanger, (b) a reverse osmosis membrane, (c) distillation column, (d) liquid-liquid extraction, (e) two heat exchangers in series, and (f) water remediation.

After the six systems were presented, students were required to form a group of four to five students and select one of the six UO Laboratory systems to design a control system for. For each system, a description was provided recognizing certain parameters that were fluctuating and variables that needed to be controlled and regulated. For example, the reverse osmosis system required a minimal salt concentration in the final output flow, a monitored pressure in the flow entering the membrane to prevent damage to the system, monitored temperature in the flow to prevent overheating in any recirculated fluid, Students were informed that their control system could apply any combination of feedback and/or feedforward control, including variations on cascade control.

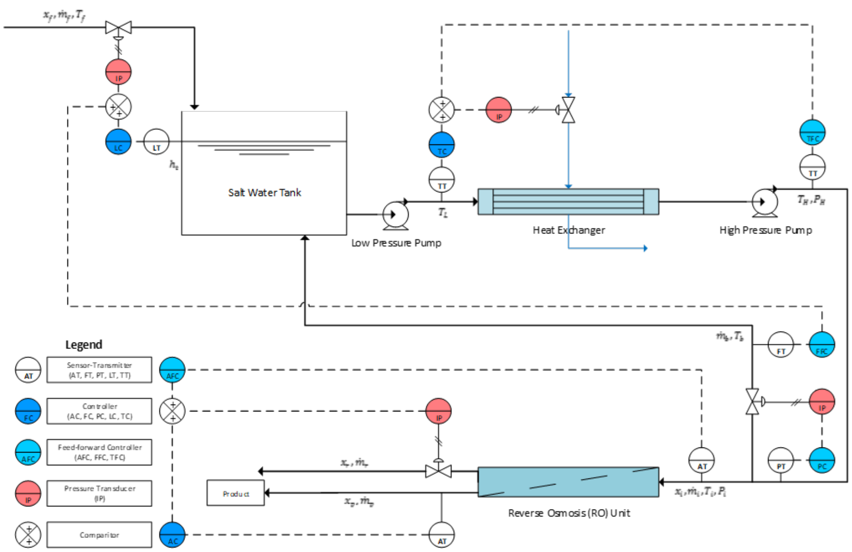
With the priority on this being an open-ended project, students were allowed to consider for themselves which parameters could be held constant or have negligible deviation. These decisions had to be justified in the explanation of their control system. In the diagrams themselves, some valves and pumps were indicated, but students were encouraged to consider additional valves or pumps as necessary in their design.

With the general system diagrams and case scenarios provided, students were then tasked over the course of the semester to develop a control system and simulate its performance with several intermediate steps. Several periods of class (at least three 65-minute in-class periods with instructor and TA(s) present) throughout the semester were solely devoted to allowing groups to plan and work on their project with the instructor's immediate feedback and help, enabling students to produce:

- Derivation of any mass and energy balances. These calculations generally required linearization to prepare any necessary transfer functions relating input and output variables, and so this was required as a problem set assignment approximately one-third of the way into the semester. The derivation allowed students to identify all potential disturbances on their system's operation in addition to the primary means of controlling and moderating variables of concern. Identification of time constants, time delays, or residence time in their models also helped students determine where their control design might result in dynamic errors and so might need to be specifically addressed within their control system. Any necessary steady-state values or other constants were provided based on student operation of the equipment in previous courses.

- General design of the control system. Groups were encouraged to consider any combination of feedback, feedforward, and/or cascade control for their system. This design was frequently modified as work on the project continued, or based on analysis of their simulating the system's performance. However, encouraging early design helped groups to connect and apply their derivations to the theoretical control design. Block diagrams were also required to ensure student understood how all variables from the balance derivations were incorporated

  An example of one group's proposed control system is presented in Figure 2, in this case for the reverse osmosis process.




| Unit | Variable Type | Variable |
|---|---|---|
| *Unit 1* Composition Control | Controlled | $x_p$ |
| | Manipulated | $\dot{m}_r$ |
| | Load | $x_i$ |
| *Unit 2* Temperature Control | Controlled | $T_i$ |
| | Manipulated | $\dot{m}_c$ |
| | Load | $T_L$ (affected by $\dot{m}_b$) |
| *Unit 3* Pressure Control | Controlled | $P_i$ |
| | Manipulated | $\dot{m}_b$ |
| | Load | $P_H$ |
| *Unit 3* Level Control | Controlled | $h_t$ |
| | Manipulated | $\dot{m}_f$ |
| | Load | $\dot{m}_b$ |

**Figure 2.** Example control system design produced by a group for the reverse osmosis membrane system, incorporating both feedback and feedforward control for different concentration, temperature, and level measurements.

- Identification of necessary sensors and equipment components. Groups were required to research both manufacturer listings and research papers on control systems to determine the necessary auxiliary equipment that their theoretical control system would need. This included finding sensors with appropriate span and reasonable dynamics; transmitters or transducers as necessary with input and output signals in acceptable ranges; and control valves permitting flow in the necessary range. Dynamic values were sometimes difficult for groups to find, in which case the instructors would point students towards published research papers with gains and dynamic values listed.

- Implementation of the control system into Simulink. In order to simulate the designed control system's performance, groups were required to develop their control system in Simulink. This MATLAB component can potentially be coded but can also be implemented through simple drag-and-drop techniques, allowing students of any computing ability to be able to analyze their control system. All input variables were required to at least have step-input calculations for determining the shape and stability of the control system's response in any variables of concern. This tool would then allow for a simulated analysis of the theoretical control system.

- Determination of PID tuning parameters. Groups were instructed during the semester on both Routh stability criterion approach and direct substitution methods for determining values for $K_c$, $\tau_I$, and $\tau_D$ with different models for PID controllers. In addition to these techniques, Simulink also provided a means of auto-tuning the implemented controller; depending on the rest of the design, these auto-tuned control parameters could potentially be dramatically impractical, in which case redesign or limitation of the auto-tuning was suggested. Students were allowed to use any method for determining their necessary tuning parameters.

- Safety analysis. Groups were expected to produce a layer-of-protection analysis (LOPA) after being provided with instruction on alarms, safety interlock systems, and broader process safety concerns. Their theoretical control system was required to incorporate alarms as appropriate, along with safety explanations for the selection of control valves with either fail-close or fail-open operation, but the emphasis was placed on the LOPA to consider the areas of greatest safety concern and develop a plan beyond plant operation to community response.

- Analysis through simulation. With the theoretical system in Simulink, groups needed to run the operation after step changes to all setpoints and disturbances. Analysis of the system's performance in terms of offset, response time, and stability could be conducted through plots of the system response, as well as consideration of any safety hazards that oscillations or the time of response might represent. Example of the simulated response as developed by one student group is presented in Figure 3.

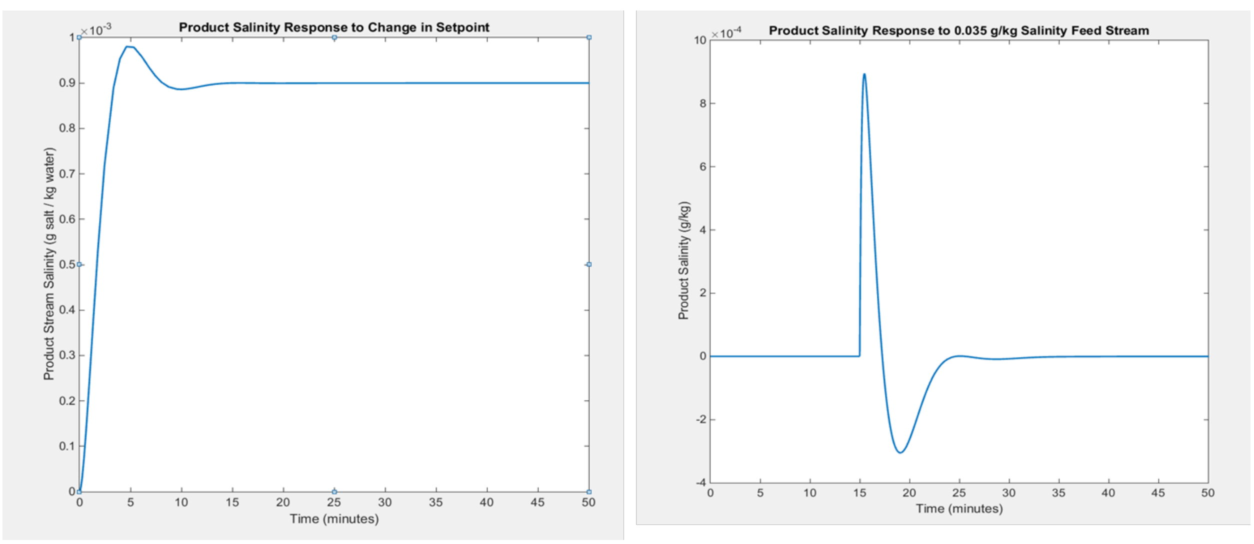



**Figure 3.** Example of student-produced simulated control response from Simulink.

At the end of the semester, the main deliverables for the project from each group were to conduct a ten-minute presentation to the instructor on the proposed control system, safety, and the simulation analysis, as well as a report providing explanations for all the intermediate steps previously listed. After the presentation, the instructor would ask a few short questions depending on any concerns with the designed system and its performance, before concluding by asking students about any major practical takeaways that the project had provided them that might influence their engineering and professional approaches in their careers after graduation.

Throughout each iteration of the project, the open-ended nature was apparent based on the range of choices groups could make or apply for their systems:

- Which parameters to control
- Which parameters are left as uncontrolled and measured/unmeasured disturbances
- How and which measurements are taken
- What valves/transducers/sensors/transmitters used
- If P-only, PI, or PID controllers are selected
- Tuning parameter selections and modifications, depending on degree of oscillation and overall response time desired

These variations allowed for significant student control over the direction of their developed control system, as well as variations on the success of their system.

The two main deliverables for the project were the paper describing these elements of the design as listed, with special emphasis on the LOPA, and a 10-15 minute presentation directly to the instructor. The grading weight of the elements fluctuated over the semesters as adjustments were made to the course, but the project as a whole generally amounted to approximately 25 percent of each student's final course grade, of which 10 percent was dependent on the LOPA, 25 percent on the presentation, and the remainder on the paper.

**Results**

In the fifteen semesters since this project was first implemented in the spring of 2015, groups have produced a wide range of proposed systems, with nearly every control design differing in implementation despite having only six different systems that students are designing for. Of the 165 student groups, the selection has been well dispersed among the options except for the river project, which is particularly known among the students to be a challenging experiment and difficult to control, and thus less likely to be an option they would want to design a control system for. The one exception was a single group proposing to do a project connected with their Capstone project; this has been an option open to students, but rarely selected given group membership and differences in courses that students are currently taking.

**Table 1.** Groups over the past 15 semesters that have selected the different respective project types.

| Project Type | Number of Groups |
|---|---|
| Distillation | 32 |
| Heat Skid | 42 |
| Helicoil | 20 |
| LLE | 20 |
| River | 2 |
| RO | 48 |

Students in general have responded positively to the project each semester. Feedback has focused on the practical and applied aspect of the design, allowing students to move beyond the theoretical conceptual discussion, even if the proposed control system at the end is still a theoretical proposal. Having personal connection to the actual equipment from experimentation experiences in the lab courses helps to provide the 'real world' perspective:

- "The final project was a vital part of the class, allowing for a "real world" application of sorts. As with any complicated system, there are a lot of variables involved. . ."
- "The project is a great way to bring everything together . . . it is extremely useful to have a project because it pushes students to think more critically and gives them a way to apply the concepts of the course to real world applications. It puts the material in perspective and makes students understand why process controls are useful what the point is of learning about them."
- "The final project was a great comprehensive learning tool to fully wrap up the course."
- "Course project was challenging but I learned a lot from it."

Students have expressed some concerns about the open-ended nature of the project at times.

- "The course project being so open ended was both a blessing and a curse. I wish the problem statements for the project were a little more focused and detailed with regard to steady state values and specifications."

Some students did express their desire for a hand-on component as opposed to designing a theoretical system.

- "It would be nice if there was a control system in the UO lab to learn from."

The majority of complaints have been with respect to the implementation of the project into the course timeline, as opposed to the value of the project itself. Despite holding multiple project days each semester, students frequently reflect on the stress of having too much of the project to finish at the end of the semester. Of particular note is the degree to which students are uncomfortable with the use of Simulink, and the amount of instruction they receive on it; students expect at least one class period of instruction and frequently have requested more, despite Simulink being just the simulation tool used to analyze the control system.

In terms of assessment of student performance and understanding, the project provided a culmination of the course concepts and connected to a majority of the course outcomes, including linearization of balances, system design, feedback control, PID tuning, and safety analysis. Because of the feedback provided throughout the semester, groups routinely perform well on all aspects of the project, having had opportunities to correct errors, receive guidance in their calculations and analysis, and have sufficient time to complete their technical writing. In Spring 2021 with 19 groups, the average LOPA grade was $91.4 \pm 4.7$, the average grade on the presentation was $93.4 \pm 2.3$, and the average grade on the report was $92.7 \pm 2.1$. Consideration of these grades in comparison to semesters before the project was instituted are difficult to evaluate, given the authors effectively instituted the project from the beginning of their instruction of the course, and had different conceptual emphasis throughout the course compared to previous instructors.

The project in particular has been useful in recognizing the gaps in student understanding specifically in terms of the individual concepts addressed through instruction and their ability to piece all the work together and apply the information. These gaps are identified during the in-class discussions and project work in conversations with the instructor, as students that may have performed well on exams in the course suddenly find the complexity of a practical control system or seeing the simulation result of their proposed design to be a challenge. For example, recognizing how many disturbance variables should be accounted for based on the energy balances conducted and implementing them into their block control diagram, especially when the student group proposes multiple control systems for the equipment, causes students to grasp how interconnected each control system is; correcting for a disturbance in one system may in itself induce a disturbance in a different control system. The awareness of this interconnectedness was often the most consistent comment that arose in discussions with students, and in addressing that gap, the project helped to better reinforce the students' understanding by forcing them to apply the concepts and theory on broader design.

## Conclusions

Process Control projects designed around the development of a theoretical control system have been shown to be useful assignments when hands-on modules are not available. Connecting the control systems to unit operations equipment or other experiments that students have had previous familiarity with can help to draw a deeper practical connection between the concepts address and their potential application. The projects give students an opportunity to connect classroom learning to an open system with real-world association, effectively summarizing the course while challenging the students through open-ended inquiry-based learning. Students have responded positively for the most part, with concerns primarily rooted in the timeline for the project and the degree to which it can be integrated into the course as opposed to being an additional assignment to be completed. Integration into in-person class time and assignments during the semester is thus vital to overcoming student resistance and apprehension.

While many other approaches to applied process control experiences can be developed, these projects provide one approach that can be readily adapted by other institutions with no cost or equipment necessary, and still allow for student understanding that can be assessed and mapped to a range of course outcomes.

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