A Temperature Control Project that Facilitates Learning of Difficult Concepts in Control Theory

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ABSTRACT

This paper presents a design project and its assessment in an undergraduate control theory course. In the project, students mathematically modeled the thermal dynamics of a glass incubator and its heat source. Based on these models, they designed a lag compensator to keep the incubator temperature in a safe range when the external temperature fluctuates. It is hypothesized that activities planned in this real-world project can facilitate the learning of difficult controller design via the frequency response method. Multiple facets of student learning were assessed, including (a) a two-level objective assessment based on students' written reports and (b) four-category student self-evaluation surveys. The former identifies how the project helps achieve ABET outcomes and how each of the four project activities support learning outcomes. Surveys assess students' factorial knowledge and their perception about the project. Assessment results demonstrate that this project-based-learning experience effectively aids students in grasping difficult frequency-domain concepts and design methods.

Key words: project-based learning, simulation, student assessment rubrics.

INTRODUCTION

In a typical undergraduate Controls course, controller (or compensator) design with two general methods is usually introduced: design via root locus and design via frequency response [1]. In the former approach, the location of the system's dominating closed-loop poles on the complex plane is directly related to the system performance: the real part determines the settling time Ts, the imaginary part determines the peak time Tp, and a radial line with an angle determines the damping coefficient, in turn, the system percent overshoot (P.O.). These direct connections provide guidelines for designing compensators via the root locus method. Improving specific performance

Figure. 1. Intuitive connection between locations of system closed-loop poles and system time-domain performance.
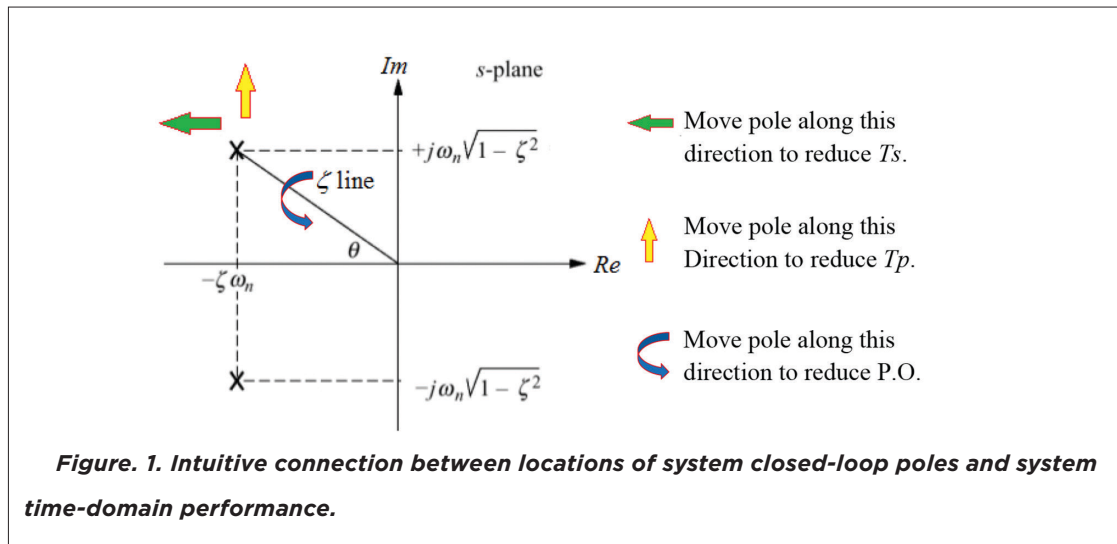
can be achieved by moving the closed-loop poles in their respective directions in the complex plane as shown in Figure 1. Students, after a regular lecture, can often make the connection between the desired performance improvement and the direction to move the dominating closed-loop poles, therefore formulating necessary compensators.

Concepts and relationships in the frequency domain, however, are not as straightforward. Magnitude response and phase response determine how a system responds as the signal frequency varies. Their connection to the time domain performance parameters is very intricate. For example, the relationship between the phase margin and damping ratio is denoted by:

$$\Phi_m = \tan^{-1}\left(\frac{2\zeta}{\sqrt{-2\zeta^2 + \sqrt{1 + 4\zeta^4}}}\right) \tag{1}$$

Since the damping ratio ζ is related to P.O., the phase margin Φ_m is also connected to P.O. However, this strong nonlinear formula does not provide any intuitive insights between the two domains. Even worse, the connections between other frequency response characteristics (gain margin, bandwidth, etc.) and time-domain performance (Ts, Tp, etc.) are empirical (and often confusing) curves from which no intuitive insights can be perceived. Because of the ambiguous connection between a system's frequency response characteristics and its time-domain performance parameters, control design via the frequency response method is usually considered more difficult than that of root locus. Few instructional strategies have been reported to mitigate learning obstacles existing in control system design via frequency response methods.

Project-Based-Learning, or PBL, has been broadly adopted by the engineering education community [2-8] as an effective instructional approach. Cohesive PBL pedagogy brings many advantages: it motivates students, offers student-centered learning [7], makes meaningful connections to the real world [8], and facilitates communication among students [9]. Specific to control theory teaching, PBL has been utilized to help students to learn about function blocks in a feedback control system [10-12] and to design advanced controllers [13-17]. Recognizing teaching/learning benefits through PBL, the author developed a MATLAB/SIMULINK control system design project to alleviate learning difficulties involved in frequency-domain controller design [18]. Specifically, PBL in this course is anticipated to improve learning the following:

- Determine a system's gain/phase margins and their corresponding frequencies from a Bode plot;
- Estimate a system's steady state error (SSE) via its frequency response (i.e., Bode plot);
- Estimate a system's percent overshoot (P.O.) via its frequency response;
- Determine the gain of the compensator via the frequency response method;
- Construct a lag compensator via the frequency response method to satisfy both SSE and P.O. requirements. This further includes determining the compensator break frequencies and its slope.

This paper, after briefly introducing the framework of the project, highlights several improvements from its first ASEE conference appearance [18] which reported the experience gained from the project when it was first offered. The improvements include a very intuitive day/night ambient temperature changing cycle case study and a better description of the compensator design procedure, without unnecessary repetition of what has been presented in [18]. More importantly, it recognizes the importance of objective assessment methods for instructional innovations like this. Attempting to meet these needs, the paper presents a multi-level, multi-facet assessment plan for this unique PBL experience and reports results and findings from this comprehensive assessment effort.

PROJECT DESIGN AND IMPLEMENTATION METHODOLOGY

The details of the project's methodology and implementation are omitted here as those have been disseminated at the 2015 American Society of Engineering Education conference [18]. Only the project framework and several improvements that were not discussed in [18] are introduced here to provide the necessary background to understand the assessment work.

General Approach for PBL Implementation

To address concerns encountered [19] when PBL instruction was adopted, we employed a hybrid PBL approach where important control theory was briefly introduced first to provide enough guidance that allowed the students to start working individually without being overwhelmed.

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The Water Fowl Incubator Temperature Control

The project aims to design a temperature control system for an incubator in a waterfowl park in the eastern North Carolina area. Sixty-Watt tungsten incandescent bulbs are the heat source that maintains the temperature inside a glass incubator where the external (room) temperature fluctuates during a day/night cycle.

The modeling of the incubator and the tungsten bulb has referred to [20, 21]. The bulb thermal model is fairly sophisticated and, therefore, elaborated upon here. With some simplification, the thermal dynamics (heat flow) of the filament and the bulb envelope can be modeled with a second-order differential equation in Eq. 2.

$$R_b C_b R_f C_f \frac{d^2 T_b}{dt^2} + (R_b C_b + R_f C_f) \frac{dT_b}{dt} + T_b = R_b Q_m + R_f C_f \frac{dT_a}{dt} + T_a \tag{2}$$

where:

T_f = filament temperature [°K]

T_b = bulb envelope temperature [°K]

T_a = ambient temperature (inside incubator) [°K]

Q_{in} = heat input from filament (i.e., electricity) [W]

Q_f = heat flow from the filament to the bulb [W]

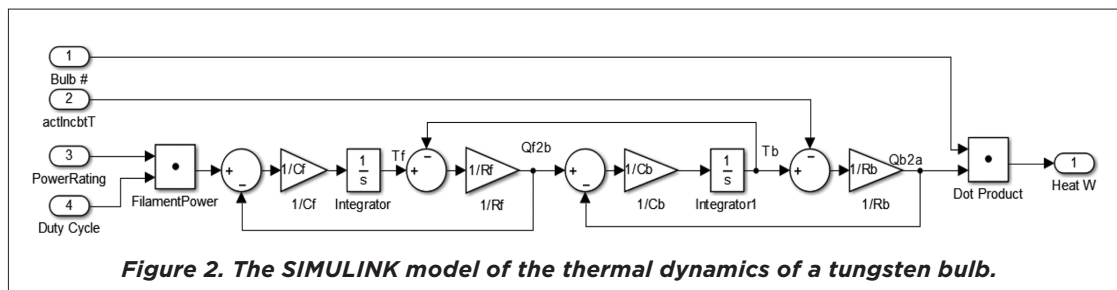Q_{bulb} = heat flow from the bulb to ambient (incubator) [W]

C_f = thermal capacitance of filament [J/°K]

C_b = thermal capacitance of envelope [J/°K]

R_f = thermal resistance from filament to envelope [°C/W]

R_b = thermal resistance from envelope to incubator [°C/W]

Equation (2) allows us to build the SIMULINK model of the dynamics of a tungsten bulb as illustrated by Figure 2. This bulb thermal model can be validated by verifying the temperature of the bulb filament and glass envelope. The temperature and time constant should be approximately 2500°C and 0.04 seconds for the filament and 200°C ~130 seconds for the bulb envelope.

Figure 2. The SIMULINK model of the thermal dynamics of a tungsten bulb.

Figure 3. The complete temperature control system with the controller transfer function and the number of bulbs to be determined.
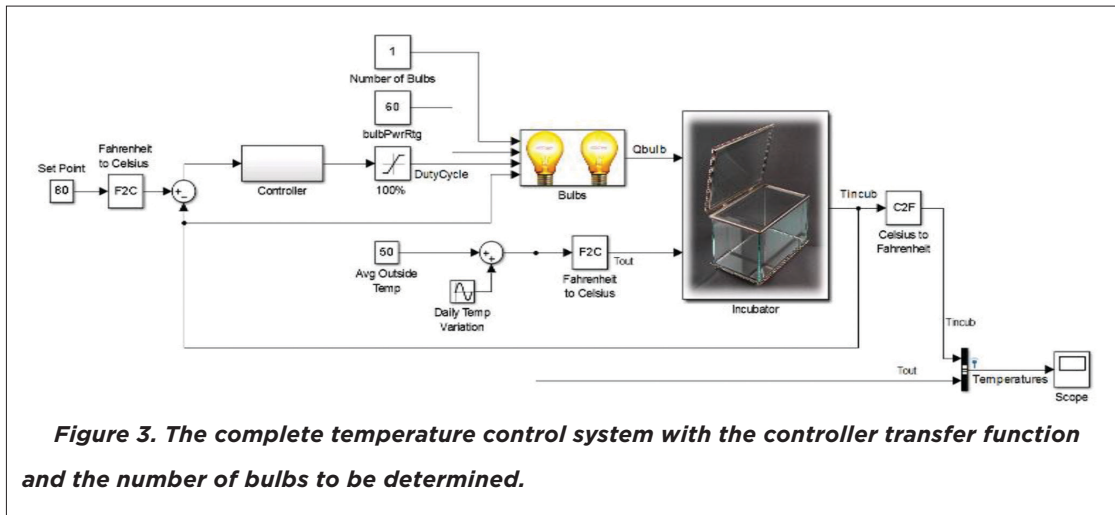
Figure 3 illustrates the block diagram of the closed-loop system with the feedback and a controller (whose transfer function is yet to be determined at this point). Note that in Figure 3, since the relationship between the electrical power (and therefore thermal power) and controlled filament voltage is nonlinear, pulse-width-modulation (PWM) of the bulb voltage has been exploited in order to linearize the relationship between the power and the output from the controller. In other words, what the controller adjusts is the duty cycle (rather than the voltage itself) of the electricity going to the bulbs.

Project Delivery

As discussed in [1], designing a compensator via the frequency domain method must follow multiple steps including: a). use MATLAB to plot the Bode plots with an existing open-loop gain K; b). find the desired phase margin Φ_M that satisfies the P.O. requirement; c). determine phase margin frequency $\omega_{\Phi M}$ from the Bode plot; d). find the required magnitude change ΔM at $\omega_{\Phi M}$; and e). determine the required gain adjustment from required magnitude change obtained in step d). These theoretic steps were converted into five relevant project activities under the incubator control context to guide the students through the modeling, design, and test work:

1. Develop the incubator and bulb thermal model.
2. Find the temperature step response and frequency response of the open-loop system (incubator and one bulb).
3. Determine the desired open-loop gain, i.e., the number of bulbs needed, from the steady-state-error in Step 2.
4. Design a lag compensator to ensure the temperature overshoot is in the acceptable range.
5. Simulate and evaluate the performance of the designed system against the egg hatching temperature requirements.

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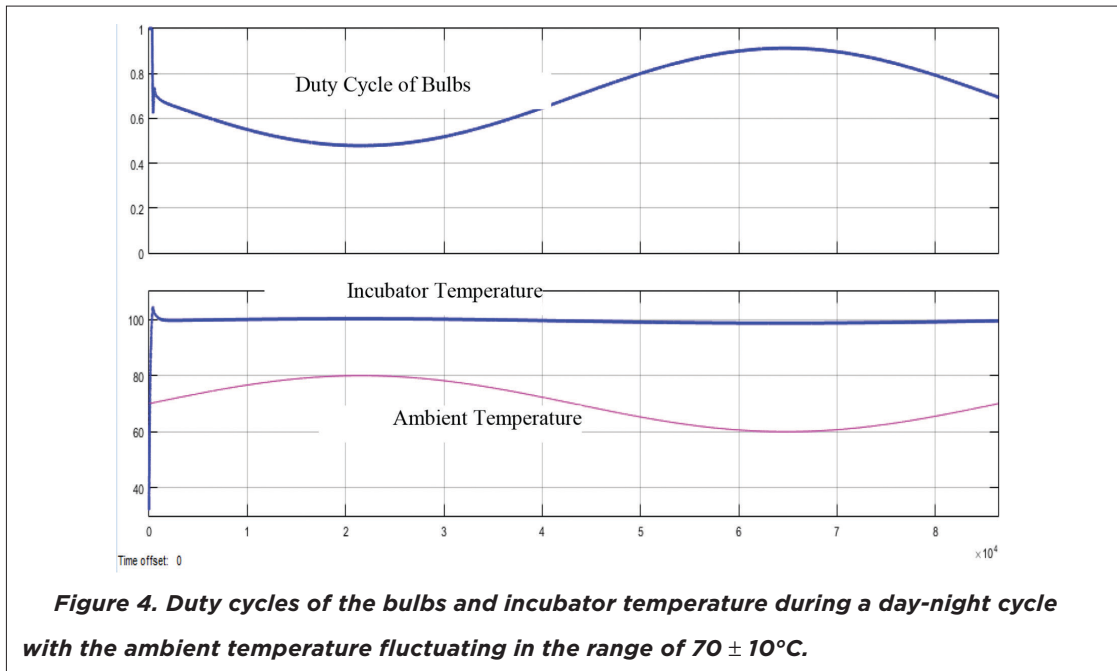
Figure 4. Duty cycles of the bulbs and incubator temperature during a day-night cycle with the ambient temperature fluctuating in the range of 70 ± 10°C.

Project Activities and Learning Outcomes Mapping

The five project activities coherently provide rich opportunities that allow students to learn and practice difficult frequency domain concepts and to connect these concepts with the time-domain performance parameters. Table 1 lists the primary targeted learning outcomes corresponding to

Table 1. Mapping Between Project Activities and Targeted Learning Outcomes Supported by Them.

Project Activities	Targeted Learning Outcomes
1. Develop incubator and bulb models.	Mostly in time domain; nothing particular for frequency domain.
2. Find step and frequency response of the open-loop system.	• Determine gain/phase margins and their corresponding frequencies • Estimate SSE from Bode plot • Estimate P.O. from Bode plot • Connect f-characteristics and time-domain performance
3. Determine the desired open-loop gain, i.e., the number of bulbs needed.	• Estimate SSE from Bode plot • Determine controller gain via frequency method • Connect f-characteristics and time-domain performance
4. Design a lag compensator to ensure overshoot in range.	• Estimate P.O. from Bode plot • Determine compensator break frequencies • Determine slope change due to pole/zero • Construct lag compensators • Connect f-characteristics and time-domain performance
5. Test the performance of the designed system.	• Estimate SSE from Bode plot • Estimate P.O. from Bode plot • Connect f-characteristics and time-domain performance

each of the five project activities. This mapping allows an instructor to objectively assess the learning outcomes at the overall project and activity levels. It is noteworthy that many other frequency domain concepts are also embedded in these activities, although less explicitly.

Written Project Report

At the end of the project, each student was asked to write an individual project report that includes seven specific sections: Introduction, Design Requirements, System Modeling, System Frequency Analysis, Compensator Design, Performance Evaluation, and Conclusion. They were also asked to electronically turn in the MATLAB/SIMULINK files along with the write-up. The grading rubrics emphasize these requirements to ensure the students provide detailed specifics in each defined section to support objective learning outcome assessment.

PROJECT ASSESSMENT AND RESULTS

To date, the project has been offered four times since 2013. During the most recent three offers (2014-2016), careful assessment was conducted at the completion of the project.

Assessment Instruments

Two main instruments, written project reports and student self-evaluation survey questionnaires, were utilized to assess the effectiveness and impact of the project. The first instrument, the project reports, was utilized for assessment at two granularity levels. These assessment components are introduced below with their results following.

As part of the department ABET assessment plan, the project reports were collected to evaluate students' overall ability to design a temperature control system that meets the hatching requirement (ABET Outcome c: Design) and their ability to articulate the design process (ABET Outcome g: Communication). Rubrics for this level of assessment are defined in Table 2.

Note that although the two outcomes above were assessed by evaluating the reports from this project, these outcomes were not results solely of the project learning, but also of other learning experiences such as lectures, homework assignments, etc. Data directly evaluating how the project helped the students learn specific and difficult frequency domain concepts were collected and assessed at a more granular level as explained later.

Quantitative Measures of Expected Learning Outcomes

Quantitative measures of how students achieved the expected learning outcomes from each project activity were analyzed by reviewing individual sections (namely, System Modeling, System

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Table 2. Rubrics for student's ability to (1) perform temperature control design and (2) Articulate the design Process.

Perform Temperature Control Design

4 (Superior): The designed system provided steady-state error and overshoot temperature that are both within the safe egg hatching range. The system performance was thoroughly analyzed against the egg hatching requirements identified earlier.

3 (Satisfactory): The designed system provided steady-state error and overshoot temperature that are generally within the safe egg hatching range. The system performance was analyzed with minor mistakes.

2 (Below Expectation): The designed system did not provide a safe egg hatching temperature. The system performance was not well analyzed.

1 (No Progress Shown): The design was incomplete. The system performance was not analyzed.

Articulate the Design Process

4 (Superior): The design process was clearly and logically described. The use of equations, figures, and other visual aids was effective.

3 (Satisfactory). The design process was generally described clearly and logically. The use of equations, figures, and other visual aids was generally effective with minor issues.

2 (Below Expectation): The design process was described with major mistakes. The use of equations, figures, and other visual aids was ineffective.

1 (No Progress Shown): The design process was not logically described. The use of equations, figures, and other visual aids was inappropriate.

Frequency Analysis, Compensator Design, Performance Evaluation) of the project reports using the project activity-learning outcome mapping in TABLE 1.

To make the three years of assessment consistent, reports from the last three rounds were gathered indiscriminately and reviewed at the same time. Evidences of a student's ability to carry out tasks related to those targeted learning outcomes were examined section by section. A three-level scoring system was utilized to evaluate each ability: '2' means that evidences from a section clearly show that the student can accomplish a task in frequency domain; '1' denotes that the student had some level of ability; and '0' indicates no evidence was found for a learning outcome from that section. These section by section assessment results for individual students were recorded.

Project Impact Measures

Three categories of project impact to students, covering both technical and non-technical aspects, were assessed using carefully developed student self-evaluation questionnaires: (a) the technical learning objectives (further broken into the three sub-areas: a1. control theory, a2. thermal dynamics, and a3. MATLAB/SIMULINK software tools), (b) the impact of the project on the students' perception of electrical engineering (EE), as well as (c) their general perception about the project itself.

The student self-evaluation survey started with 12 questions that covered categories (a) and (c) in 2014, and was expanded to 19 questions in 2015 and 2016 in order to improve the reliability

of the results. In the latter two rounds, two questions for category (b) assessment - students' EE perception change - were added. The perception assessment questions (categories (b) and (c)) are similar to those from the validated survey for freshman engineering students [22]. TABLE 5 lists a shortened version of the survey questions sorted by their assessment categories (most of the questions begin with "I am able to…" or "I believe the project has…"). The survey questions used a five-level Likert scale with 5 representing "Strongly Agree" and 1 representing "Strongly Disagree". The survey also included open-ended questions to solicit students' inputs for future improvement opportunities.

Assessment Results

Out of the four times the project was offered since 2013, assessment data were incomplete in the first year due to the immaturity of the project. Therefore, only the most recent three years (2014, 2015, and 2016) of data are analyzed here. The numbers of students for these three years are 12, 17, and 21, respectively.

ABET 3.c and 3.g Assessment Results

The overall assessment results for ABET Outcome 3.c and 3.g from the rounds are summarized in TABLEs 3 and 4. In 2014, the percent of students whose abilities of designing and communicating rated as "Superior" or "Satisfactory" was about 54% and 60%, respectively. For the next two years, these percent numbers are in the range of 68-71%, generally meeting the assessment goals of 70% defined by the department. Comparing the three years, a clear rising trend can be observed in both outcomes.

1. The effectiveness of how the four project activities (Activities #2 to #5) have supported the students learning their targeted frequency domain concepts is shown in Figure 5 to Figure 8. Again, a three-level scoring system was used for the effectiveness and these plots compare the averages and standard deviations of the three years side by side.

Table 3. ABET Outcome 3.c assessment results.

	2014	2015	2016
4 = Student demonstrates superior achievement	3	6	7
3 = Student demonstrates satisfactory achievement	5	9	10
2 = Student's achievement falls below expectations	3	2	3
1 = Student shows no significant achievement	1	2	1
Average Rating	2.8	3.0	3.1
% of Samples Rated 3 or 4	54	68	71

Table 4. ABET Outcome 3.g assessment results.

	2014	2015	2016
4 = Student demonstrates superior achievement	3	7	8
3 = Student demonstrates satisfactory achievement	6	8	9
2 = Student's achievement falls below expectations	2	2	3
1 = Student shows no significant achievement	1	2	1
Average Rating	2.9	3.1	3.1
% of Samples Rated 3 or 4	60	68	70
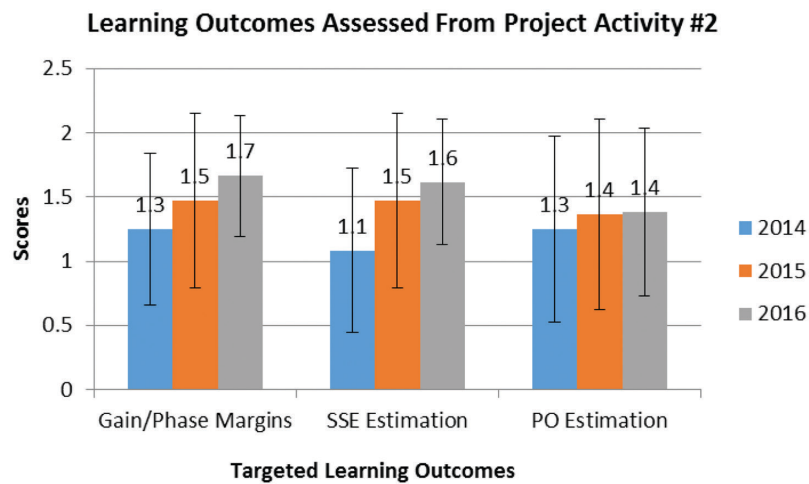
Figure 5. Effectiveness of Activity #2 Supporting its Outcomes.
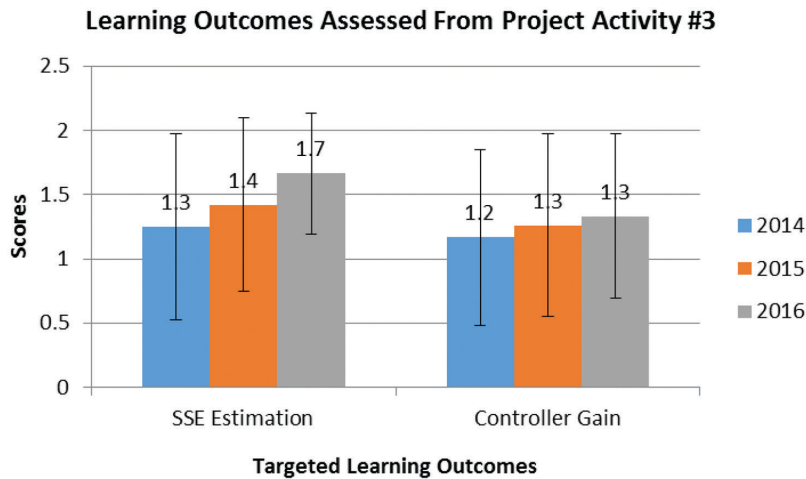
Figure 6. Effectiveness of Activity #3 Supporting its Outcomes.

Figure 7. Effectiveness of Activity #4 Supporting its Outcomes.

Figure 8. Effectiveness of Activity #5 Supporting its Outcomes.
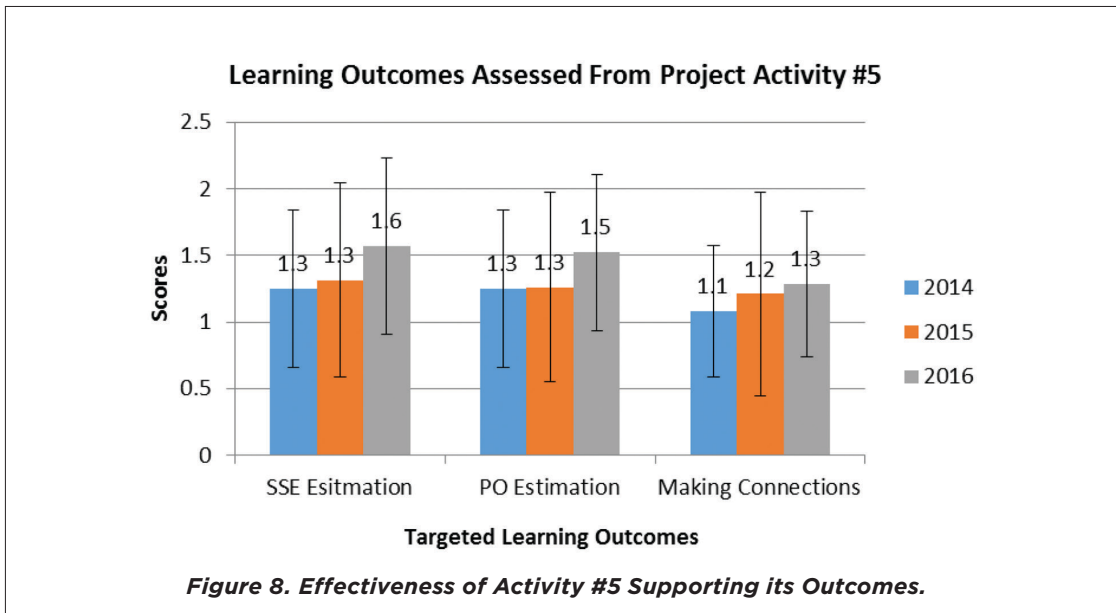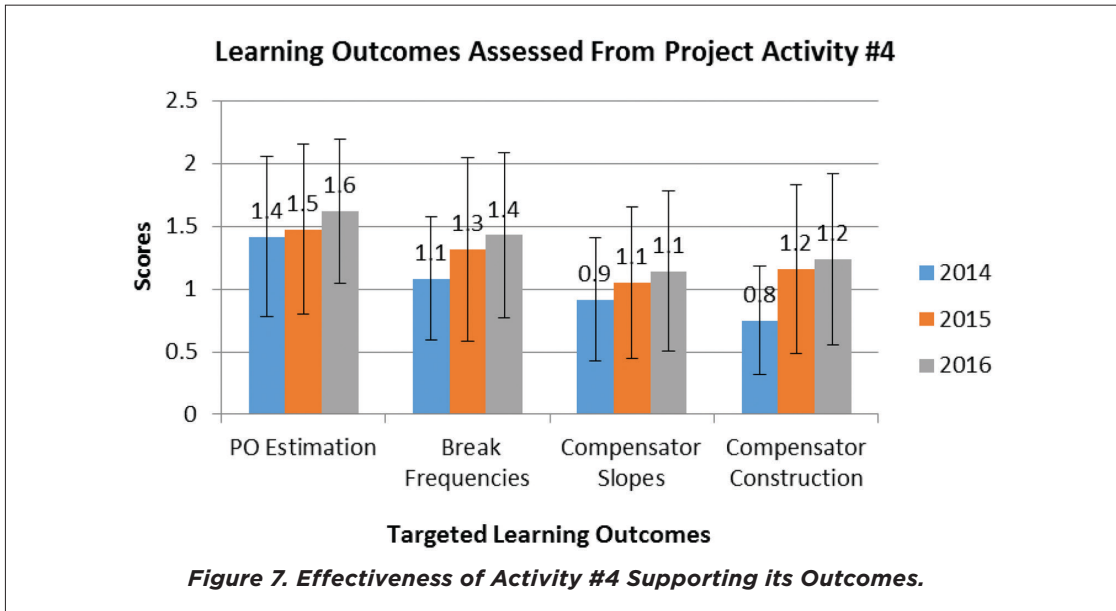
End of Project Survey

An end-of-project survey was administered for each of the three years. The survey questionnaires were expanded from 12 questions in 2014 to 19 questions for the last two rounds to provide a more complete understanding of the project's impact. Eight out of 12 students in 2014, 15 out of 19 in

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Table 5. 2015/2016 Assessment Survey Results.

		Average	STD	%>=4
(a1) Learning Area #1: Control Theory				
1	Use math to solve controls problem	4.1/3.8	0.5/0.9	93/69
5	Find SSE from Bode plots	4.5/4.3	0.6/0.9	93/94
6	Understand gain/phase margin	4.6/4.6	0.5/0.5	100/100
14	Design control systems	3.7/3.8	1.2/0.9	71/69
(a2) Learning Area #2: Domain of Thermal				
3	Helpfulness of thermal dynamics	3.3/3.3	1.3/1.2	53/50
4	Helpfulness to thermal dynamics	4.1/3.9	0.8/0.6	87/81
(a3) Learning Area #3: ATLAB/SIMULINK				
2	Improved MATLAB skill	4.5/4.5	0.5/0.7	100/94
7	Use MATLAB/Simulink to analyze and design	4.5/4.3	0.5/0.9	100/75
8	Learned MATLAB and Simulink	4.5/4.3	0.5/0.7	100/88
9	Like MATLAB and Simulink	4.4/3.9	0.8/0.9	93/81
(b) EE Perception				
15	Positive about EE concentration	4.3/3.9	0.8/1.3	79/69
18	Understand EE better	4.1/3.6	0.7/1	79/63
(c) Project Perception				
10	Understanding of Impact	4.0/4.1	0.9/0.7	79/81
11	Sense of accomplishment	4.2/3.9	0.8/1.2	71/75
12	Learned a lot from writing report	3.6/3.8	1.0/0.7	57/56
13	Interesting and Motivational	4.1/3.9	0.9/0.5	79/69
16	Wish more assistance available	4.1/3.8	1.1/0.9	79/69
17	Makes learning controls easier	4.0/3.9	0.6/1.3	79/69
19	Wish did not have to work on it*	2.9/2.7	0.7/0.9	64/50

Results to the reversely worded question have been processed.

2015, and 16 out of 21 in 2016 responded to the survey. TABLE 5 reports on the combined 2015–2016 results, including the average score and the standard deviation of the responses to each question in the three categories. The number of each question reflects the order of how the questions were asked in the survey. The percentage of responses with a score of 4 or 5 ("Agree" or "Strongly Agree") is also included in the last column of the table.

Survey results from the three years, after the subject learning outcomes and perception data are collectively processed by category, are visually compared side by side as shown in Figure 9. In the graph, the mean values of the responses to the questions under a category and their standard deviations are both included to extract insights into student opinions on how and whether the project facilitated learning and changed their perceptions.

Figure 9. 2014–2016 collective comparison of survey results by category.
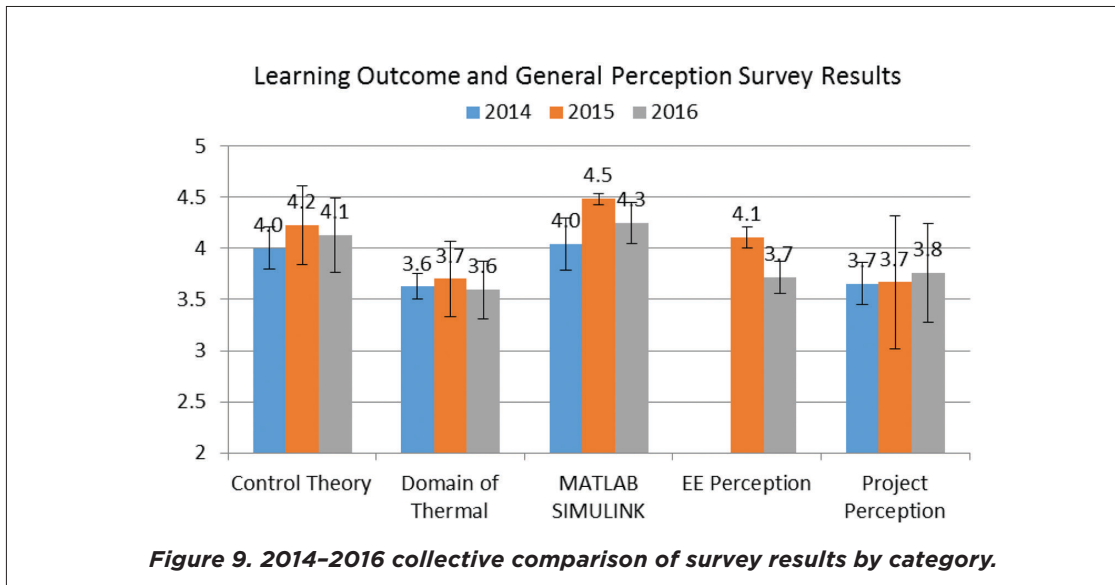
DISCUSSION

While the idea of controlling the temperature for an egg incubator is straightforward, the theory and steps involved in thermal system modeling and compensator design in frequency domain may appear prohibitive to undergraduate students, especially when this is the first time they have been exposed to these topics. Regardless, the assessment results in Tables 3 and 4 show that the most of the students could satisfactorily achieve the two assessed ABET outcomes.

Learning outcomes have significantly improved from 2014 (only 54% of students rated 3 or 4 for Outcome c and 60% for Outcome g) to 2015 (68% for both outcomes). This learning improvement could be attributed to a change: instead of allowing students to turn in everything at the end, the project was split into two separate parts and students were required to submit deliverables at various stages of the project, including (1) a simulation example chosen from the MathWorks website [23]; (2) the incubator's SIMULINK model; (3) the tungsten bulb's SIMULINK model; (3) the open-loop system block diagram with the incubator and the bulb masked as two subsystems; (4) the block diagram of the completed closed-loop system; and (5) the final report that elaborates the detailed design steps and testing re-sults. The students' responses to the open-ended survey questions also confirmed that they welcomed the step-by-step approach because this milestone delivery had not only ensured reasonable progress through time; it had also allowed periodic, just-in-time feedback from the instructor at each phase.

Results from Figure 5 to Figure 8 show uniform improvement over the three years regarding how four project activities supported progress in their targeted learning outcomes. It can be observed

that students received higher ratings for the earlier analysis-related tasks, such as determining the gain/phase margins, than the ratings for designing and constructing a lag compensator. This can be interpreted as the latter synergistic tasks were based upon the success of the earlier tasks, yet involved a higher level of challenge that lowered the rating.

Two out of the 19 students in 2015 did not turn in a final report and received a rating of zero for all of the learning outcomes. The two outliers resulted in the fact that standard deviations for most of the outcome ratings from the second year are slightly larger than the other two years.

Data in Table 5 and Figure 9 show that students from 2015 and 2016 responded to questions of different areas in a fairly consistent manner. It can be clearly observed that students of both years believed that their MATLAB/SIMULINK skills (Learning Area a3) have benefited the most from the project, followed by their learning of control theory (Learning Area a1). Overall, they did not believe the project improved their domain knowledge of thermal dynamics (Learning Area a2), although the successful modeling of the incubator and bulb requires a good understanding of the thermal subject.

Survey results from categories (b) and (c) assessments are similar: most students agreed that the project made them feel more positive about EE and understand EE better, and they considered the project interesting and motivational, as well as giving them a sense of achievement, and making the learning of controls subject easier. A noticeably lower percent of the students responded positively to questions 12 (on writing reports) and 19 (like to work on the project), revealing that the students, overall, were honest when completing the surveys. The survey results also indicate certain areas in which the students felt that the project could be improved: the majority of the students wished more assistance had been available for such a challenging project. It is desirable to develop a good balance between effectively guiding student learning and encouraging students to self-teach the use of new tools that are outside their comfort zone.

Comments received from student surveys convey useful insights. For example, the effectiveness of student learning is often sensitive to logistical pitfalls, such as unexpected technical difficulties. Careful planning ensures smooth project progress and maximizes student learning. Student comments also repetitively mentioned two additional issues:

a. SIMULINK is a sophisticated tool that requires significant learning before one can use it proficiently. This project was the first time the students used this tool. Some level of introduction is necessary so that the students have the basics to start their modeling and design. Several students commented that they appreciated the MathWorks examples that they were asked to run and practice at the beginning.

b. For multi-week projects like this, it is critical for students to receive timely feedback to their progress at various stages. This prevents them from diverging too far from the right track, avoids unnecessary frustration, and ultimately enhances their learning experience.

CONCLUSIONS

This paper presented a PBL case study in an undergraduate controls course where students used MATLAB and SIMULINK tools and frequency response methods to design an incubator temperature control system. The effectiveness of how this cohesive learning experience facilitated student learning was assessed at the project and project activity levels. The project's impact on the students' perception about electrical engineering was assessed through student self-evaluation and project reports. Results show that, with careful planning and proper preparation, simulation-based real-world projects like this not only effectively facilitate student learning and make the intricate frequency methods easier to understand, they also boost student perception on their areas of study (and possibly their future career) due to the positive experience and enhanced understanding of relevance.

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