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# A multi-course project for mechatronics, system dynamics, and control experimentation courses.

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## Abstract

This work-in-progress paper presents a multi-course project designed to integrate the concepts from Mechatronics, System Dynamics, and Controls and Vibrations Experiments courses into a single, continuous project. Different portions of the project are covered in each course, illustrating for students the connection between the courses beyond curriculum pre-requisites. A temperature control system was chosen as the platform for this project. The goal is to help students make connections between course content and deepen their understanding of the subjects. In the Mechatronics course, students focus on the hardware components of the temperature control system, learning to use an Arduino microcontroller and dimmer control to adjust the speed of a fan or brightness of an incandescent light bulb. Tangentially, System Dynamics I introduces students to physical system modeling and simulation of the response of the temperature control system. The students are asked to derive the transfer function of the temperature control system and then simulate the step response using simulation software. Subsequently, System Dynamics II presents feedback control of closed-loop systems, where students are asked to design a controller for the system they modeled in System Dynamics I. Finally, in the Controls and Vibrations Experimentation course, students will build a physical prototype, implement the controller, and evaluate its performance. The project was first introduced in the System Dynamics I and II courses during the Fall 2024 semester and will be incorporated into the Mechatronics and Controls and Vibrations Experiments courses in the Spring 2025 semester. Surveys will be conducted at the end of each course to assess whether students' understanding of the content has improved.



## Keywords

Engineering education, multi-course project.


## Background and Introduction

Utah Valley University is a public, dual-mission university with nearly 47,000 students that offers 110 bachelor's and 20 master's degrees. In 2018, Utah Valley University established a bachelor's degree in mechanical engineering, receiving full ABET accreditation in 2021. Currently the mechanical engineering program enrolls over 500 students, with just over 50 graduates in the Spring 2024. Despite being a new program, the mechanical engineering faculty have undergone some comprehensive curriculum changes in the past 2 years as new faculty joined the program and new resources such as laboratories and equipment become available. One of these curriculum changes is a redesign and expansion of the required system dynamics portion of the curriculum. Part of the redesign was to better clarify the cohesion between the three originally created upper division courses, ME 3010 System Dynamics I (previously named Linear Systems), ME 4010 System Dynamics II (previously named Automatic Controls), and ME 4015 Control and Vibration Experimentation. Additionally, a fourth course, ME 3050 Mechatronics was recently added to complement these existing courses.

Due to the growing size of the mechanical engineering program, many different faculty had been teaching both the System Dynamics I course and the Control and Vibration Experimentation lab, leading to inconsistent material coverage and perceived gaps in student understanding of concepts that were covered in the entire system dynamics sequence. From the authors' previous experience at other universities, this was not a unique challenge. This is also shown by [1,2]. In addition, projects in System Dynamics, Mechatronics and Controls courses provide students with an opportunity to reinforce their learning while seeing real-world applications [3-6]. As a result, the authors decided to develop a project that could be broken up into four parts, with one part utilized in each of the four system dynamics courses. The goal would be to show the students how their work from one course would be utilized and built upon in other courses, thereby providing the student with better context for what they were doing and potentially providing some motivation to fully understand the concepts and perform well in their current course.

The project was first implemented across System Dynamics I and System Dynamics II during the Fall 2024 semester, which were offered simultaneously to two different groups of mechanical engineering students. Each course was taught by a different mechanical engineering faculty member. Students enrolled in System Dynamics II had not previously completed the multi-course project in their System Dynamics I course. This simultaneous offering provides an opportunity to compare student experiences and outcomes between those exposed to the multi-course project and those who were not. To ensure a cohesive multi-course experience, both instructors met regularly before and throughout the academic term to establish shared learning outcomes, timelines, assessment strategies, and survey questions to evaluate student progress and perceptions. At the start of the project in each course, instructors introduced the students to the multi-course nature of the project, clarifying the tasks they would complete during the current course and explaining what to expect in the subsequent course(s). This approach provided students with a clear understanding of how their work in each course contributed to the larger project. At the end of the fall semester, the instructors reconvened to review the implementation, discuss feedback, and identify potential improvements to refine the project for the Spring 2025 semester. This iterative process highlights the importance of continuous communication, collaborative planning, and adaptability in managing a multi-course, multi-faculty project.

## A Multi-Course Project

A temperature control system was selected as the platform for a multi-course project. In ME 3050 Mechatronics, students are introduced to the hardware and software components of the temperature control system. In ME 3010 System Dynamics I, students learn to model and simulate the response of the temperature control system. Building on this foundation, ME 4010 System Dynamics II focuses on designing a closed-loop control system for the temperature control system. Finally, in ME 4015 Vibrations and Controls Experimentation, students build a physical temperature control system, design a controller, and evaluate its performance.

- **ME 3010 System Dynamics I**
  The multi-course project was first implemented in ME 3010 System Dynamics I and ME 4010 System Dynamics II during the Fall 2024 semester. In System Dynamics I, students model the temperature control system as a first-order system by deriving its transfer function and analytical step response. They determine the system parameters using data from the experimental step response. After calculating the parameters, students verify the

values of the system parameters by comparing the simulation results with the experimental data. Students worked in a team of two. Each team submitted a brief report including their answers to the assessment questions. The System Dynamics I part of the project aims to provide students with practical experience in mathematical modeling through the transfer function approach, deepening their understanding of system responses and laying the groundwork for controller design in ME 4010 System Dynamics II. Equations (1) and (2) present the governing equation and its corresponding transfer function of the temperature control system.

$$\tau \dot{y}(t) + y(t) = Ku(t - t_d) \tag{1}$$

$$\mathrm{G(s)} = \frac{K}{\tau s + 1} e^{-t_d s} \tag{2}$$

Where $y$(t) is the output and $u$(t) is the input. $K$ is steady state gain, $\tau$ is the time constant and $t_d$ is the time delay of the input.

Fig.1 presents a comparison between the experimental and simulated step responses for $K$=0.752, τ=211 s, and $t_d = 30$ s.

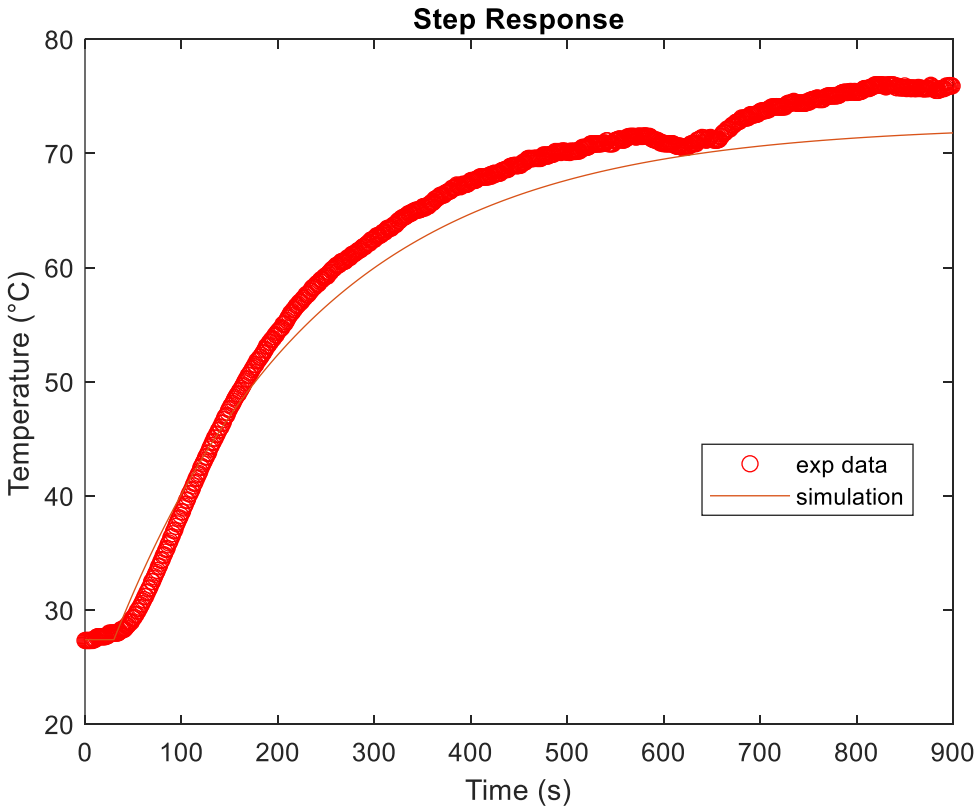


Fig. 1 Comparison of experimental and simulated step responses for the temperature control system

- **ME 4010 System Dynamics II**

In ME 4010 System Dynamics II, students were asked to utilize the heating and cooling transfer function models that were developed in ME 3010 System Dynamics I to design a closed-loop controller to meet the following specifications:

1. Heat the box from 72° F to 100° F in under 5 while holding the temperature to 100° F (+/- 1° F) for 60 seconds
2. Cool the box from 100° F to 80° F in under 5 while holding the temperature to 80° F (+/- 1° F) for 60 seconds

Students worked in teams of two or three to design any type of controller they deemed suitable. They were all given the same transfer functions to model the heating, cooling, and thermocouple sensor. Because this was the first time this project was assigned, the transfer functions shown in Equations (3) – (5) below were estimated by the faculty and represent simplified models of the physical system they will be testing in ME 4015 Control and Vibration Experimentation.

Combined Plant/Actuator for Heating: $\frac{1}{100s+1}$ (3)

Combined Plant/Actuator for Cooling: $\frac{1}{120s+1}$ (4)

Thermocouple: $\frac{1}{0.05s+1}$ (5)

The students were asked to model and simulate their system using MATLAB/Simulink and submit a written technical report no longer than nine total pages. In addition, the students were required to perform a peer-review of another group's initial report draft, providing them with feedback before the final report was submitted. The goal of the peer-review was to allow students to see how other groups approached their simulation and controller design and potentially revise their own approach if they thought it necessary.

**Project Experience Survey**

The multi-course project was first implemented in System Dynamics I and II in the Fall 2024 semester. At the end of the semester, surveys were created and conducted in both courses to learn about students' experience with the multi-course project.

- **ME 3010 System Dynamics I**
  In System Dynamics I, a total of 31 students enrolled in two sections of class completed the survey. Responses to questions Q1 to Q7 were on a 5-point Likert scale. (5 – Extremely 4 – Very, 3 – Moderately, 2 – Slightly, and 1 – Not at all) and are listed in Table I. The survey results for the ME 3010 course project indicate that students generally found the multi-course project valuable. The highest-rated aspect was the importance of having a project with real-world applications, with an average rating of 4.39. Students also appreciated the project's role in helping them see the practical

relevance and application of system dynamics (4.00). The project was moderately effective in enhancing understanding of system response (3.68), facilitating a connection between System Dynamics I and II (3.68) and enhancing their understanding of modeling using transfer function approach (3.54). However, the project was less effective in helping students understand the development of governing equations for dynamic systems (3.42) and modeling and simulation using MATLAB (3.39). Overall, the project seemed well-received, with students recognizing its value in enhancing their understanding of key concepts.

Table I: ME 3010 Responses to Q1 to Q7

Q1: How well did the multi-course project help you understand the development of governing equations for dynamic systems?

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 0 | 4 | 10 | 17 | 0 | 3.42 | 31 |

Q2: How valuable was the multi-course project in enhancing your understanding of modeling using transfer function approach?

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 1 | 2 | 9 | 17 | 2 | 3.55 | 31 |

Q3: How valuable was the multi-course project in enhancing your understanding of system response?

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 1 | 2 | 7 | 17 | 4 | 3.68 | 31 |

Q4: How valuable was the multi-course project in enhancing your understanding of modeling and simulation using MATLAB?

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 1 | 7 | 5 | 15 | 3 | 3.39 | 31 |

Q5: To what extent did working on the multi-course project help you see the practical relevance and application of system dynamics?

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 0 | 2 | 7 | 11 | 11 | 4.0 | 31 |

Q6: How well do you think the multi-course project facilitated a connection between system dynamics I and system dynamics II?

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 0 | 5 | 6 | 14 | 6 | 3.68 | 31 |

Q7: How important is having a project with real-world applications to your understanding of the concepts covered in the course you are taking?

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 0 | 0 | 4 | 11 | 16 | 4.39 | 31 |

Q8 to Q11 are short answer type questions and they are listed in Table II. For Q8, students appreciated the real-world application of the ME 3010 project but faced challenges with coding, particularly in Python and MATLAB. They suggested more in-class explanations and examples to better understand the project. Many students struggled with the coding aspects, indicating a need for more support and clearer instructions. Despite these difficulties, students valued the practical relevance of the project, which helped them understand the real-world applications of the concepts learned in class. There is a strong desire for more in-class time dedicated to explaining and working through the project, particularly the coding components. Overall, many students enjoyed the project and felt it enhanced their learning experience. For Q9, students found the multi-course project valuable for its real-world applications, which helped them connect classroom learning to practical problems and future professional scenarios. They appreciated how the project integrated knowledge from multiple courses and enhanced their understanding and motivation. For Q10, students suggested improvements to the multi-course project, focusing on more in-class support for coding, breaking the project into smaller parts throughout the semester, and clearer instructions. For Q11, most students supported the idea of incorporating more multi-course projects into the Mechanical Engineering curriculum. They believed these projects help connect different subjects, provide real-world applications, and enhance learning and motivation. However, some students noted that the timing of courses is important to maximize the benefits. The following quotes from student surveys are presented verbatim to preserve the authenticity of their responses.

Table II: ME 3010: Short answer type Q8 to Q11

| |
|---|
| Q8: Feel free to provide any additional comments or insights regarding the projects and course overall.<br>**Representative Responses**:<br>• "We did have some issues with the python code given which I do not know much about. Luckily my teammate was able to figure it out. I really like using the math we learn in class to a real-world problem."<br>• "Coding was the hardest part; please make it easier next year."<br>• "I think solving for the transfer function analytically went well, I believe a lot of students get lost when it comes to using some of the functions in Matlab, we're not really sure how Matlab is performing the operations. I think we made a good connection to spring-mass-damper systems and how to model them. "<br>• "Real-life applications make it much better for understanding."<br>• "I really enjoyed the course even though it was challenging; I felt I learned more than I tend to from other classes."<br>• "I would like to be solving more real-life problems throughout the semester like the project. " |
| Q9: What value, if any, does the multi-course project have on your educational experience?<br>**Representative Responses**:<br>• "Projects with real-world applications are super valuable as it helps connect school to the real world."<br>• "It helps me apply what I am learning in class to a real-world problem." |

- "It gives me a glimpse into what we will be doing in the future and how the things we learn are utilized in the professional world."
- "It helps draw a connection between courses and helps to build on the knowledge we gained in a previous course."
- "It shows us real-life application which not only makes the course topics easier to understand, but it also provides more motivation in learning and seeking to understand better."

Q10: What would you change about the multi-course project?
**Representative Responses**:

- "Possibly spending a small amount of class time to show how to set up the project, since I was having issues with running the initial code."
- "I think it would be nice to have a project where we slowly work on it throughout the semester."
- "Have it easier to run the program in Python. I would love to take time to collect the data in-class and afterwards as a group analyze the data and provide the answers to the assessment."
- "I would say to make it groups of 3, and have a section that explains MATLAB a bit more, in case you are new to coding."
- "The code to get it all started was confusing, and I wish there were more detailed steps or debugging help in the instructions."

Q11: Would you like to have more multi-course projects incorporated into the Mechanical Engineering curriculum (for instance, in Fluids, Thermo and Thermo-Fluid Experimentation courses or Manufacturing Process and Machine Design)? Why or Why not
**Representative Responses**:

- "Yes, I really enjoy seeing the application more and course projects are an effective way of learning."
- "I think it would be helpful to have more projects like this in the curriculum, as it helps to draw the connection between courses and solidify the knowledge we've gained."
- "Yes, very much so because it gives motivation into learning topics and inspires students as well."
- "I think it's important to give students the opportunity to problem solve with a real-world project that involves working in teams and more exposure to projects to further our understanding."
- "Yes, because it helps see real-world examples."
- “yes definitely, lots of classes feel disconnected from each other and being able to see how they connect and how you could use all the subjects together in your career is nice.”

- **ME 4010 System Dynamics II**
  In the Fall 2024 semester, a total of 50 students were enrolled in two sections of System Dynamics II, both taught by the same instructor. The survey given to these students was similar to that of System Dynamics I, with some questions tailored to the portion of the project utilized in System Dynamics II. A total of seven Likert scale questions and three short answer questions were utilized in the survey. The summary of the Likert question responses are shown below in Table III, while a sample of student responses to the open ended questions are included in Table IV.

Table III: ME 4010 Responses to Q1 thru Q7

Q1: How valuable was the multi-course project to your understanding of controller design? (1 = Not at all, 5 = Extremely valuable)

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 0 | 1 | 8 | 26 | 12 | 4.04 | 47 |

Q2: How valuable was the multi-course project to your understanding of system performance (rise time, settling time, overshoot, etc.)? (1 = Not at all, 5 = Extremely valuable)

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 0 | 4 | 11 | 17 | 14 | 3.88 | 47 |

Q3: How valuable was the multi-course project to your understanding of concepts learned in ME 3010 System Dynamics I? (1 = Not at all, 5 = Extremely valuable)

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 4 | 9 | 13 | 14 | 6 | 3.13 | 47 |

Q4: How valuable do you believe continuing the multi-course project in ME 4015 Control and Vibration Experimentation will be to your learning experience? (1 = Not at all, 5 = Extremely valuable)

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 0 | 1 | 8 | 13 | 25 | 4.32 | 47 |

Q5: After having completed the multi-course project, how confident are you in designing a controller to meet specific requirements? (1 = Not at all, 5 = Extremely confident)

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 1 | 1 | 14 | 21 | 9 | 3.78 | 47 |

Q6: How well do you think the multi-course project facilitated a connection between ME 3010 System Dynamics I and ME 4010 System Dynamics II? (1 = Not at all, 5 = Extremely well)

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 1 | 3 | 20 | 12 | 11 | 3.62 | 47 |

Q7: How important is having a project with real-world applications to your understanding of the concepts covered in the course you are taking? (1 = Not at all, 5 = Extremely important)

| 1 | 2 | 3 | 4 | 5 | Avg | n |
|---|---|---|---|---|---|---|
| 1 | 1 | 3 | 9 | 33 | 4.53 | 47 |

The average for each of the Likert questions is above 3.1/5.0, with Q4 and Q7 having the highest averages of 4.32/5.0 and 4.53/5.0 respectively. Q4 is related to the students' perception of the value of the multi-course project to their future Control and Experimentation course and Q7 is related to how much value the students place on a project with real-world applications. These results match quite well with the students' free response answers to the value they perceived the project having in their educational experience.

The question with the lowest average, of 3.13/5.0, was related to how well the project tied concepts from System Dynamics I. It is interesting that a similar question, Q6, which explicitly asks the students to rate how well the project established a connection between concepts taught in System Dynamics I and System Dynamics II, had a higher average of 3.62/5.0. Given this group of students did not complete the first part of this multi-course project when they took System Dynamics I, they were more able to see the connection between the courses but didn't feel the project helped them understand the earlier concepts quite as much. It is worth noting that the students were explicitly told about the multi-course nature of the project and that the students currently taking System Dynamics I were completing the first part of the same project. It will be important to see how, if at all, the responses change in future semesters when students are able to complete the entire project in all four courses.

Table IV: ME 4010: Short answer type Q8 to Q11

Q8: What value, if any, does the multi-course project have on your educational experience?
**Representative Responses**:

- " It adds value in how it applies the concepts to a real problem. Controls can be a very abstract topic, so it is nice to be involved with a tangible application."
- " I love the idea of applying concepts from one class to do part of the project and then continuing the same project as an application of concepts from another class. I think it ties the concepts from the classes together in a great way."
- " Tying the things I've been learning to a project that was easy for me to understand helped my learning a lot. Sometimes it can be hard to see exactly how the things I'm learning will be tried to a physical application but this project helped me establish that connection."
- " I thought that it was a great project. The only reason I put three on some of the answers is because I wasn't involved in the ME3010 portion. I feel like it was beneficial and I feel like it is very important to have a real world situation to apply the theoretical concepts we are learning in class. It improves my educational experience."
- " It has significant value in allowing for a practical integration of concepts learned across courses, strengthening my overall understanding of design and analysis. Additionally, it provides a clearer view of how topics are applied together to solve complex problems."
- " A multi-course project is more applicable to actual career type work. The connection between what is physical and what is theoretical or digital is necessary for anyone who makes controllers, designs systems, or measures systems."
- "I like this approach to learning. Lots of classes build on each other but its only obvious looking back on it. Lots of times its hard to get a grasp on the idea of a class because "you'll learn more in a

later class" then that later class doesn't explicitly connect to the first. This project solves that problem and I wish there were more of them."
- "knowing we'll get the opportunity to test this system in the controls lab next semester, does force me to put some more thought into how well the system actually performs. In a sense, there's sort of a higher purpose/goal to this because I want to see the system I designed perform well."

Q9: What would you change about the multi-course project?
**Representative Responses**:

- "Perhaps increase it's complexity for the opportunity to design additional features of a controller."
- "Maybe a little more explanation of how the actual system is going to behave and not just the controller designed response. For example, how does it work when it reaches its settling time? Does the system just short cycle on and off to maintain the temperature? Does it oscillate back and forth between the bulb and the fan? How practical is the controller design in reference to the real world. Things like that."
- "I do wish in ME 4010 we did a little bit more going over the designing part with the professor, as I mostly used online resources to help me, but what we covered in class did allow me to understand what those resources were actually talking about."
- "I would have liked project parts throughout the semester to connect the new concepts we learned to the project. possibly instead of some of the homework assignments(which everyone definitely does), we could have done smaller parts of the project and then compiled that all in the final report and have several model iterations with different methods."
- "I think it was a good project. I think it would have been a lot more interesting than the project i did in system dynamics 1. but I think that the system wasn't as interesting in this class since there wasn't very many design constraints. I' sure implementing it in the next course will have plenty of challenges, but it felt like you couldn't really go wrong with the controller for the system in this class. so maybe ad an extra requirement that doesn't almost automatically get fulfilled with any controller."

Q10: Would you like to have more multi-course projects incorporated into the Mechanical Engineering curriculum (for instance, in Fluids, Thermo and Thermo-Fluid Experimentation courses or Manufacturing Processes and Machine Design)? Why or Why not?
**Representative Responses**:

- "I think it could be a useful way of tying several courses together, which can help make clear the relevance to one another, as well as how the course material can be applied to real scenarios. I think it's a good way to show how a real job might use knowledge gained from several of these courses in one project."
- "Yes, I feel like it would help connect what can feel like many disconnected subjects and help unify the concepts across different professors."
- "I think multi-course projects among all the different courses would be super cool. It is a great way to make connections outside the class and understand when and where these topics appear in the real-world of engineering."
- "Yes. I think it would be very helpful. That is how capstone is, you start a project and work all the way through it start to end, and i think having other classes that follow that same step would be very helpful. It also helps you understand the whole project more when you do all the different steps to it."
- "I think that it would be great. It would be better than just one-off projects that don't really have much meaning. I kind of like the idea of a multi-course platform where it's a big culminating project and you get to see the entire process."

- "No, because incorporating more projects from multiple courses could overload the curriculum and make time management difficult for students who have not been good at certain classes and need to catch up. Also, not all courses have such a direct connection to warrant an integrated project, and it could lead to more confusion than meaningful learning."
- "Yes. It is less daunting to refer back to an earlier project rather than starting from scratch in every class. It also helps me feel like I'm investing in an actual project that is meaningful and not just a box to check to get a good grade."

Table IV includes a sample of student responses to the three short answer questions. For Q8, there was an overwhelming consensus that the more valuable part of the project is the real-world context of the project and helping the students tie theoretical concepts covered in the course to a problem they might try to solve as a practicing engineer. One of the goals of the authors with implementing this unique project was to help the students better understand how all the different concepts they learn in different courses are tied together. Based on the student responses, it would seem this type of project could help facilitate those connections without the instructors having to spend extra time in class. Student responses to Q9 were quite interesting, as many students commented on the project being too "easy" or wanting additional components to work on. For Q10, a majority of the students were open to the idea of more multi-course projects being incorporated into the curriculum, similar to the responses from the System Dynamics I survey. The quotes from student surveys in Table IV are presented verbatim to preserve the authenticity of their responses.

## Conclusions

This work-in-progress paper presented the design and integration of a multi-course project into courses within the mechanical engineering curriculum. A temperature control system served as the platform for the multi-course project, which was first implemented in System Dynamic I and System Dynamics II during the Fall 2024 semester. In System Dynamics I, students modeled the temperature control system using transfer function approach, while in System Dynamics II, students designed closed-loop controllers for the system.

Survey results from both courses indicate that students found the project moderately beneficial in enhancing their understanding of key concepts. Students reported that the project helped them connect concepts across courses, see the practical application of theoretical knowledge, and stay engaged with the material.

The project will be extended in future semesters to include students who experience the multi-course project in both System Dynamics I and II. The same survey will be utilized in both courses to compare the students' learning experiences. Additionally, the multi-course project will be implemented in Control and Vibration Experimentation and Mechatronics courses. New survey questions will be developed to better understand the students' experiences in the multi-course project. Future iterations of the project will incorporate student feedback to improve instructional design and enhance learning outcomes.

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