Design and Evaluation Method in Capstone Project: Robot Project Case Study

Jihoon Lim, Seattle Pacific University

Jihoon Lim received his Ph.D. in Mechanical Engineering from the University of British Columbia, Canada, in 2021. He is currently an Assistant Professor at Seattle Pacific University, United States. His research interests include optimal and robust control design, robotics, mechatronics, and engineering education. He also has over a decade of industrial experience in automotive engine control design, aftertreatment control systems, solar thermal control systems, and autonomous mobile robots.

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Abstract

This paper presents the design and evaluation process of a robot project conducted by a multidisciplinary student team. The novelty of this work lies in the following aspects: (1) Design and evaluation method are developed for a robot project, (2) The proposed work is implemented on the project and carried out by interdisciplinary engineering teams at Seattle Pacific University, consisting of undergraduate students from three disciplines—Electrical Engineering, Mechanical Engineering, and Computer Engineering, and (3) Lessons learned are derived from a year-long project performed in the Engineering Design Course.

The paper consists of three main sections. First, the paper describes the entire sequence of the project, including project ideation, risk reduction proposal, functional specification development, etc. Second, the paper outlines the design and evaluation procedure in robot projects. As a case study, a robot project is presented, emphasizing the design and evaluation method, and procedures. Finally, lessons learned, and students' feedback are discussed.

Introduction

Robotics has rapidly evolved into a fundamental component of industries ranging from household appliances to heavy equipment. As automated devices become increasingly integrated into modern society, the demand for skilled engineers capable of designing, programming, and managing robotic systems has never been greater. While the importance of robotics engineers continues to rise, education in the development of robotic applications has played a critical role in equipping students with the knowledge and skills necessary to thrive in the industry [1], [2]. The education of robot control in simulation environments has gained focus due to its advantages, such as being free and open source [3]. Additionally, effectively evaluating the outcomes of robotics-related projects is equally crucial to ensure that students gain both theoretical understanding and practical competence.

However, traditional engineering design and evaluation methods in robotics education have proven insufficient for providing students with a balanced exposure to cutting-edge technologies and practical activities [4]. One major reason is that robotics is a multidisciplinary field encompassing electrical engineering, mechanical engineering, computer science, and more. As a result, numerous challenges and ambiguities exist within educational and learning environments. Given the complexities of learning robotics, there is potential for the development of more effective evaluation methods in robotics education. To identify effective methods for design and evaluation in a robotics engineering design course, the previously developed engineering senior design methodology was applied in a project-based capstone course [5]. This paper proposes a design and evaluation method for robotics projects at the university level.

The paper is organized as follows. First, the structure of the engineering design course will be outlined. Second, the design and evaluation processes are presented based on the components integrated into the course. Next, the case study for velocity control is described. Finally, budget constraints and lessons learned throughout the course are discussed.

Structure of the engineering design course

Engineering educators have primarily discussed the novelty of industry sponsorship in capstone projects [5] and the importance of teaching teamwork to students [6]. While some projects are directly sponsored by industry, most are based on students' own ideas, which leads to greater engagement and passion. This allows students to engage in "needs-finding," a key opportunity highlighted [7]. The literature also emphasizes the importance of effective team functioning, with capstone courses providing guidance on teamwork. The entire sequence of the engineering design course is shown in Table 1.

Table 1. Structure of the Engineering Design Course

Period	Contents	Outcome
1st Quarter	Team formation and Problem research Project ideation, research, and scoping Risk Reduction Prototype (RRP) Design Review 1.1 Advisory Board Meeting (Presentation) Design Review 1.2	Required knowledge list Design Review 1.1 Design Review 1.2 Prototype (Simulation) demo for RRP
2nd Quarter	Lectures for required knowledge list Full Specifications definitions Design Review 2.1 Advisory Board Meeting (Presentation) Analysis and Testing (Simulation) for Full Specification Design Review 2.2	Design Review 2.1 Design Review 2.2 Demonstrate full models
3rd Quarter	Formal Test Plans Risk analysis and Safety Engineering Project Impact Reflection Conference Presentation Design Review 3.1 Demonstration to Public and Advisory Board	Design Review 3.1 Full Prototype

The goal of the first quarter is to initiate and develop the project. During the team formation process, project teams are created based on similar research interests of the students, considering race, gender, and major. Once the teams are formed, students start researching and selecting a real-world problem to solve. The instructors provide the students with their ideas and evaluate its feasibility. During the project scoping phase, students define the project specifications. In the first quarter, the focus is on the Risk Reduction Prototype (RRP), which addresses the parts of the project that may involve risk. Students develop the RRP specifications and confirm them through a rapid prototyping approach at the end of the first quarter. In design reviews, students present their RRP specifications. The advisory board meeting offers students the opportunity to present their progress to the industrial advisory board.

The objective of the second quarter is to expand the project scope to include the entire system. Building on the work completed in the first quarter, students now focus on the overall system design and evaluation. A key feature of the second quarter is the opportunity for students to secure additional funding by presenting their progress and the financial requirements for further development during the industrial advisory board meeting.

In the final phase, the third quarter, students focus on developing the test plan, as well as addressing risk and safety engineering. Their primary task is to construct the entire system and evaluate the performance of the prototypes. As a final step, they will present a demonstration to both the public and the industrial advisory board.

Proposed Design and Evaluation method

Design method: To reinforce the course outcomes and ensure students' efficient learning, this paper proposes new steps for design and evaluation in both the first quarter. In the first quarter, after conducting project scoping, students in the robotics project team define the technical skills and knowledge they need to acquire to successfully complete their project without delays or failure. This step has similarity with how a company hires new employees with the required skills. When companies in industries decide to develop a product, they research to make a list including the required knowledge and skills. After extruding the list, they make open positions to hire the engineers who have key qualifications and preferred background. Although the team is interdisciplinary in the engineering design course, it does not imply that all members possess the necessary knowledge and skills for developing all products.

To find what students need to possess in terms of knowledge and skills, they create a robot control system diagram based on their project scoping, as shown in Figure 1.

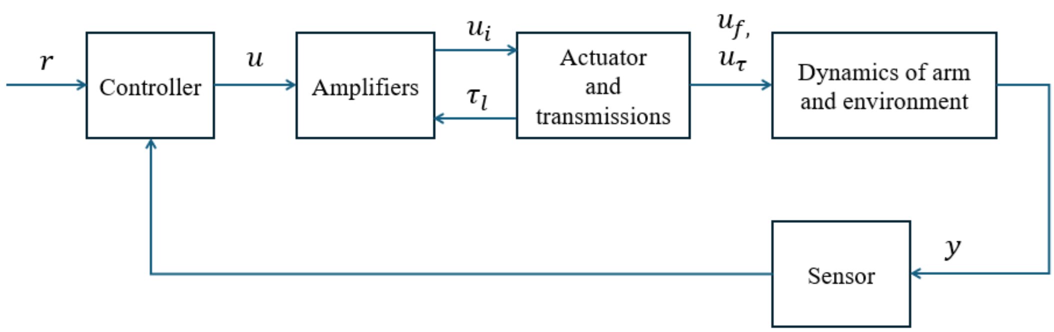


Figure 1. Typical Robot Control System

where, r, u, u_i, τ_l, u_f, u_τ and y represent desired behavior, low power controls, high power controls, local feedback signals, forces and torques, motions and forces, respectively. Each component and signals can be determined based on the results of the project scoping. Students also list the required knowledge and skills for developing each component, continuously refining this list throughout the course.

At this stage, students also identify ways to acquire the required knowledge and skills, and the instructors provide guidance. The solution involves finding other team members who are familiar with the knowledge and skills needed or requesting short lectures or connections to other experts through the instructor. If the relevant knowledge is simple and readily accessible, there is no issue. However, if the knowledge is difficult to acquire or cannot be obtained within several weeks, the scope of the project must be carefully modified and reconfirmed with the instructors.

If there is a possibility to take the short lectures given by instructors or other professors at the university, the schedule for these lectures or information-sharing sessions can be arranged in the remaining the first quarter or the upcoming second quarter.

Evaluation method: Providing the criterion allows students to gain a clearer understanding and enables their prototypes to be assessed using a technically validated method. The proposed evaluation procedure is as follows: (1) Confirm the setpoint value of the system. (2) If the setpoint is desired trajectory, measure the positions, x, y, and orientation of the system. (3) If the setpoint is desired velocity, measure the left-side and right-side velocity of the system. (4) Plot the setpoint and the measured output signals. (5) Analyze the step response specifications.

The robot control system can be assessed based on the step response [8]. This method is commonly used in modern control system designs. If the desired velocity is $v_d(t)$ and the actual velocity is $v(t)$, the velocity error can be defined as

$$v_e(t) = v_d(t) - v(t).$$

The differential equation of the velocity error, $v_e(t)$ of the robot control system is called error dynamics. The objective of the robot controller is to create the error dynamics, $v_e(t)$, tends to a small value or zero. There are three step response specifications: steady-state error, overshoot, and settling time. The steady-state error, e_{ss}, is the asymptotic error $v_e(t)$ as time increases to infinity. In other words, it is the difference between the desired output and the actual output once the system has settled. The overshoot occurs if the response overshoots the steady-state value and can be defined as

$$Overshoot = \left|\frac{v_{e,max} - e_{ss}}{v_e(0) - e_{ss}}\right| \times 100\%,$$

where $v_{e,max}$ is the peak value achieved by error.

The 3% settling time is the first time such that difference between $v_e(t)$ and e_{ss} is less than 3 % of difference between $v_e(0)$ error and e_{ss}. The detailed level of the step response specification can be determined based on the customer requirement by the students with the instructors. Figure 2 shows an example of the error response determined by

- Little or no overshoot,
- Little or no steady state error,
- Short 2 - 3 % settling time.

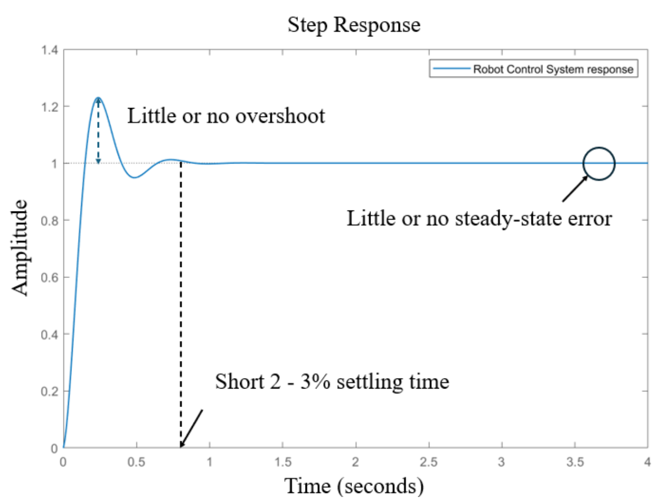


Figure 2. Typical step response

It is observed that the robot control system tracks the setpoint value at around 0.8 seconds with little or no overshoot and steady-state error.

Proposed design and evaluation method: The sequence of design and evaluation in the first quarter is enforced based on the proposed design and evaluation method as shown in Figure 3 (See the bold-faced step).

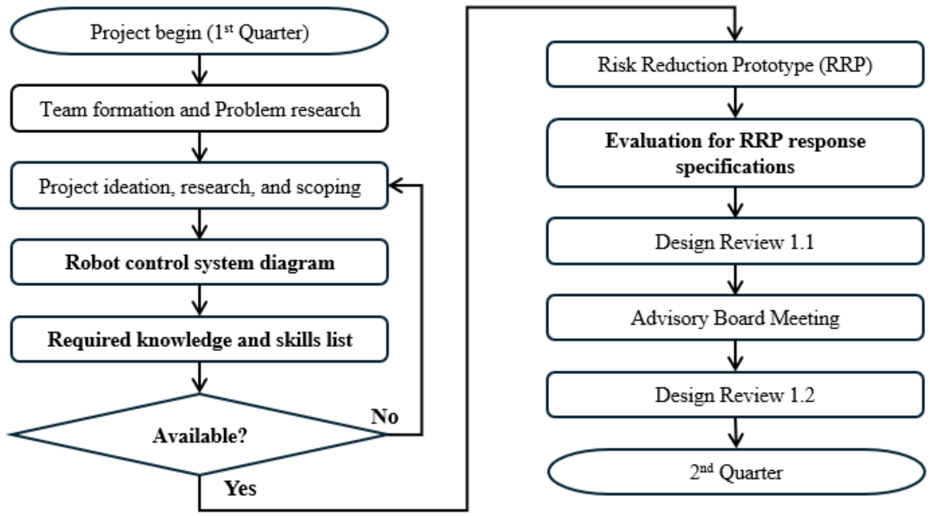


Figure 3. Sequence of Design and Evaluation in the first Quarter

Case study: Velocity Control in Mobile Robot

The robot design team is formed in the engineering senior design course. The key features of the team are as follows: (1) limited experience in robotics and controls, (2) university senior student level knowledge and skills for 3D modeling, mechanical structure design, electrical circuit design, and computer programming skills, and (3) budget constraints. The robot control system diagram is designed as shown in Figure 4.

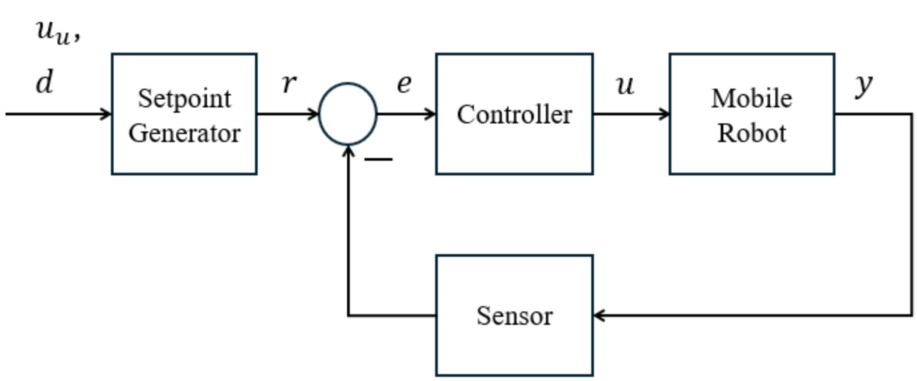


Figure 4. Robot Control System Diagram

Here, u_u, d, r, e, u, and y represent user input, disturbance, setpoint, error, control input, and system output, respectively. Table 2. Shows the required knowledge and skills to develop the mobile robot.

Table 2. Required knowledge and Skills list

Modules	Required knowledge and Skills	Status	Plan
Setpoint Generator	Wireless communication, Computer vision (image processing), Electronic circuit design.	Y N Y	- Lecture by Instructor -
Controller	Control theory, Microcontroller, Programming (Python, C, C++, etc).	N Y Y	Lecture by Instructor - -
Actuator	Electric motor (Stepper, DC, BLDC, etc).	Y	-
Mobile Robot	Kinematics and Control, Dynamics, Robot Operating System (ROS). 3D modeling 3D printing	N Y N Y N	Lecture by Instructor - Self-study - Lab. Technician
Sensor	Ultrasound sensors, Loadcell, Camera Sensor fusion.	Y N	- Group-study

Budget Constraint

Since a budget constraint was enforced on the students, it caused challenges in developing prototypes. However, it also helped them cultivate responsibility and problem-solving skills in a challenging development environment. The students reused parts and components from previously used prototypes and the university's inventory. By utilizing parts that were either initially provided or previously used, they were able to identify the pros and cons of these components, allowing them to assess the applicability of the products they were developing. This experience enabled them to make more informed and effective decisions when requesting funds in the second quarter.

Lessons learned

Importance of fundamental knowledge: In the capstone project, the level of understanding is crucial for successful project execution. Most students without relevant experience struggled during the project, as the lack of foundational knowledge led to delays and challenges in development. While using YouTube videos or internet blogs can provide some intuition, their usefulness is limited for completing the project. Carefully considering the basic qualifications of team members in relation to the project scope is a critical step that students need to address.

Collaboration with different fields: In the robotics team, a total of eleven students participated: five from the engineering team and six from the software team. The team members attended a joint meeting every week, with one professor leading the session from either the engineering or software team. Since close collaboration between the teams was essential, these regular weekly meetings played a key role in fostering communication and cooperation. Sharing objectives, expectations, and technical information each week during the joint meetings enhanced students' understanding of the entire project and helped reduce barriers between the teams, fostering a more collaborative environment.

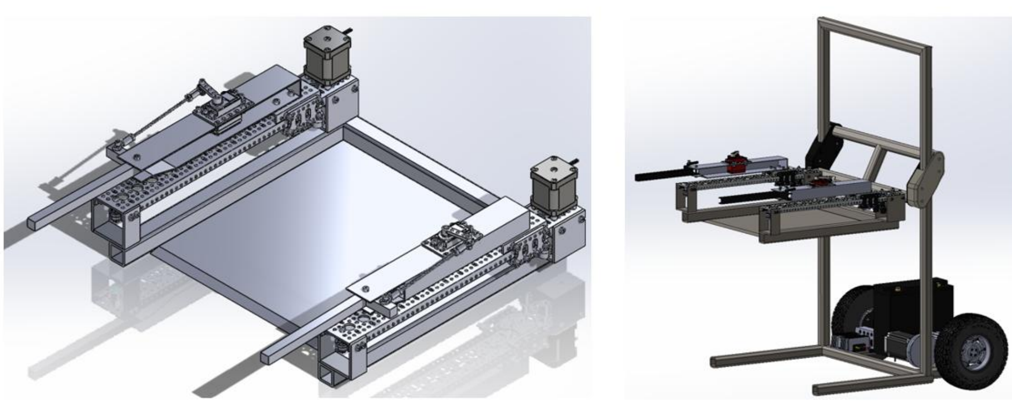
Students' feedback

It was observed from the students' feedback that the proposed design method is effective. The main feedback from the students is as follows:

- The informative lecture by the professor was very helpful in identifying gaps in our knowledge.
- I appreciate the weekly meetings with the teams and professors to check on project progress.
- The feedback in class and from the board was very useful in identifying problem areas we had not considered or lacked strong knowledge about.
- The professors visiting each team to check in and provide feedback was very helpful.

Preliminary Project Deliverables

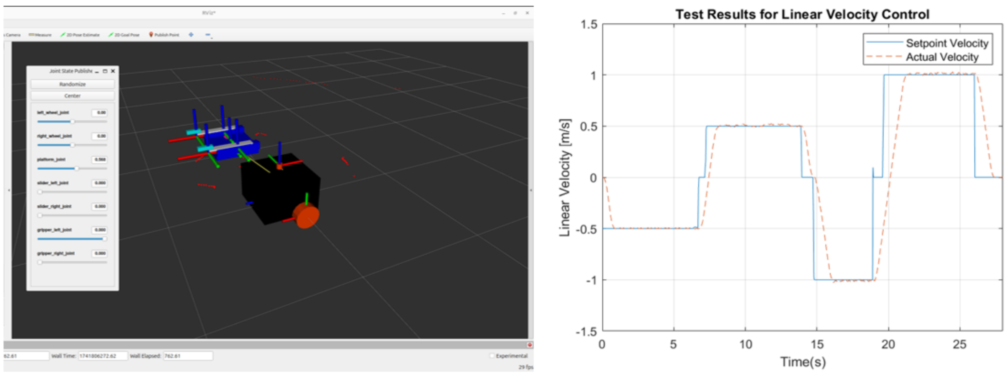
Figures 5 and 6 show examples of the project deliverables related to 3D modeling, simulation, and testing. The 3D model of the grippers is shown in Figure 5(a), and the complete robot assembly model is depicted in Figure 5(b). The robot's purpose is to lift heavy objects to the desired height based on the user's demand, featuring both remote control and autonomous drive capabilities.



(a) (b)

Figure 5. 3D models developed by students: (a) 3D model of the grippers, (b) Complete robot assembly model

Figure 6 (a) shows the results of the simulation test using Robot Operating System (ROS). Students developed the robot control system based on ROS and implemented tuned control gains into the practical robot system. The result of the experiment is shown in Figure 6 (b). As shown in Figure 6 (b), the system was evaluated based on the proposed evaluation method with the comparison of setpoint values with actual values.



(a) (b)

Figure 6. Simulation tests and Experiments conducted by students: (a) Results of the simulation test using Robot Operating System (ROS). (b) Result of the experiment

Conclusions

In this paper, design and evaluation methods are proposed based on system diagrams and step response evaluation. The robot control system diagram developed during the design phase was found to be effective in helping students identify the components they need for the development stage. During evaluation, students gained a clearer understanding of which tests to perform and how to prepare for prototyping. A case study on velocity control for mobile robots was conducted using the proposed design and evaluation methods. Based on student feedback, it was confirmed that these methods improved their design performance. As future work, more data will be collected on students' progress to assess whether the educational objectives of the project were achieved. Additionally, the proposed method will be further refined for use by other educators and practitioners.

Acknowledgements

I acknowledge Dr. Lin Liu, who is a co-instructor in the Engineering Senior Design Course, as well as all the students from Mechanical Engineering, Electrical Engineering, and Computer Engineering, who have been working on their projects since September 2024. I also acknowledge that most of the senior engineering course sequence described here was primarily developed by Dr. Kevin Bolding, Dr. Adam Arabian, Dr. James Gordon Walker, Gina Howe, and

Dr. Melani Plett, who collectively developed and taught our university's engineering design course. Additionally, I would like to acknowledge Professor Andy Cameron, who works with the guidelines for the joint robotic team.

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