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Implementing Industry Practices for an Undergraduate Engineering Senior Design Capstone Program

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Project Management and Systems Engineering are integral components of the Senior Design Capstone Program in Mechanical Engineering at San Diego State University. Requirements management, risk management, cost, schedule and scope management, requirements verification and key program milestones including design reviews have been implemented. This paper provides an overview of the program with emphasis on the implementation of Project Management and Systems Engineering practices. Key course metrics are provided as well as project sponsor and student feedback.

Keywords: Systems Engineering, Project Management, Engineering Design, Senior Design Capstone Programs

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Introduction

The San Diego State University (SDSU) Mechanical Engineering (ME) Senior Design Capstone Program is comprised of a two-semester course sequence designated as ME 490A/B. The program is project based with sponsorship by industry, non-profit organizations, the US government and by SDSU faculty. During the program, students work on a design challenge progressing through project management, systems engineering, preliminary design, engineering analysis, trade studies, critical (final) design and then onto fabrication, assembly, and testing. The Senior Design Capstone Program milestones are provided in Figure 1.

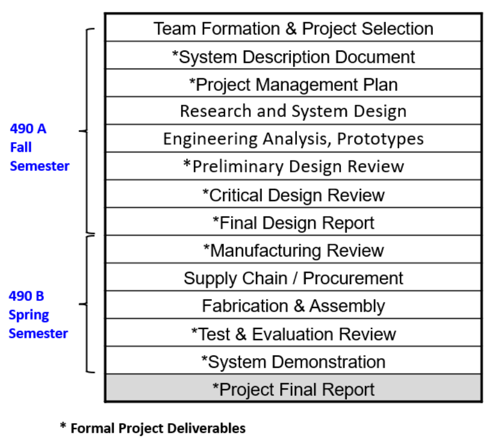

Figure 1 Senior Design Capstone Program Milestones

Project team sizes range from 3 to 6 students, with most teams comprised of 5 students. Project teams are formed using the Purdue University CATME[1] system which has been shown to be very effective for student team formation[2]. We also utilize the CATME system for peer-to-peer surveys which provides an effective means to understand individual or team performance issues[3]. Typical total labor hours spent by a ME project team over the academic year on a project is in the range of 1,500 to 2,000 hours. Project material budgets provided by sponsors have ranged from \$500 to \$70,000, with an average of \$2,800 per project. The higher cost projects often involved the purchase of commercial subsystems.

In the ME program, students learn how to work effectively in teams, apply conceptual design methods, and take a project from a customer need to an operational system. At the end of the program, students are required to demonstrate the functionality of their design as set forth in a requirements document. Upon completion of a project, the goal is for students to be able to:

- Apply engineering principles and design techniques to the design of an engineering system.
- Apply principles of project management and systems engineering to the design of an engineering system.
- Fabricate an engineering system that meets specified design goals, and test and demonstrate its functionality.
- Function effectively in teams whose members together provide leadership, create collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.
- Communicate effectively, orally and in writing, with a range of audiences.

- Recognize ethical and professional responsibilities in engineering situations and make informed judgements, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.

The SDSU ME Senior Design Capstone program has also developed a strong cross-disciplinary aspect that is unusual in undergraduate education, and yet mirrors how projects are completed in industry. This involves conducting joint projects with the ME and Electrical and Computer Engineering (ECE) Departments. In our 2021-2022 program for example, we have 18 joint ME/ECE projects. These projects are typically comprised of 5 ME students and 5 ECE students. Joint teams work to common project definition documents and milestones.

The SDSU Senior Design Capstone program includes collaboration between SDSU colleges. For example, Engineering has teamed with the SDSU Arts + Design College on one of our joint ME/ECE projects. In that project, the Arts + Design students created the product branding including the product's external graphics. In addition to this collaboration, the SDSU Fowler School of Business has assigned business students to create business plans in support of ME capstone projects.

The rest of the paper will cover the foundation for our capstone program, which is Project Management and Systems Engineering.

Project Management

Given that Project Management has been well established as a methodology to manage projects in industry and government through a set of common practices such as those provided by the Project Management Institute[4], there is value in applying it to capstone programs in academia. In our program, all student teams create a Project Management Plan within the first few weeks of the project. This plan includes student work scope, project schedule, team organization and material budget. For project schedules, teams will create a Gantt chart. In the 2021-2022 academic year, we adopted the use of an on-line tool called TeamGantt[5] which provides real-time access by faculty, project sponsors and students. For the project scope, a Work Breakdown Structure is created.

Once the project is fully defined and the project plan completed, the student project teams conduct research followed by design work to include brainstorming, trade studies and engineering analysis using modeling and simulation tools. Our teams utilize a collaborative sketch method for initial design brainstorming. Project teams are required to create prototypes as well as conducting subsystem testing early in the design process. Project communications include weekly status reports published to project sponsors, course advisors and all team members. The student's design solutions are evaluated and approved through Preliminary Design and Critical Design Reviews.

Following design approval, the teams begin materials procurement followed by manufacturing including fabrication and assembly. A test and evaluation phase follows manufacturing. During this portion of the capstone program, manufacturing and test reviews are conducted. We will now discuss the integration of Systems Engineering practices in the program.

Systems Engineering

Systems Engineering (SE) practices are a key part of the SDSU Senior Design Capstone program. Students utilize SE guides such as the one used by NASA[6]. The SE model adopted for our program is shown in Figure 2.0.

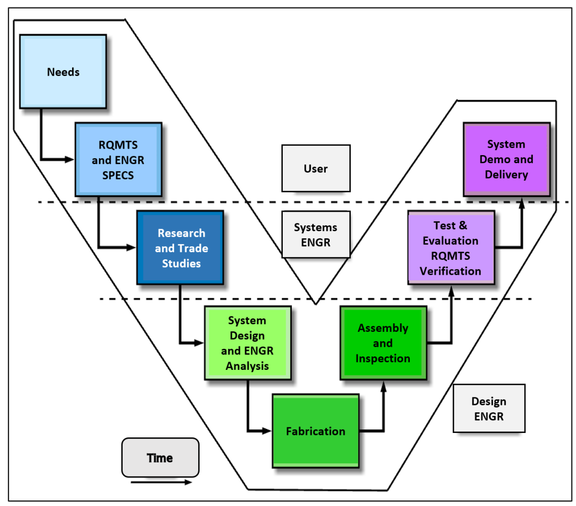

Figure 2 Senior Design Capstone Program System Engineering Vee

Systems Engineering tools employed by our program include requirements management, requirements verification, system level diagrams and risk management. Each of these will be described next.

Risk Management

All teams are required to identify risks and actively manage those risks including implementing mitigation steps throughout their project. Both technical and project management related risks are included. If a risk is realized it will transition to an issue for the team to manage. If a risk is successfully mitigated, it is then retired (removed) from the risk plan. The use of risk management in our program was a significant reason why our project teams were able to complete their work during the COVID pandemic in that all teams identified a COVID related risk early in 2020 and implemented mitigation steps for fabrication and testing. This was critical when SDSU closed their campus in early 2020.

An example of a senior design project risk management plan with risk cube is provided in Figure 3.

Risk Management			
	Code	Risk Statement	Mitigation Strategy
Manufacturing	A	If the desired materials are unavailable when the manufacturing process begins, then the manufacturing schedule will be delayed.	Multiple sufficient materials and suppliers will be chosen through trade studies to prepare secondary options to ensure the schedule remains on track.
Manufacturing	B	If the desired machines at the SDSU machine shop are unavailable, then the manufacturing schedule will be delayed.	Alternative machining strategies will be made prior to the manufacturing phase. Other machine shops and services will also be found to use if needed.
Design	C	If the material is not sufficient to handle the applied loads, then the device will break and the user will likely be injured.	Trade studies will be performed to choose adequate materials and prototypes will be tested to ensure materials meet the requirements.
Design	D	If the geometry of the device is not sufficient to handle the applied loads, then the device will break and the user will likely be injured.	FEA analysis of the CAD designs will be performed to obtain information on the strength of the geometry prior to manufacturing. Prototype testing will be conducted to ensure that the device geometry will not fail.
Design	E	If the contact of the ASA on the handlebar does not maintain, then the device will fail and may provide insufficient grip which may result in injury.	Material and mechanical testing of prototypes will reveal the effectiveness of the device in performing its primary function. Focus here will be on material contact and tightening mechanism of device.
Design	F	If the device is uncomfortable during use, then the device has provided discomfort to the user and may be disregarded.	Testing of the device's comfort will be done by the team and prototypes of the device and materials will be shipped to the client for feedback to ensure there is no discomfort in the final design.
Design	G	If the device prevents the user from safely and immediately detaching from the handlebar, then the user will be at a higher risk of serious injury.	Testing of prototypes and final design with local riders will ensure that safe and immediate dismount is never compromised.
Design	H	If the client does not like the device for any reason, then the device may not be utilized.	Communication with the client will be maintained throughout the rest of the design phase and the maufacturing phase for the team to recieve feedback from the client.

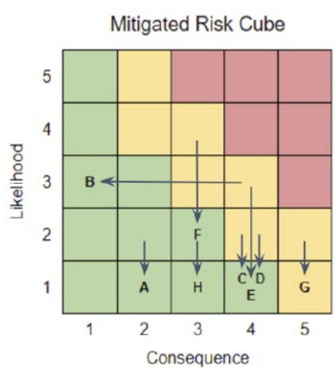

Figure 3 Example Risk Management Plan

Requirements and Specifications Management

For all projects, the project definition will start with a problem statement coupled with a set of goals and milestones. The student teams, working with their project sponsor, will develop a formal System Description Document (SDD). The SDD includes a list of requirements along with associated specifications. An example of this is provided in Figure 4. The use of requirements in engineering projects has been previously demonstrated as a key student project success factor[7]. Project constraints and assumptions are also documented in the SDD along with the team's plan for how they will verify each requirement at the end of the project.

The SDD is the only project document that is managed using a formal configuration control process. While modifications of the SDD are allowed, they are controlled via a "Change Form" which enables documentation of the change along with formal approval by the project sponsor and the course instructor. This process aids in controlling changes that could jeopardize the completion of the project within the academic year.

Specification Number	User Requirement	Engineering Specification	Justification
S1-001	The robot shall disassemble to not exceed the TSA checked bag weight limit.	The max total weight shall not be more than 50 lbs.	In order to travel by flight without a fee, the checked bag needs to be under the provided weight.
S1-002	The disassembled robot with components shall not exceed the TSA checked bag size limits.	The checked bag shall not exceed 62 linear inches total.	In order to travel by flight without a fee, the checked bag needs to be under the provided size limit.

Figure 4 Example Requirements Table

Project teams are required to identify how they will verify each requirement. The initial plan for this is included in the team's SDD, and later updated as the project progresses. Students are instructed to utilize demonstration, test, analysis and/or inspection in the requirements verification process. Each project concludes with a formal verification of the system as built against the requirements and specifications as defined via the SDD.

Systems Level Design

Students develop a diagram outlining their overall design from a system level perspective. We call this the System Level Diagram (SLD), an example of which is provided in Figure 5.

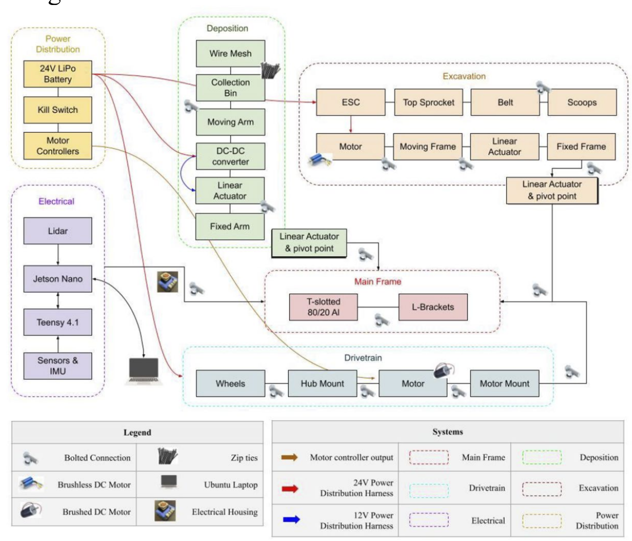

Figure 5 Example System Level Diagram

The SLD shows all the key subsystems, as well as interfaces between subsystems. The SLD is updated throughout the program as the design matures.

Sponsor and Student Outcomes

A survey of our students is conducted each year at the completion of the Senior Design Capstone Program. Key results related to the topics provided in this paper from the 2020-2021 academic year program survey, which included responses from 154 students, are provided in Figure 6. Overall, these data indicate strong support for the use of Systems Engineering and Project Management. Moreover, our students have consistently developed design solutions that have met their sponsor's project goals including satisfying the system requirements. Students have also shown a high degree of satisfaction with their overall project experience judged by post-course surveys and direct feedback. Likewise, our sponsors have provided very positive project evaluations, expressed support for our program's methodology, and have returned to sponsor projects over multiple years.

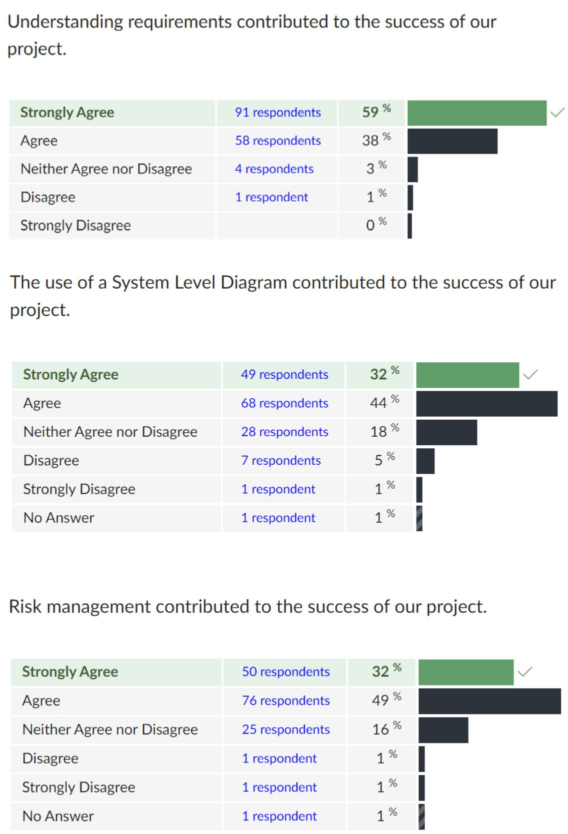

Figure 6 Student Survey Results, 2020-2021 Program

In 2020, a joint ME/ECE SDSU senior design team was selected by NASA as one of ten national collegiate teams to compete in the 2021 NASA Moon to Mars Ice Prospecting Challenge. The SDSU team, which was unique in that it was a first-year team amongst a field of returning teams, was very competitive, including achieving successful drilling operations coupled with water extraction on the first day of the event. NASA specifically cited our Project Management and Systems Engineering as SDSU team strengths. SDSU recently achieved another first-year collegiate team success via our selection in the 2022 NASA Lunabotics competition. Furthermore, in 2021, a SDSU ME senior design team took first place in the University of Texas at Arlington (UTA), 3D Printed Aircraft Competition. The results from the NASA and UTA competitions provide objective evidence for the effectiveness of the use of Systems Engineering and Project Management in our program.

Conclusion

The implementation of Systems Engineering and Project Management at SDSU in support of the Senior Design Capstone program has been successful as demonstrated through designs that have consistently met sponsor requirements, SDSU selection and placement in collegiate competitions and student/sponsor feedback. We have adopted tailored versions of key industry Systems Engineering processes for our student projects including risk management, requirements management, and System Level Diagrams. Likewise, tailored Project Management processes have been successfully utilized including those for managing project work scope, schedule, and material budget.

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