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Board 31: Case Study: Reimagining a Design Project with 3D-printed Concrete

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Re-imagining a Design Project with 3D Printed Concrete

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Abstract:

Additive manufacturing with concrete has surged over the last decade, potentially reshaping the landscape of the construction industry. This innovative technique introduces numerous engineering challenges due to the intersection of printer mechanics, volumetric extrusion dynamics, and performance-driven concrete mixture designs. In response to this evolving landscape, a integrative design project was modified to explore the emerging field of 3D printing with concrete. The objectives to this project include strengthening material design concepts, building experimental design skills, and providing hands-on experience with a new technology. Additionally, this project introduces the concept of prototyping a design which is not common in civil engineering. Students are tasked with designing and building an egg protection device using a 3D concrete printer. The initial phase consists of a mixture development phase followed by empirical testing of the fresh properties of their mixture to determine the optimal mortar mixture. In the second phase, students design their egg protection device, convert the model to machine code, print their structure and finally load test it. Reports are required at the end of each phase, and a summary presentation is made to the entire course at the end of the project. This project aims to improve several student outcomes such as experimental design and analysis, research of new technology, and communication. Initial student reflections were collected at the end of the project and are presented here. By intertwining contemporary technology with traditional course structures, we aim to reinforce the design thinking of students while providing hands-on experience with an emergent technology.

Keywords:

Integrative design course, Additive manufacturing, 3D printing with concrete, Egg Protection Device, Prototyping, Civil engineering education.

Introduction

Senior design and integrative design courses often represent the culmination of coursework for a student in an engineering program. While these courses may range in methodology or scope, the common goal is for students to apply a range of skills to develop a design project that spans their engineering discipline. In civil engineering programs, these projects may come directly from professional practice or include experiential components to develop a preliminary design [1]. With other engineering disciplines, such as mechanical or electrical, there may be requirements to develop prototypes to iterate on their designs. The prototyping and iterations provide tangible points in the engineering design process [2]–[4]. In this study, we investigated an alternative integrative design project that would incorporate prototyping and iterative design using an emergent construction technology in a concrete materials course at the University of Illinois Urbana-Champaign. The course is an upper-level undergraduate and entry-level graduate course. The majority of students enrolled are from the Civil and Environmental Engineering Department, but the course is open to any engineering discipline. The course objectives are as follows:

- Describe the production, reactions, and kinetics of Portland cement
- Select chemical and mineral admixtures to achieve desired fresh and hardened concrete properties
- Perform standard tests to characterize the fresh and hardened properties of concrete
- Design concrete mixtures to achieve a range of desired properties
- Predict the properties of concrete over time under different conditions
- Explain various specialized concrete materials and their evolving role in concrete construction

While this course reinforces the fundamentals of Portland cement and concrete, numerous new material and constructions advances are also introduced. The complimentary lecture and lab sessions allow for students to learn theory and apply it in a hand-on environment.

Re-Imagining a Design Project

The previous integrative design project for students focusing on construction materials was housed in the aforementioned Concrete Materials course. The project required students to develop several different concrete mixtures to meet specific targets for workability, strength, durability, and ductility. Most property targets would reflect requirements for structural or transportation infrastructure design. Students would use their measured properties in the preliminary design of structures, pavements, or geotechnical applications. This approach provided connections between the course materials with other civil engineering disciplines. Various reports and presentations would be used to document students' progress.

While this approach satisfied various ABET and curriculum requirements, we felt there was an opportunity to leverage a new construction technology that would maintain the interdisciplinary nature of the project while exposing students to an alternative engineering design method involving prototyping. The technology is additive manufacturing or 3D printing. While 3D printing concrete is still primarily in the research stage of development, there are several industries looking to deploy this technology in the near future for the military, housing, and even off-world applications [5]–[7].

The 3D printers for concrete represent a shift in concrete construction technology. At their core, these printers' function by extruding a specially formulated concrete mix layer by layer, following digital blueprints, to construct a variety of structures instead of convention formwork. This process is typically managed by software that converts architectural designs into precise printing instructions, ensuring accuracy and efficiency. The primary advantage of this technology lies in its speed and efficiency, significantly reducing construction time compared to traditional methods. Additionally, it offers substantial cost savings through reduced labor and material wastage, while also allowing for unprecedented design flexibility and complexity.

While there are numerous advantages to 3D printed concrete, there are opportunities for students to explore the challenges that persist in this technology. These challenges serve as the basis for the design project described herein. The first challenge is the specialized rheology. Mixtures should have a low viscosity in order to be pumped and extruded, but they also must develop yield strength rapidly to maintain the extruded shape. This challenge also allows students to practice designing experimental testing plans. Another challenge is that printed structures do not have to conform to typical prismatic members. Material placement can be optimized to reduce self-weight and material usage. Finally, this technology is relatively new to the civil engineering discipline, but they are likely to encounter it in their future careers. Students must interact with robotics and machine coding to generate a printed structure. Despite these unique opportunities, 3D printing concrete in a civil engineering course is not well-documented [8]. This work serves to provide an example of using 3D printed concrete in an integrative design project.

Educational Objectives

The outcome of this project is to design and fabricate an “egg protection device” utilizing concrete, 3D printer. To find out the optimal mix design for the device conventional construction materials: cement, sand, and water have been used. These materials were chosen for their proven reliability in construction applications and were subjected to qualitative assessments of their fresh properties to ensure compatibility with 3D printing technologies. Then the construction of the device was facilitated using a concrete 3-D printer, available at the institution’s concrete lab. To prepare for printing, a structural print path is to be created using the Ultimaker Cura or similar software, which is then converted into G-code format suitable for the 3D printer. An important aspect of the design strategy was the decision to utilize a 100% infill density. This decision was based on the goal of creating a cohesive structure, where each line of print contributes to an uninterrupted, solid mass, thereby enhancing the device's capability to protect the egg. Furthermore, students should opt for a concentric infill pattern in the 3D printing process. This pattern choice was strategic, aimed at reducing the frequency of start-and-stop actions of the printer, which in turn minimized potential discontinuities within the printed structure. Careful consideration of infill patterns and density is crucial in ensuring the structural integrity and functionality of the final egg protection device.

This project supports several course and curriculum-level objectives that were assessed at the end of the project through a survey. The objectives are as follows:

i) Describe the construction process for concrete infrastructure (Course Objective)
ii) Describe the process of additive manufacturing (3D printing) (ABET #7)
iii) Incorporate the multiple engineering disciplines to develop a new design (ABET #2)
iv) Demonstrate the engineering design process (ABET SO #2)
v) Design and execute an experimental plan (ABET SO #6)
vi) Communicate engineering results (ABET SO #3)

This study utilizes survey data to systematically examine the effects of the project on student learning and professional development in civil engineering. The research questions intended to be addressed through this study are outlined as follows:

(i) How does participation in an integrative design project involving 3D printing with concrete influence students' understanding of engineering design processes?

(ii) To what extent do projects incorporating emerging additive technologies like 3D concrete printing enhance students' skills in experimental design and material design concepts within a civil engineering curriculum?

(iii) Given that prototyping is not commonly emphasized in civil engineering, what are students' perceptions of the value and relevance of prototyping in civil engineering after participating in the project?

Project Format and Logistics

Deliverables

The project integrates foundational knowledge of solid mechanics, structural design and analysis, and concrete materials to produce a concrete structure that is 3D printed. The context for the project is that students will work as a team, competing with the other teams in the course, to develop the following deliverables:

1. Designing an Experiment for 3D printed concrete: Throughout the course, students are exposed to a range of tests for concrete, many of which are empirical. Since 3D printing concrete is an emergent technology with unique demands for characterization such as “printability”, students are challenged to develop their own empirical test that will differentiate different concrete materials in the application of 3D printing. In the interim and final report, students detail their test procedure and report the results of their test on different mortar mixtures.

2. Mixture design development: In conjunction with designing a unique test method, students design a custom mortar mixture that will be used in a 3D printer for their structure. In this deliverable, students develop an experimental design where at least two variables are tested at two different levels. Students choose their experimental variables to test and which experimental tests will serve as the outputs. From this work, students choose their final mixture design to print.

3. 3D Modeling and Printing Technology: Students are tasked with 3D modeling, translating designs into machine-readable formats, and learning the operational aspects of 3D printing technology. While modeling is not unique to civil engineering students, generating machine code (“g-code”) is and students must learn the features of the coding to optimize tool pathing and balance extrusion parameters.

4. Designing and Prototyping: Teams are given dimensional constraints, and are encouraged to explore multiple designs. In the modeling software, students can analyze the stresses and remove material to optimize the self-weight of the egg-protection device (EPD). This iterative design approach is reinforced through a prototyping phase where students design, print, test, and then refine their design, print, and test again.

5. Technical communication: This project requires student teams to communicate their progress and findings in two written reports and an oral presentation. The first written report is focused on their mixture testing and their standard test development. This report is in the form of a memorandum where conciseness and precision are emphasized in the writing. The second report is the culmination of the project with all of their testing, iterative design documentation, and comparison of performance of the final products. In addition to the final report, students present to the instructors and peers which allows them to ask questions and compare methodologies between the groups as they prepare the final written report. The three report styles (memorandum, presentation, and comprehensive report) mirror the styles covered in the prerequisite advanced composition course. Peer evaluations and team reflections are also gathered with the final report. In the evaluations, students identify strengths, weaknesses, and areas for improvement.

These goals collectively aim to provide a comprehensive educational experience that blends theoretical knowledge with practical skills, fostering a new generation of civil engineers adept in both traditional and innovative construction technologies.

Timeframe and Assessment

The timeline for the project reflects a scaffolded approach where the first half of the semester is spent on fundamental knowledge of concrete materials, and the second half is dedicated to the project. The core information is presented in lectures and readings, and students gain hands-on experience in structured laboratory exercises. The laboratory exercises provide experience with mixture design and material testing that will become critical when the project begins. The lectures include specialized content regarding the rheology of cementitious materials and the fundamentals of 3D printing as students begin to work on the project. The timeline for the experimentation and subsequent deliverables under this project is organized as follows:

(i)**Experimental Mixture Development and Test Development Report Submission:** The brief, memorandum report detailing the experimental process and test development for the mortar mixture is submitted two weeks after the project is initiated. The report composes 25% of the project grade and is assessed following a standard rubric that addresses both writing quality and technical content.

(ii) **3D Printed Structures:** Teams must design, print and test at least two iterations of their EPD three weeks after their mixture design memorandum is submitted. Multiple printing sessions are provided to ensure all teams have adequate opportunities for successful printing. Teams also demonstrate and justify to the instructors where changes were made to their model or mixture prior to subsequent prints. The final testing date is shared for all teams. While there is no direct assessment of the printed structure, student teams do need to compare their performance as part of the final presentation and written report. Teams only lose credit (10%) if they are unable to complete their two iterations by the deadline.

(iii)**Final Presentations:** Each student team presents their project to the other students one week after the final structural testing. Presentations include key information that is outlined in a standard rubric and account for 25% of the project grade (Figure A-1). Teams are also required to compare the various performance metrics of their project with those of the other teams. For example, a group may chose to prioritize strength where another may prioritize the cost of materials (as determined by the mixture design). In addition to the technical content from the project, presentation style and slide format is assessed for clarity and professionalism.

(iv) **Final Written Report:** Each team submits their final report one week after their presentation. The intent is that the presentations will provide additional feedback that may be incorporated into the report. The final reports which comprise 50% of the project grade are assessed with a standard rubric for technical content and writing quality (Figure A-2). At the same time, but separate from the report, each student will submit a peer evaluation of their teammates and a reflection on their groups' performance directly to the instructors. While only one peer evaluation is conducted at the end of the project, these teams provide additional evaluations prior to the start of the project based on the work in the first half of the semester. The trends established in the peer evaluations may modify final lab and project grades if problems persisted throughout the semester.

With the current format, this project fits into the second half of a fourteen-week semester. Much of the testing and group work is accomplished during the regularly scheduled laboratory sessions, but some additional time is required for the printing sessions which can take 1-2 hours for each print.

Student Feedback and Analysis

Students were given a survey at the end of the semester to reflect on the project and what they've learned throughout the semester. All students enrolled in the Fall 2022 course were given the survey with 7 responding. The surveys were anonymous and no demographic information was gathered. The goal of the survey was to provide some initial feedback about the structure of the course and the semester project. Several of the questions reflected the objectives of the project to provide insight on whether students saw improvements in these areas. There were 13 questions total about feedback with 9 questions being on a Likert scale and the other 4 being open-ended. Table 1 lists all of the questions asked and their question type. The 4 open-ended questions were analyzed for commonly mentioned themes by a graduate student. Additional analysis and data collection in the future will be guided by these initial responses.

Table 1: Survey questions distributed at the end of the project

Question	Question Type
1.) Prior to this course, how well did you understand current concrete construction practice?	Likert Scale *1 – No understanding* *3 – Some understanding* *5 – High level understanding*
2.) Throughout the course, how did your understanding of concrete construction practices change?	
3.) Prior to this course, how well did you understand 3d printing or additive manufacturing?	
4.) Through the project, how did your understanding of 3d printing change?	
5.) To what level do you agree with the following statement: This project caused me to be more interested in concrete construction.	Likert Scale *1 – Strongly Disagree* *3 – Neutral* *5 – Strongly Agree*
6.) To what level do you agree with the following statement: I used my knowledge from multiple areas of engineering to complete this project.	
7.) Which areas of engineering or technology did you use?	Open ended
8.) What engineering skills or technologies did you learn independently during the course of this project?	Open ended
9.) To what degree did this project affect your understanding of the engineering design process?	Likert Scale *1 – Very low* *3 – Neutral* *5 – Very high*
10.) Explain your previous answer	Open ended
11.) To what degree did this project affect your ability to design and run experiments?	Likert Scale *1 – Very low* *3 – Neutral* *5 – Very high*
12.) To what degree did this project affect your technical communication skills through written reports and presentations?	
13.) Explain your previous answer.	Open ended

Questions 1 – 4 revolved around how students saw their understanding change over the course of the semester. Since students have very different backgrounds, these paired questions provided some insight to their overall experience with the course and project concepts. Table 2 shows the mean and standard deviation (STD) of the four questions. For Questions 1 and 3, the means were 2.71 and 2.43 respectively, while the standard deviations were 1.25 and 1.27 respectively. This shows that students generally had minimal experience prior to the course. For Questions 2 and 4, the means were 4.86 and 4.71 respectively with standard deviations were 0.38 and 0.49 respectively. As expected, students' felt that their understanding of the topics improved over the semester.

Table 2: Survey questions with Likert scale results (n=7)

Question	Mean	STD
1.) Prior to this course, how well did you understand current concrete construction practice?	2.71	1.25
2.) Throughout the course, how did your understanding of concrete construction practices change?	4.86	0.38
3.) Prior to this course, how well did you understand 3d printing or additive manufacturing?	2.43	1.27
4.) Through the project, how did your understanding of 3d printing change?	4.71	0.49
5.) To what level do you agree with the following statement: This project caused me to be more interested in concrete construction.	5.00	0.00
6.) To what level do you agree with the following statement: I used my knowledge from multiple areas of engineering to complete this project.	4.57	0.53
9.) To what degree did this project affect your understanding of the engineering design process?	4.57	0.79
11.) To what degree did this project affect your ability to design and run experiments?	4.71	0.49
12.) To what degree did this project affect your technical communication skills through written reports and presentations?	4.43	0.53

Along similar lines, Question 5 of the survey aimed to determine if students felt the project caused them to be more interested in concrete construction. Table 2 shows the mean and STD of the responses which in this instance, all responses were "strongly agree".

The next three questions asked about use or learning of engineering knowledge, skills, and or technologies. Question 6 was on a Likert scale and asked students to what level they agreed with the statement that they used knowledge from multiple areas of engineering to complete the project. 1 was strongly disagree, 3 was neutral, and 5 was strongly agree. Question 7 allowed the students to elaborate and say what areas of engineering or technology they used, while Question 8 focused on what engineering skills or technologies the students learned independently during the course of the project.

For Question 6, Table 2 shows the mean and STD of the responses. The mean was 4.57 with a STD of 0.53. This shows that students agreed to strongly agreed that they used their knowledge from multiple areas of engineering to complete the project, which could indicate that the project was perceived as multidisciplinary by the students.

For Question 7, students mentioned what areas of engineering or technology they used. Table 3 shows the percentage of students that mentioned a certain engineering area along with corresponding example phrases from the survey responses. Materials science and structural engineering were the most mentioned at rates of 57.14% and 42.86% respectively. Civil engineering was also said by 28.57% of students, while construction management, computer science, and modeling were only declared by 14.29% of students each. Additionally, 14.29% of students left the question blank.

Table 3: Survey Question 7 Results (n=7)

Engineering Area	Percentage
Materials Science	57.14%
Structural Engineering	42.9%
Civil Engineering	28.6%
Construction Management	14.3%
Computer Science	14.3%
Modeling	14.3%
No response	14.3%

For Question 8, students stated what engineering skills or technologies they learned independently during the course of the project. The responses varied but seem to be able to be roughly divided into four main themes: experimental design skills, experimental testing skills, specific softwares, and soft skills. Experimental design skills encompass skills required to design an experiment such as drawings and mix designs, while experimental testing skills involves skills required to execute an experiment such as 3D printing, testing concrete, and analyses. Specific softwares cover softwares that are specifically mentioned by the students, and soft skills include communication, leadership, teamwork, and time management.

Table 4 shows the percentage of students that mentioned each of the four main themes along with corresponding example phrases from the survey responses. Experimental testing skills and specific softwares were the most mentioned themes with rates of 42.86% each. Meanwhile, experimental design skills and soft skills were mentioned at rates of 28.57% each. 14.29% claimed they learned none for this project, while 14.29% left the question blank.

Table 4: Survey Question 8 Results (n=7, one blank response)

Theme	Percentage
Experimental Testing Skills	42.86%
Specific Softwares	42.86%
Experimental Design Skills	28.57%
Soft Skills	28.57%
None	14.29%

Questions 9 – 13 revolved around how the project affected students in various ways. Question 9 asked to what degree the project affected student's understanding of the engineering design process, while Question 10 allowed students a chance to elaborate on Question 9. Question 11 asked to what degree the project affected student's ability to design and run experiments, while Question 12 similarly asked to what degree the project affected the student's technical communication skills through written reports and presentations. Question 13 allowed students a chance to elaborate on Question 12. Questions 9, 11, and 12 were on a Likert Scale with 1 being very low, 3 being neutral, and 5 being very high.

For Question 9, Table 2 shows the mean and STD of the responses as 4.57 and 0.79 respectively. This shows students felt high to very high that the project affected their understanding of the engineering design process. From Question 10 responses, all students but one mentioned the design process, though in different ways. One student mentioned having "an overall understanding of basic design process associated with any concrete 3D printing", while another student mentioned that they "have taken enough courses and done enough projects on [their] own that [they] understand the design process well". One other student mentioned how making the designs and reviewing them with the professor helped them "make a good structure that would print fast". On the other hand, another student thought the project "helped a great deal since [they] were able to work independently". They then mentioned the project was a "great learning experience" through conducting research to make an efficient model and testing it with an actual printer. One student thought the project "opened [their] eyes to the many facets of running an engineering design project" and listed the complications that they learned regarding the design process through the project, while another student mentioned working through the entire design process with the project and listed some of the tasks they did. One student did not elaborate on their response to Question 9.

For Question 11, Table 2 shows the mean and STD of the responses as 4.71 and 0.49 respectively. This shows students felt high to very high that the project affected their ability to design and run experiments.

For Question 12, Table 2 shows the mean and STD of the responses as 4.43 and 0.53 respectively. This shows students felt high to very high that the project affected their technical communication skills through written reports and presentations. From Question 13 responses, all but one student felt positively about the communication deliverables of the project. Two students mentioned the presentation: one student felt they have a better understanding of "how to present a design with the intention of selling your idea", while another student stated the presentation "forced [them] to articulate [their] design process and solutions. One student stated, "The memo and final report were very professional" and how it helped them in presenting their work. Three students mentioned both deliverable types: one student said that the rubrics and guidance on formatting helped to improve their writing skills, particularly for academic and research purposes, while another student mentioned that not many of the activities provided feedback on how clearly they communicated and that the main deliverable that did was the first draft of the full report, which they feel they didn't spend enough time on. Both of these students mentioned that the communications workload was adequate or that there was a lot of these activities and that the activities helped understand what the student was learning. The third student mentioned they felt nothing introduced was new to them since they had previous experience with presenting and writing reports through other classes and professional experiences; however, the expectations for the deliverables, particularly the final report, were higher than other courses they have taken.

Summary and Future Improvements

The student survey focused on evaluating the impact of a semester-long project on students' understanding and interest in concrete construction and 3D printing. Initially, students had limited understanding of these topics, with mean scores around 2.5. Post-course, their understanding significantly improved, with mean scores above 4.7. While the number of responses was limited, the surveys indicated that the educational outcomes were being met. All students reported increased interest in concrete construction, reflecting a highly positive response to the project. Students widely recognized the multidisciplinary nature of the project, utilizing various engineering skills and technologies. They also developed experimental design and testing skills, as well as software proficiency. The project was perceived to greatly enhance their understanding of the engineering design process, ability to design and run experiments, and technical communication skills, particularly in writing reports and making presentations. However, some students noted that more feedback on communication clarity could be beneficial, and one student felt the project didn't introduce new concepts due to their prior exposure. The majority of the questions being on Likert scale, the employed survey method can be best described as a "retrospective survey". We recognize this method allows for the collection of valuable historical perspectives from the respondents, pertinent to our research objectives. However, it is important to note the inherent limitations associated with retrospective surveys, particularly the reliance on the memory of participants. Memory recall can be affected by various factors, including the length of time since the events in question and individual differences in memory retention and accuracy. This dependency on participants' recollection could potentially lead to biases or inaccuracies in the data collected. To address the limitations associated with memory recall in retrospective surveys, several strategies can be implemented. Enhancing the accuracy of participant responses can be achieved by using specific, detailed questions and incorporating timelines or reference events to assist in memory recall. Triangulating survey data with other sources, such as archival records or additional interviews, can provide a more comprehensive view and validate the responses received. Employing cognitive prompting techniques, such as asking participants to recall events in different sequences, can unearth more accurate and detailed information.

Now that the core details of the project have been developed, the instructors plan to gather feedback from future project groups to bolster the preliminary data presented here. Refinement of the survey and additional surveys will be needed to document how well the educational objectives are being met. Additionally, the instructors will study how the perception of the design process changes over the course of the project and how students perceive the new technology.

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Appendix

							Points
	Presentation Style						
Voice	0	Too fast, too quiet, facing away, no practice	3	Some presenters are not practiced	5	Clear, audible, paced, practiced	
Time limit	0	+/- 5 minutes	5	+/- 3 min	10	+/- 30s of limit	
Answer Questions	0	No answer	3	Some answers, some "I don't know"	5	Clear, concise answers	
	Slides						
Readability	0	Font is large/small and slides are wordy	3	Some wordiness, some slides have poor clarity	5	Slide text is appropriate in amount and size	
Consistency	0	Slide format changes throughout	3	A few slides are inconsistent	5	Slides are consistent	
Images and figures	0	Unclear, no labels	3	Mostly clear, but some obvious errors	5	Clear, readable, and complete	
Organization	0	No logical flow, content is separated	3	Some errors and missing transitions	5	Logical organization and transitions	
	Technical content						
Mix design development	0	Trial and error, less than 4 trials	5	4 trials, no test matrix or different variables for each	10	Matrix tests two variables and informs on final mix	
Model design	0	No consideration to mechanics	5	Some optimization and tie to mechanics	10	Optimization of model with clear tie to mechanics	
Printing	0	Simple mention that printing was done	5	Mention what was changed between prints, but little to no discussion	10	Discussion of challenges, what was learned between prints	
Results	0	Missing results and analysis	5	Mention team's results only	10	Disucssion of results and how they compare with other teams	
Conculsions	0	New information presented, not supported by data	5	Incomplete, not fully supported by data	10	Fully supported and justified	
Justification	0	Not included	5	Mentioned but not supported	10	Logical and compelling support for their work	

Figure A-1 Rubric for final oral presentation

Front Matter							Points
Biography	0	Missing	1	Missing one or more members	3	All members present	
Abstract	0	Missing substantial content	3	Most required parts present, <50 words over limit	5	All required components, precise and concise writing	
Keywords	0	None	1	Words are vague, irrelevant	2	Precise, descriptive	
Introduction							
Background	0	Little to no background	5	Some background or not relevant to topic, no references	10	Thorough, well-referenced	
Research Significance	0	Missing	3	Irrelevant or vague	5	Relevant and reflects the project objectives	
Testing							
Experimental Investigation	0	Trial and error, missing materials and tests	10	Incomplete list of materials and tests, no mention of experimental design	20	Complete list of materials, tests, and experiemntal design	
Results and Discussion	0	Missing and incomplete results, no discussion	15	Most results, incomplete discussion with minimal explanation for design choices	30	Complete and correct results, thorough analysis, clear justification for design choices	
Concluions	0	Vague statements or conclusions without tie to data/analysis	2	Conclusions are mostly complete and address most research objectives	3	Clear direct conclusions that reflect the research objectives	
References	0	Missing and improper formatting	3	Some mistakes for formatting or some missing references	5	Complete and correctly formatted	
Appendix	0	Missing when it should be included	3	Some of the data is not present, or some is not located correctly	5	Complete data, appropriately located	
Writing Mechanics							
Formatting	0	Frequent and constant mistakes	3	Several formatting deviations from the guide	5	Followed format guidelines	
Grammar	0	8+ mistakes per section	3	3-8 mistakes per section	5	Less than 3 mistakes per section	

Figure A-2. Rubric for final project report