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Applied Research in Undergraduate Capstone Classes

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Abstract

The objective of this paper is to discuss the different aspects of applied research carried in typical mechanical engineering undergraduate capstone classes, and to what extent it helps students to meet their objectives and quality of their project work. Since our university operates on a quarter academic system, each course needs to be completed in just 11 weeks. The number of members in each group of a capstone is either 3 or 4. One example of the project dealing with an automated bed clearing mechanism of a 3D printing machine is presented in this paper. A group of 4 students developed two ideas of this system. The design details of one of these ideas is presented in this paper. The 3D printer in this example uses Fused Deposition Modelling (FDM) process. Many automotive, aerospace and other sectors are focusing on using functional 3D printed parts to either reduce the weight or to replace metal parts that otherwise require complex processes and assemblies. The applied research component of the work presented in this paper is to design the systems that are user-friendly and be able to print multiple parts without human interaction. This saves time to load and unload one component at a time. These projects represent uniqueness in the sense that the students were able to successfully complete the projects in one term, and communicate their designs effectively through an engineering report, power point slide presentation and by a poster. Each report contains several items including the safety issues, ethics and impact to society due to poor designs. The teaching and learning parts of undertaking this and other capstone projects will be briefly discussed in this paper.

Introduction

Both senior cornerstone (elective) and capstone courses provide excellent opportunity to show-case students' final program outcomes and applied research experiences of an academic department and the university as a whole. Cornerstone courses include specific program related electives or they could be free electives. In either case, they provide ultimate academic experience to students at the end of their academic career. Capstone courses build up on the learning outcomes from previous courses they take at undergraduate level. Students are challenged to innovatively design, analyse, develop and test their ideas – in simple terms, from concept to production. According to Tomorrow's Professor Postings on Teaching and Learning (Stanford University) [1], many capstone courses require students to not only apply the concepts and principles learned in theory classes but also to fabricate a device that satisfies the original requirements set forth in the project proposal. However, *from the students' perspective* completing an applied research project without having to fabricate the device will give more time to carry out high quality theoretical project that may give competitive advantage in gaining admission to a graduate school or demonstrating discipline-related skills for the job market.

There are numerous papers available in the literature and published in ASEE and other technical and educational journals of repute. Funding agencies such as NSF also encourage inter-collegiate capstone projects and classes coordinated both from within USA and between US colleges and colleges abroad. Professional organizations such as ASME organize inter-collegiate design contests. Most participating colleges assign these as senior capstone projects comprising of inter-disciplinary teams derived not only from the parent department but also from other engineering, business or social science departments. Currently, many capstone courses in engineering and business departments are undertaken keeping in view the needs of the communities and the societies they live in, and not necessarily only targeting the growth of engineering products for companies.

The department of Applied Mathematics and Statistics at New Jersey Institute of Technology (NJIT) was awarded an NSF grant to establish an undergrad computational laboratory for their capstone course [2]. Capstone courses and built projects help students learn to combine experimental methods, mathematical and statistical modelling techniques, and computational skills to study physical problems and processes. They also provide the experience of integrating different areas of students' education in order to develop the technological and critical thinking skills necessary in today's workplace. The theoretical concepts covered in lectures are complimented by physical experimentation, data collection, and computer laboratory sessions. Many times, case studies are used to provide capstone project examples from available resources and to encourage original thinking and self-confidence in students to carry their own project ideas. Faculty-guided student research projects also help some students to pursue higher studies in their chosen discipline.

Students taking the capstone classes are also expected to communicate their work effectively not only to peers in the classroom, but also to audience in others disciplines and perhaps to the community they live in. For this, they have to understand how to use appropriate and relevant content to develop and explore ideas in writing [3]. In the final project report and/or in the presentation, students must be able to (i) display skills at many levels: sentence, paragraph, and in the entire essay; (ii) use evidence to support a claim in an academic argument and give credit to a source; and (iii) provide the reader with documentation of research with a reference page. The criteria for many capstone project reports usually follow the Association of American Colleges and Universities (AACU) guidelines for assessment rubrics. Students are encouraged to review the AACU website regarding capstone standards.

Hur, who taught a graduate capstone course at New York University (NYU) as a part of Wagoner Capstone program, expected students in the Applied Research track to work in teams to identify and address an important policy question in the field of their choice [4]. In this course, lasting one academic year, the students will design the approach, conduct the data collection and analysis, and present findings, both orally and in writing. Overall, the students of this track 'should demonstrate a capacity for flexibility and resilience, as shown by adapting to changing and complex circumstances, balancing competing demands, accepting uncertainty and ambiguity, and knowing when to consult with their Capstone instructor'. As with any capstone course, project planning, team management, applied research and communication are important aspects to be demonstrated by the students.

Callender, et al participated in a breakout session at the 2012 Trends in Undergraduate Research in the Mathematical Sciences conference [5]. They concluded that there is not one design for a capstone course that will satisfy the needs and goals of every mathematics program, but a department seeking to implement undergraduate research as a capstone requirement may benefit from the experiences of other departments. They outlined the common objectives of a capstone in mathematical sciences and presented several successful models that incorporate undergraduate research in a capstone experience. The challenges and questions associated with each model are also discussed in their paper.

Moore views that a capstone course gives an opportunity to the students to demonstrate that they have achieved the goals for learning as established by their academic departments and the educational institution as a whole [6]. Davis et al produced a set of ten holistic roles of an engineer. These are categorized under three main roles such as technical role, interpersonal skills role, and professional role. Also, the course expects that each student takes the behaviour role of an analyst, problem solver, designer, researcher, etc., as outlined in their paper [7]. Plumley, et al discussed the learning outcomes of assigning a common capstone project involving freshmen and senior students in the mechanical engineering department [8].

All capstone instructors and institutions strive that capstone courses should mimic authentic open-ended, real world engineering experiences involving an interaction with real clients and industry professionals. While this is very desirable, it is not easy for many colleges. Lutz at al thought about an opposite view to understand how students in capstone courses describe their learning gains. To address this question, they presented findings from a larger multi-case study of capstone teaching and learning [9]. The full data set for each case included classroom observations, faculty interviews, and student interviews gathered at multiple points in time across the capstone experience. Their findings were specifically focused on data from student interviews and focus groups. These interviews explored students' perceptions of capstone design, including their experiences with mentors, the challenges they faced, their beliefs about what they learned, and their perceived level of preparation for the future. Their interviews were audio recorded, transcribed verbatim, and analysed using an open coding process. Their findings based on one of the main themes of their students' outcomes, namely, 'development of an engineering identity', suggests that faculty should work with students as colleagues just like what engineers at work do. In the process, faculty shares their own thought process in how to approach and use applied research methods to solve a problem.

Pearson, et al conducted studies to describe the rationale and implementation of an applied research experience into an Exercise Science (EXS) curriculum, and to evaluate EXS undergraduate students' perceptions of an applied research experience [10]. An EXS measurement course was chosen for implementation of an applied research experience. The applied research experience required groups of students to design, implement, and evaluate a student-led research project. Majority of their students perceived the experience as educationally enriching, although they felt that the experience was academically challenging. Their studies suggest that an applied research experience has the potential to help further the development of undergraduate students. Other useful references confirming the usefulness of doing applied research in undergraduate capstone courses are in [11 to 14].

With the understanding that applied research helps in all STEM courses, particularly in capstone courses, the next step can be that these projects have some relevance to community and to an industry. As mentioned before, industry-sponsored capstone projects are routine for some colleges (for example, Harvey Mudd College, etc.), but it is not true for many others. Sometimes, it is a 'hit-and-miss' in which occasionally an industry approaches a college to do a short term project work involving students. The work may involve designing and developing a new engineering product or subsystem and to test it on campus, or to carry out extensive experimental work at the industrial facility. Coordinating the latter with student groups will be very challenging due to class schedules and safety issues both in commuting to and within an industry environment.

Regardless of how diverse the ideas are about handling capstone classes, the process of including applied research content in a capstone course follows a systematic design process which includes: recognition of opportunities that help in generating several ideas for the project, identifying and synthesizing existing research relevant to the project, brainstorming conceptual ideas that result in developing preliminary designs, performing iterative designs using CAE and math tools to achieve optimum design, carrying out analysis on the optimized design, identifying and implementing appropriate data analysis procedures, finalizing the design, procuring material, fabrication of the prototype, testing the device based on the original objectives, and finally, communicating (to assess) the strengths and weaknesses of their project work (ABET criterion (g)). This process is carried thru weekly progress report presentations. The work plan by no means is a serial activity, but it is iterative by students revisiting the each step of the design, manufacturing and testing cycles several times to assure that their designs shape up to reality. Students are also expected to discuss the scalability of the project idea to other potential applications. Finally, they are expected to document the difficulties and hurdles if any, faced during any stages of their product and process cycles, and what steps and changes are needed to be done at which design process stage, to overcome the difficulties faced. Library and online resources using search engines are expected to be used for literature review.

There are many other papers available in the literature on how applied research is used in mechanical systems design stream of capstone courses. Based on the several capstone projects carried out by the senior students at Kettering University [15], the present author discussed and presented the challenges faced by the students, the learning outcomes, and the different assessment tools used to judge the quality of their work at different conferences. The main aim of the present paper is to provide brief technical details of how applied research is incorporated while designing the devices developed in the projects. Assessment of these and other projects will be covered briefly in this paper. In the next section, brief technical details about one of the capstone projects on 3D bed clearing mechanism is presented along with their performance metrics, namely, whether the original objectives of the project ideas are achieved, and if not, whether the students identified the short-comings of their designs and proposed solution to address these.

Sample capstone design project [15]

Automatic bed clearing mechanism for a 3D printer

Background and need

The concept behind the idea was to allow every 3D printing user to be able to print multiple prints without human interaction. The idea started out as a universal bed clearing mechanism, for most brands of 3D printers. Upon researching into the many different styles and designs of printers, it became apparent that the designs differ to a great extent in order to create a universal product. The design team consisting of 4 members, decided to aim for the most common style of 3D printer, which the team also had a model to test the design. Two separate designs were explored, the first one being a ‘treadmill’ design that would rotate a conveyor belt and peel the part off of the belt. The second design had a pushing mechanism that would clear the entire glass bed and replace it with a new one. To accomplish these tasks, the design team printed 3D parts of their own, as 3D printing allows simplification of the manufacturing process and better-optimized parts. Online data and research tools were used to determine the actual strength of these 3D printed parts, as their properties do not follow classically manufactured plastics. The electronics used to run both designs were Arduino brand microcontrollers. These controllers allowed the team to automate the movement of the system along with servos and small DC motors. In this paper the design details of the conveyor belt system will be briefly presented.

Market research & current design

There are only one or two other design currently on the market that clears the 3D printing bed automatically and allows for no human interaction. The SAAM (Small Area Additive Manufacturing) sold by Cincinnati Incorporated is “the only 3D printer that enable continuous, unattended 3D printing courtesy of [their] patented Automated Ejection System” (CISAAM, n.d.) with an ideal conditions version and a high temperature version [16]. The SAAM removes parts using an inclined sweeper to peel the part off of the bed while also passing under the part. After that, the sweeper resets back to its home position while also sweeping the part off of the bed. This device can be purchased as a stand-alone printer with the bed clearing mechanism included, or the clearing mechanism can be purchased separately. The base model printer is illustrated below in Figure 1, and the separate bed clearing mechanism is shown in Figure 2.

Figure 1: SAAM 3D Printer [16]

Figure 2: SAAM Part Ejection System [16]

With the SAAM being modelled for commercial applications, there are a number of limitations that minimize the usefulness of the designs for the standard consumer. The team's ideal standard customer is an individual who owns a printer such as Anet A8 for non-profit and most likely for hobby use. The price of the SAAM 3D printer starts at $20,999 for the base model and $21,499 for the high temperature model [16]. The stand-alone bed clearing mechanism starts at $2,500 for the basic part ejection system and nearly $10,000 for the part ejection system and enclosed chamber [16]. Upon brainstorming and research online, the capstone team also thought that the size and complexity of the part ejection system can be improved, with a conveyor belt design instead of a moving blade system. Overall, the design could be made more compact and lower weight, which would result in large price drops and allow for the device to be affordable to all consumers.

There are many other 3D printer models available in the market such as Printrbot and Printrbelt (https://www.brookdrumm.com/designs) that have much cheaper price range than SAAM but offer modern functionalities needed by a standard or a commercial user. The details of these are not covered in this paper.

Problem statement

Integrate two different design ideas in to an existing 3D printing machine that clears the printed parts automatically from the printer bed.

Motivation

The idea started out as a universal bed clearing mechanism for most brands of 3-D printers. Upon researching into the many different styles and designs of printers, it became apparent that the designs different too much to create a universal product. The team decided to aim for the most common style of 3-D printer, which the team also owns to test the design. 3D printers are an amazing tool that anyone can buy and use properly. However, 3D printers require user interaction after a print is completed to remove the part and then start the next print. This would not be an issue if prints were completed in a short period of time, but some prints take several hours to complete. This requires the user to return to the printer every few hours just to reset the printer and start the program again. This becomes an issue when print times do not line up with the user’s schedule and leads to increased downtime. The designs proposed by the team attempts to eliminate or reduce this problem by allowing the printer to remove the printed part in one of two ways and allowing the system to start the next print automatically. This frees the user to be gone for a long time, for instances such as going to work or sleeping, without having to worry about printer downtime while the printer waits for user interaction.

Due to the size (number of members in the group being 4), two separate ideas have been researched by the team to balance the workload. As mentioned before, the team already owns a 3D printer and the idea is to integrate the developed functionalities in to this machine. The first design was a treadmill design that would rotate a conveyor belt and peel the part off of the belt. The second design had a pushing mechanism that would clear the entire glass bed and replace it with a new one.

Prior knowledge/gaps in knowledge

To complete this project, knowledge from the following courses were used from their time at the university:

- Mechanical Engineering Circuits: Used to design the wiring diagram needed to run the motor
- Electronics I: Used in the development of the control circuits and integrating the Arduino
- Statics and Mechanics of Materials: Used to draw free body diagrams and to perform hand calculations
- Computer Aided Engineering: FEA analysis on all of the parts
- Mechatronics Laboratory: Used to design and fabricate devices using wood material
- Mechanical Component Design I: Used to design the lifting mechanism and to perform stress analysis calculations

However, the team documented that there seems to be a deficiency in their learning of computer science that they had to learn on our own due to incorporating an Arduino that automated the bed clearing process. They were required to learn how to create basic code that would allow an Arduino to pick up and transmit signals. These signals were used to rotate motors and servos at certain times and for specific durations to ensure that the printed parts are cleared off the bed.

Initial hand drawings of conceptual designs

During the first week of the class, the team developed few hand drawn sketches of both the designs. Figure 3 shows the initial idea (which was adopted in the final design) of the cam locking mechanism.

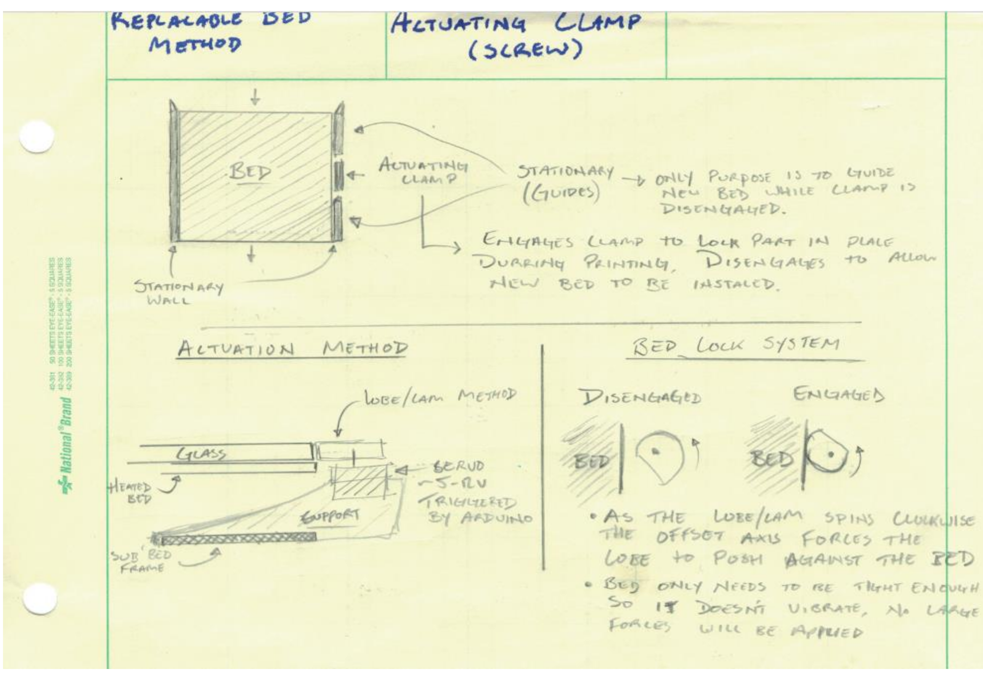

Figure 3: Initial Idea of the Cam Locking Mechanism

Figure 4 shows early iterations of the mechanism using hand-drawn sketches. This sketch shows (i) an early design for the bed queue platform legs, (ii) an early design for the main platform support that connects to the printer which later was decided to be too permanent and opted for a simpler version that need not be glued to the queue platform, and (iii) a scraped design for some pegs designed to keep the glass plates on the queue platform, which again was discarded in the later design iterations.

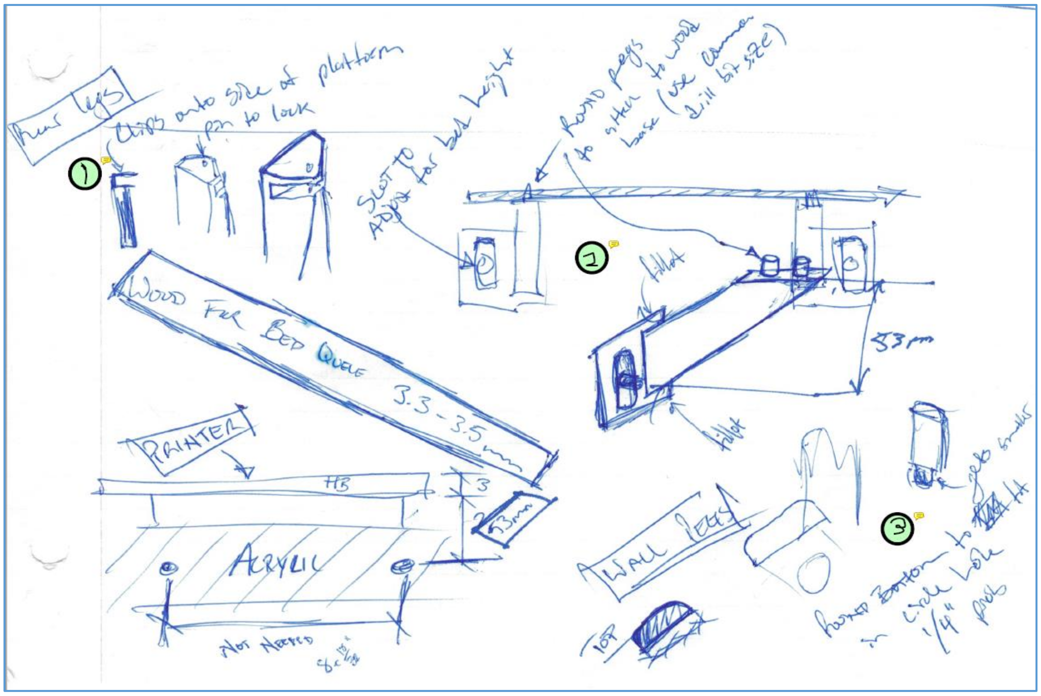

Figure 4: Early hand-drawn sketches showing the iterations of the bed replacer design

The team generated several other hand-drawn sketches inputting their creative and critical thinking skills before using a computer to generate the initial and final CAD models of the treadmill design. Figure 5 shows the final version of the CAD model of the bed replacer (treadmill) design which will be attached to the main Anet A8 printer.

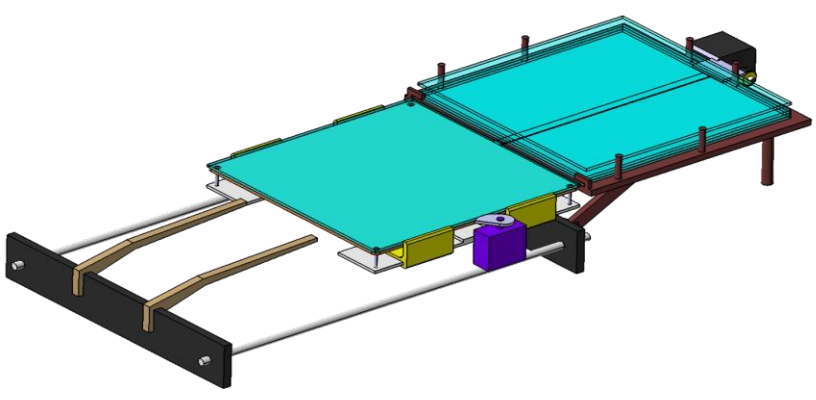

Figure 5: Final CAD assembly design of the bed replacer model

Figures 6 and 7 show the view of the position of the stepper motor relative to the replacement bed plates, and the cam locking mechanism to lock the active bed plate when a part is being printed. Once a part is printed, the Arduino activates the stepper motor, which in turn pushes the top bed plate out of way so that the next part can be printed on the second lower bed plate. The actual Anet A8 machine to which the treadmill system is attached is not shown.

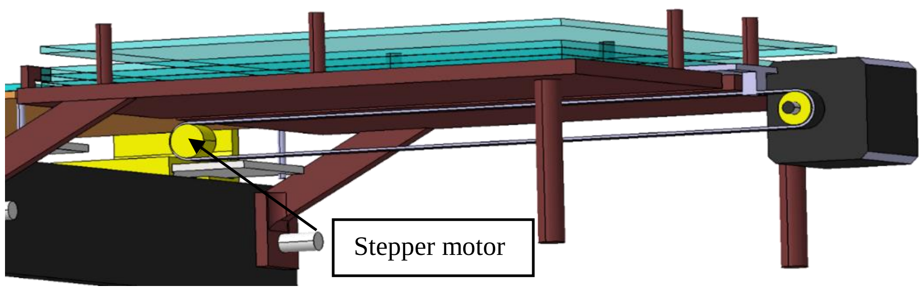

Figure 6: Final assembly drawing of the bed replacer treadmill mechanism and stepper motor

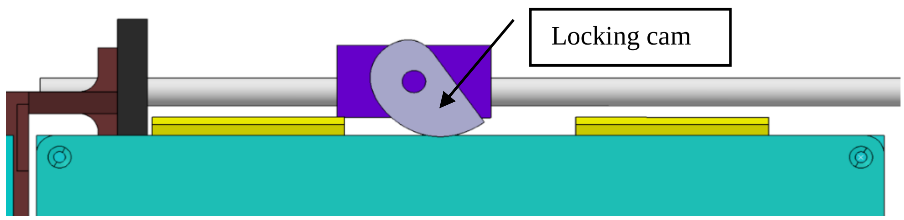

Figure 7: Final assembly drawing of the bed replacer treadmill mechanism with cam

Several machine design and finite element analysis calculations have been made to make sure that none of the components of the treadmill system would fail. If the safety factor is lower than 3, that particular component has been redesigned and fitted back in to the assembly [15]. The calculation details and the finite element analysis results are not presented here; however, they become part of the applied research tools that the students needed to use due to complex geometry of some components.

Once the team proved their design and analysis, a bill of materials was prepared. Only very few parts (nuts and bolts) needed to be purchased while majority of the components were 3D printed using the same Anet A8 machine that the students owned. After successful assembly of all parts, they began the testing phase of the device to find some problems with the smooth movement of the special glass bed. This was due to friction between the moving components (belt, pulley, cam, etc.). After few trials and adjustments, the device worked as planned, and the team was very happy that their original requirements were met. The team was very satisfied that the applied research tools used from concept to prototype production and testing of the 3D treadmill design were beneficial to advance their knowledge in automated 3D printing devices. Much confidence was gained as the team implemented their prior knowledge from courses taken, and the newly acquired knowledge thru self-learning to program the servo motor and its controls.

Figure 8 shows the sequence of design activities that resulted in the final design of the treadmill idea from concept to prototype production. As mentioned earlier in the paper, a second design using conveyor belt design concept was also implemented and tested to the satisfaction of the team members. Students identified and documented the drawbacks of their two designs.

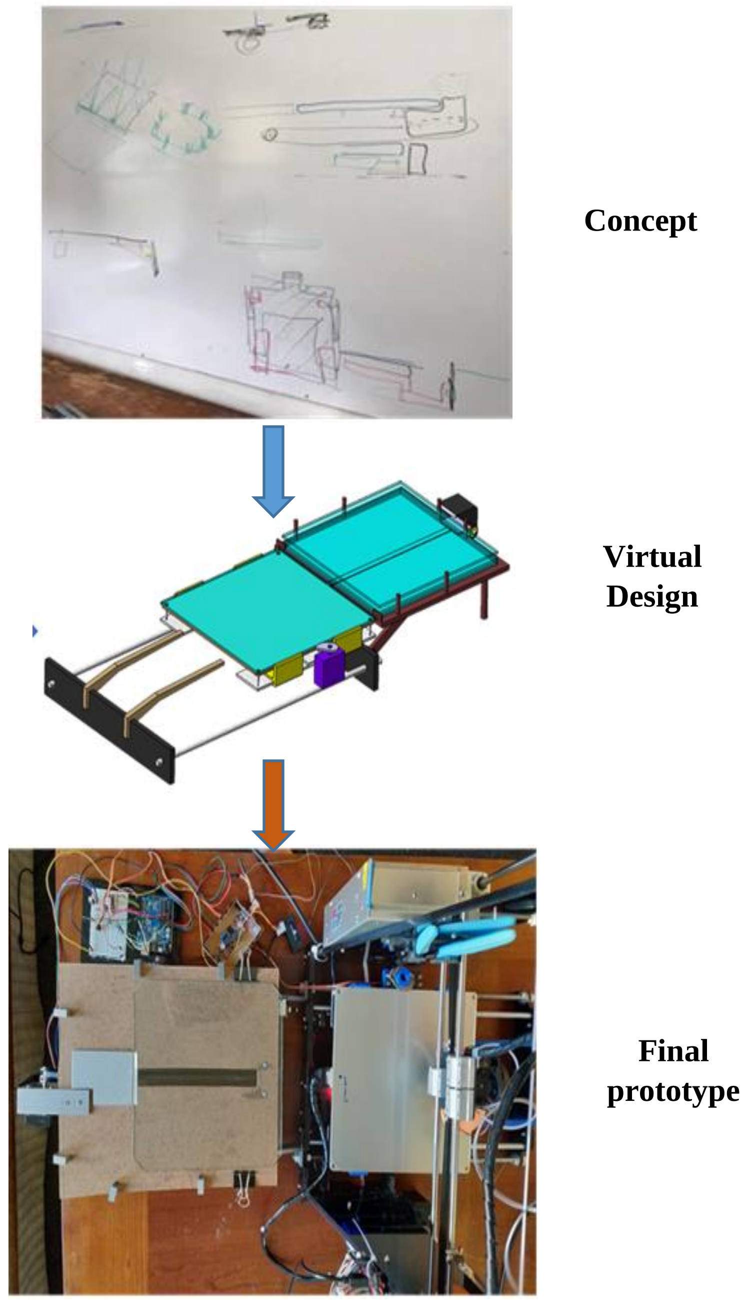

Figure 8: Bed Replacer Design Process Flowchart

Brief discussion about assessment of the project

All capstone projects are assessed based on *weekly progress* report presentations. *Feedback of students* from other group members was also sought and weighed in the grade assessment. Grade rubrics were provided at the beginning of the class and explained. It was made clear that *applied research tools* need to be used while doing literature survey which includes *patent search*, searching for *prior and existing designs* of the proposed idea for the project (using Google or other search engines). Use of *math and CAE tools* for performing parametric studies was required, and bulk grade was assigned for this phase. *Project management* skills and *team working* to divide the workload was part of the grade. Each member of the group needed to clearly *identify and document the specific task assigned* to that member, and whether that task was completed, and if not, the reasons why. Each team member was required to perform design calculations to some extent *using the math and/or CAE tools*, and just not assume a managerial role. *Identifying and procurement of BOM* (either from outside vendors or from within the university) is another major task that each member needed to do. *Fabrication of components* (machining) and subassemblies (joining using fasteners or welding, etc.) is a major task that each group member has to organize, to complete the device outside the class hours, and in coordination with the lab technicians. *Test procedure* needed to be documented before-hand. This is one of the difficult tasks for the students, as they do not have much exposure to measurement devices (sensors, etc.), nor have individually done real laboratory experiments. Most lab experiments in other courses are performed as a group and not individually. *Report writing and design communication* via presentation is the final task that includes documenting the hurdles faced at every step of the design process, including analysis, fabrication, assembly of the device and testing phases. *Ways to mitigate the difficulties faced* needed to be documented. *Future recommendations*, *ethical issues*, *societal impact due to poorly designed* components or devices needs to be documented in the final report. *Peer evaluation* from other group members is solicited confidentially. This feedback is to be generated using a 70-100 points scale, and is based on the relative workload of each presenting member, complexity of the chosen project compared to their own, uniqueness of the idea, completion and novel testing procedures used for testing.

Summary and conclusions

In this paper, the role of applied research in mechanical engineering capstone courses is outlined. This is exemplified by presenting an example of automated bed clearing mechanism for a 3D printer device. An existing 3D printer (Anet A8) that the students owned has been to chosen and two separate mechanism devices have been proposed and fabricated to clear the bed after each 3D print is completed. Students were extremely happy to be guided thru this project that resulted in successful completion from concept to testing phases. Students realized the role of applied research tools used and gained self-confidence of how they help in the real world work environment. Students understood the design assumptions they made, and their limitations for real world materials. Learning from failures is strongly felt by the students as they faced hurdles at different stages of the design → fabrication → testing. Students felt the importance of using knowledge from prior courses, as they also self-taught (or with the help of the instructor) to bridge the gaps in knowledge.

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