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Realizing Proof of Concept in Machine Design with 3D Printing

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Abstract

The Virtual Machine Design course was developed to teach basic concepts of mechanical component design to mechatronics engineering students. The laboratory section of the course is geared towards designing electromechanical devices. Students develop prototypes of their designs in order to strengthen their design and visualization skills. The prototypes also give students the opportunity for hands-on learning. 3D printers, which can convert a CAD model to a physical product, are popular among the designers and inventors. As the printers become more affordable, 3D printing is moving from being a demo technology to being a hands on production device. These days, engineering students can successfully build physical models of their designs with low-cost 3D printers. In this paper, the applicability of 3D rapid prototyping in a virtual machine design course is investigated, and impact of this technology on student learning is also reported.

The design projects were assigned to the selectively random group of students. Mechanical devices of different energy generation technologies involving both stationary and dynamic parts were designed and prototyped for a comparative study. Each team selected one of the following energy generation technologies: hydro, wind, solar, or tidal. Students identified the components of their design and built a CAD Model of those components. Based on the loading type and the nature of the structure, they were asked to analyze force and stress; and to determine the size of their structure. Students were required to design no more than ten dissimilar components and to consider industry standards, safety, and the operating environment in addition to the functional requirements of the design. Although both 3D printing and traditional manufacturing options were available, most of the students have chosen 3D printing using ABS plastics to create their components. Once the components were built and assembled the electrical systems was installed to a complete working models for electricity generation. Students built the prototypes based on their own calculation and analysis.

The students were graded using a rubric that included expected design content and steps to be followed. The design task was divided into analytical work, simulation, and prototyping. Evidence of learning included a technical report, a working physical model, and a presentation. The effectiveness of this work was assessed by using a Likert scale survey at the end of the study period.

Integration of 3D printing helped to improve the rigor of the course by adding prototyping capability into existing analytical and simulation based instruction. As a part of the prototyping process, students were able to acquire skills in 3D printing, which will be useful to them in future coursework, including their senior capstone project, and in professional endeavors. This integration enabled the instructor to teach mechanical design in a single course starting from basics of stress analysis to prototyping.

1. Introduction

Design is one of the core competencies in the engineering curriculum and is an essential skill for any engineer. Translation of a design concept from paper to prototype is a crucial step in assessing the performance of a design, and use of prototyping as a part of design course reinforces a student's learning experience. This paper presents a study regarding the relevance and effectiveness of the use of 3D printers[1] in a junior level machine design course offered in Mechatronics , a multidisciplinary program. 3D printing was introduced to the course to provide an opportunity for students to make physical models from their SolidWorks CAD models. Students used 3D printing to create components used in different renewable technology devices. Design tasks were performed by teams of students in the mechatronics program after completing the same prerequisites. A selectively random group[2, 3] approach was used to form teams of students with diverse backgrounds. Each team was asked to select one of the following energy generation technologies: hydro, wind, solar, or tidal, based on their interest and experience. Students began their projects by identifying the main components of a given system and building CAD Models. Based on the loading type and the nature of the structure, they analyzed force and stress and determined the size of the structure. Students were asked to design no more than ten dissimilar components and to use a proper safety factor based on material type, operating environment, severity of potential failure, etc. and verify by Finite Element Analysis (FEA) before prototyping. For grading, a rubric was provided with an expected design content and steps to be followed. The evidence of learning included a Free Body Diagram (FBD) report, a stress analysis, a simulation results, presentation, and a functional physical model. Course effectiveness and the applicability of using a 3D printer in design were evaluated by student surveys at the end of the course.

2. Design and 3D Printing in Rapid Prototyping

Design is a crucial component of engineering education. It is outlined in ABET's course outcomes criteria " c" that students should have "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability"[4]. The inclusion of a prototype in the design process helps to improve the final design. Witnessing the results and learning through failure in the earlier design phase minimizes loss in the later stages of product development. Creating a physical prototype can be an effective way to observe and assess ideas before implementing production.

Different methodologies and strategies are used in prototyping based on design context variables and functionality requirements [5]. A prototype could be a basic non-functional aesthetic model or a fully functional device or replacement part. Building and testing physical models helps students to improve the functionality of their designs [6] . The combination of CAD modeling and rapid prototyping technologies enables students to be more creative and productive in doing design work[7].

Many institutions have integrated 3D printing into their design courses [8]. Lately, with open source, 3D Printers are revolutionizing manufacturing [9]. The application of this technology ranges from physical device prototypes to developing human organs and is growing exponentially[10]. 3D printing has gone from a demo technology to a handy production device. For example, Makerbot [11], which uses polyactide (PLA) and Acrylonitrile Butadiene Styrene (ABS) plastics for 3D printing, is being readily used by academia, industry, and the public. 3D printing is integrated into instruction in various universities with different modalities. Design-Built-Test is a popular approach for senior capstone design course or other customized short summer courses. Successful use of 3D printing in education ranges from K-12 schools to university professors who are able to design and build their scientific research equipment on their own using 3D printing[12.] 3D Printing is also used as a multiple competency educational tool that facilitates student learning in the areas of mechatronics, and NC programming, etc. [13]. Some institutions have used 3D printing as a part of service learning to demonstrate engineering concepts such as fluid dynamics to middle and high school students[14].

3. Course Description

As a part of the mechatronics program, the machine design lab course is designed to familiarize students with various machine components and teach them what kind of loading and stresses these elements must bear. Electro-mechanical devices are composed of both mechanical and electrical components and may have both stationary and moving parts. In this class, the design of mechanical components such as shaft, bearing, keys, gears, springs, couplings, frame, truss, and structures were covered. The types of operational loading and critical stresses that control the design were introduced. Stress analysis through computation and simulation was also taught. Students were encouraged to use industry standards for machine components selection, and they should be able to read and interpret manufacturer's specifications to select a proper material and size. After the design reviewed and approved by the instructors, students created their model and evaluated the desired functionality of the prototype.

3.1 Project selection and task distribution

Students were asked to list the most common renewable energy technologies and rank them from 1 to 3 based on their interest, 1 being the highest and 3 being the lowest priority. When multiple teams came up with the same highest rank to a particular project, the instructor made the decision and assigned the projects to a specific team based on the teams previous background. After the decision on project selection was made, following task list and guidelines were provided to facilitate the design process.

3.1.1 Tasks list

- Identify the main components and build a CAD model of the entire assembly
- Discuss whether any kind of motion is involved in the system, and determine the nature of loading
- Identify different types of forces on the system at the various stages of its life
  - Draw FBD and calculate the forces and moments
  - Determine stress: normal, shear, bending, torsion, deflection, and buckling
- Design no more than ten dissimilar components for the loading condition identified above

- Use a standard safety factor; if not available, select a safety factor between 2 and 4 with valid reasoning, and select material and size of the component
- Perform FEA analysis for stress and deflection
- Make a prototype using 3D printing or traditional manufacturing processes

3.1.2 Guidelines

Students were allowed to make assumptions about their design with valid reasons. A tentative schedule was set to ensure the timely work progression and to locate the dates of the milestones: CAD model, stress analysis, FEA, and prototyping. In addition to the team report, each team member was required to document their contribution and maintain a personal work portfolio. The following was a summary of guidelines provided to students for individual tasks.

Technical report writing

- Understand the concept of technical writing from the literature and write in your own words
- Even after paraphrasing in your own words, cite sources for any facts or information used
- Valid sources include journals, conference proceedings, and technical reports
- Expert opinion can be referenced as a personal communication
- Newspapers and wikis are the least preferable (some people do not allow)
- Use EndNote Web for (automated) reference and citing
- Use IEEE format in referencing

Prototype should have working model

- The prototype needs to be able to demonstrate that it meets basic functional requirements
- It should operate without any problems (safety, function, environment or failure)

Design iteration

- Iteration in the design process is important - start with a simple design and add complexity incrementally
- Formulate solution approach without considering size and material (simple mathematical model)
- Analyze forces and motion
- Add simple geometry and investigate the internal loading (stress)
- Select components by following industry standards when possible
- Consider loading, environmental, and stress concentration factors
- Perform FEA in SolidWorks
- Finalize the CAD model and prototype using appropriate mesh counts and 3D printing configuration settings
- Test and evaluate the design using functional loading

Design Communication

- Use eDrawing to communicate with team members
- Assign a team leader (not manager) who will supervise the design process and be a member of the team
- Send your eDrawing to the professor for review and comments

Submission

- Submit prototype model and hard copy report at the beginning of the final test in the provided format
- Save all electronic files (report, CAD) to a USB drive provided

3.2 Expectations

Expectations for the student projects were predefined with reference to course objectives and guidelines (as provided in section 3.1.2). After completing the design and 3D printing, each team assembled 3D printed mechanical parts and integrated electrical components such as dc generators, LEDs registers, etc. for electricity generation and use (the design of electrical parts was not included). Students were expected to understand loading in a given system, create CAD models, analyze forces and moments, perform stress analysis, and create prototypes. The design process and different factors to be considered in mechanical design were also explained along with specific expectations of each stage of the project.

3.2.1 Perform the design task

Understanding product requirements is the first and foremost crucial step in design. Based on the customer's order, students figured out the tools and techniques needed to satisfy the requirements. They put enough technical detail to meet the depth of the design requirements. The following were the requirements that facilitated the teams to design, build, and deliver high quality products:

- Maintain regular attendance – to take one design step at a time
- Maintain a working portfolio- to develop a habit of documentation, write what you do and do what you have written
- Divide the task among the team members- equal contribution is vital, learn from each other
- Work individually and interdependently- collaboration helps in professional development, risk taking, and persuading skills

3.2.2 Lab submission

The final report consisted of: a short description of the project, a mathematical analysis with force and stress calculations, a CAD model with dimensions, an FEA analysis with loading and appropriate support identified, results, and conclusion. The basic format of a sample report was provided to the students. The working model of the 3D printed prototype was required to be no larger than 3 ft. x 3 ft. x 3 ft. work volume. Students were encouraged to present their work using audio visual and other media. The time for presentation allotted to each team was 15 minutes followed by a five minute question and answer session. Individual portfolios with weekly progress were used to document the tasks performed by the students, and also provided formative feedback to the course. For example, remarks such as "we haven't done this in class" or "needed a lot of revision" helped the instructor to adjust the pace of lecture instruction.

3.3 Weekly Schedule

The following rubric was provided to students to plan and schedule their work:

Week 1: Design area selection
List and describe the method that is being used to select a topic and why. Present a short description of how you came to the decision, which could be a literature search, personal communication, or other method.

Week 2: Identification of need
What is the objective of the project? (Check one of these and describe)

- Deficiency of an existing system: low efficiency, poor aesthetics, unsafe, customer complaints, etc.
- Market condition: competition, customer order
- Business niche: improving the existing design to stay ahead of the curve
- Regulatory requirements and others

Week 3: Problem definition
Based on the identified need of the customer, which is usually a broad and sometimes vague description, students were asked to define the problem in engineering terms and lay out various parameters to satisfy the customer's need. This stage involved transforming customer voices into engineering transcripts.

- Functional requirements and main components
- Specifications- tentative dimensions/ power rating, etc.
- Working environment characteristics – velocity, speed ranges, loading
- Resources available and the complexity of the system
- Expected contribution of the new design

Picture, block diagram, free hand sketch, CAD model or similar physical model could be used to help with the description.

Week 4: A basic CAD model and force determination

- Create a CAD model of various components of the system (overall model only, without details)
- Identify the main components what you are planning to design (detailed drawing)

Week 5: Identify the nature of loading and the type of structure

- Loading type could be static, dynamic, continuous, intermittent, step, ramp type, etc.
- Type of structure may be static, moving, flying, rolling, sliding, etc.

Week 6: Analysis of the loads and stress (conceptual)

- Combinations of normal, shear, bearing, bending moment, torsion and deflection need to be considered based on the machine component and its loading nature

Week 7-11: Free Body Diagram and analysis of the loads and stress (detail)

- Draw FBD of individual components and show all forces and geometry
- Use the FBD to solve the forces using equation of equilibrium
- Perform the relevant stress analysis and select the proper materials
- Evaluate your design using FEA analysis tool

Week 12-13 Prototyping:

- List all materials to be used (select standard material and size)
- List of manufacturing processes to be used with selection criteria

Week 14-15: Project demonstration and submission

- Presentation
- Final Submission

4. Summary of Design Projects

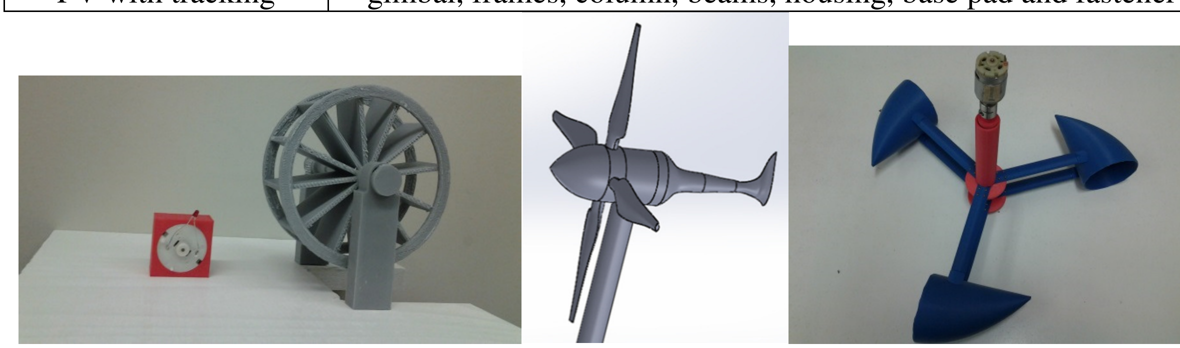
Out of various renewable technologies suggested, students selected water wheel (hydro power), wind turbine, tidal stream, and PV with tracking. A summary of the main components and pictures of these devices are shown in Table 1 and Figure 1, respectively.

4.1 Water wheel

Water-driven wheels have been implemented since ancient Greece, mostly used as water mills to drive a mechanical process for producing flour, lumber, or textiles. With today's modern technology, these water-driven wheels can be used to produce energy in a way that has less impact on the environment than fossil fuels. There are several different types of water wheel designs, such as undershot, overshot, pitchback, breastshot, and pelton wheel. This project was focused on the design and implementation of an undershot water wheel. The water wheel was assumed to be set into a river system with an assumed flow of 10 ft/s. The components designed for the water wheel system are wheel, shaft, belt, pulley and bearing. The wheel shaft is to be connected to a generator with a belt system. A journal bearing was selected based on the load requirements. The waterwheel's vanes encountered bending moment and shear force from the tangential flow of water to its circumference. A shaft was designed for torque transmitted by the wheel, and bending moment produced by its self-weight, the weight of the wheel and the radial forces of the water jet. The system was designed save money by generating free supplemental electricity while having a minimal impact on the environment.

Table 1. List of the design projects and main components

System	Components
Water Wheel	water wheel, the shaft, and the belt system, journal bearings
Wind Turbine	blades, shaft, tower, Nacelle
Tidal Stream Generator	cup, axle and vertical shaft and float
PV with tracking	gimbal, frames, column, beams, housing, base pad and fastener



a) Water Wheel b) Wind Turbine c) Tidal Stream Generator

Figure 1. Devices

4.2 Tidal Stream Generator

A tidal stream generator consists of cup, axle, vertical shaft and float. The cup was designed to receive the water stream from the tide of the ocean. Force on the cup from the tide of ocean would depend upon the direction of the flow, its velocity, the density of water, the velocity of the cup relative to the water velocity, the frontal area of the cup, and the drag coefficient. Radial and tangential stresses were analyzed to determine the thickness of the cup. The axle would receive the rotational force from the cup and was designed to withstand the bending moment caused by the force at the cup and related weights. Moment from the axle is transferred to the vertical shaft as torque. The float supports the weight of the structure, and also prevents the system from capsizing.

4.3 Wind Turbine

A wind turbine is comprised of four major components: rotor, nacelle, tower and blades. Tower height, blade length and generating capacity are the basic design parameters of horizontal wind turbines. A direct drive wind turbine, one of the newest technologies being implemented into wind turbines today, was designed for this project. The blades were designed to provide a relatively "high" surface area to harness more wind. The impact of pitch or the degree of rotation of the blades into power generation was also considered. To test the performance of the wind turbine, a box fan was used to blow wind at 10 mph, and 3V output with 280mA of current was recorded from the wind turbine. 840 mW of usable power was used to illuminate a LED.

4.4 PV Solar Tracking

A PV array with a sun tracking system generates more electricity for a given capacity than a PV array without tracking. A tracking system consists of two major subsystems: the tracking system and the support structure. Gimbal, which is the ability of a panel to both pan and tilt allowing for maximum sun exposure, was a critical component for tracking. The pan and tilt mechanism was designed to mount servomotors and to take forces of frame motion. The pan tilt mechanism was designed in multiple parts: the main bracket holds PV arrays while the second bracket acts as a mounting plate for servo. The base bracket receives the main shaft and provides a conduit for electrical wires. Through design iteration a plastics tilt bracket was found to be inadequate to withstand the weight of the panels and torque of the servomotor. This was replaced by a steel bracket. Other components were made out of PLA plastics. In addition to the tracking mechanism, frames, column, beams, base pad, electronics housing, and fastener were designed to complete the device. After modelling and stress analysis, a small prototype was built as a scaled down model. The prototype had eighteen pieces and took thirty hours to complete in 3D printing. PV panels installed outside the CSU-Pueblo Technology building were referenced in this design.

5. Course Effectiveness Assessment and Student Learning

This is the second year this course has been taught by the same instructor. To integrate the rapid prototyping, five inexpensive Makerbot 3D printers were acquired. These changes were made in response to the following comments received from the students during the previous year's course evaluation:

- *Laboratory time was taken away by the lecture, too much theory*
- *Interested in working real design projects that involve hands-on activity*
- *Would like to build a prototype and see the differences between theoretical design vs. physical outlook of the product*

In the previous year, students performed the design task analytically and computationally. They determined the material and size based on mathematical equations and empirical derivations and selected materials and components following the industry standards. In the mechatronics program course sequence, machine design is taught after statics, dynamics, and engineering materials. Without a course in mechanics of materials as a prerequisite, the instructor needed to spend a significant amount of time to introducing theoretical concepts in load determination and stress computation to prepare students for design. Unlike typical hands-on laboratory instruction, design lab involves extensive analytical and computational effort. Before the introduction of the 3D printing component, students reported feeling that the course lacked hands-on, practical instruction. The 3D printing component was added to the course in order to allay these concerns.

5.1 Learning outcomes

The purpose of the exercise was to reinforce theoretical knowledge of design with the help of a prototype. Students were able to design and prototype energy generation systems within a course using limited resources, time and manufacturing skills. For assessing projects, the following assignments were established with grade weight in parentheses.

1. Introductory Report: Submit a report with background information including literature search, discussion of the project with diagrams, and progress made so far (10%)
2. Modeling report: CAD Modeling and Force determination (10%)
3. Analysis Report: Stress Analysis and Design Review (20%)
4. 3D Printing and Prototype submission (50%)
5. Final Report (10%)

A rubric was provided for the report. Students were asked to design five to ten dissimilar parts and to use at least two different materials. Eighty percent of students in the course received a grade of eighty percent or more and met the learning outcomes of the course.

After implementing 3D prototyping in the course, students were asked to score their agreement or disagreement with the ten statements itemized in Table 2. In addition, they were encouraged to provide short comments to the questions included in the questionnaire. The following Likert scale was used to score their agreement or disagreement with the statements: 1- Strongly Disagree, 2- Disagree, 3- Somewhat Disagree, 4- Somewhat Agree, 5- Agree, 6- Strongly Agree. In the scale an even number of levels were chosen to avoid a neutral rating and students had to either indicate agreement or disagreement with the statements. 28 out of 28 students completed the survey, which is 100% response rate. As shown in Table 2, each question received an average score higher than 3.0 except question 1. In some instances students struggled to identify the dominant stresses on their designs due to the lack of well-placed prerequisites. It might be too early to investigate the statistical significance of the outcome based on a single small data set (28 < 30 response). However, the goal of this laboratory, which was "to design and build a prototype that generates electricity with four milestones (force and stress analysis, CAD modelling and FEA analysis, prototyping, and report submission)", was successfully achieved. This suggests that 3D printers improved student learning in a mechanical design course in a multidisciplinary program.

Table 2. Survey Response

		Disagree			Agree			
		1	2	3	4	5	6	mean
1	*The course was appropriate with sufficient preparation from pre-requisites*	1	5	15	5	1	1	2.9
2	*The course provided guidance on how to formulate an engineering design problem*	1	2	2	10	8	5	4.0
3	*The lab complemented my understanding of the lectures*		2	6	10	5	5	3.9
4	*The course helped me make progress in Solid works and 3D printing*			3	20	2	3	3.9
5	*The course developed my ability to apply design theory to practice*			4	15	8	1	3.9
6	*The course allowed me to synthesize fundamental knowledge in design and skills that is needed to prototype*	2	2	7	10	5	2	3.5
7	*The course gave me a deeper insight into the machine design*			5	11	10	2	4.0
8	*3D Printed parts help me better understand the design process*	1	1	6	17	2	1	3.5
9	*I am satisfied with this course*	1	1	5	14	6	1	3.7
10	*Considering both the limitations and possibilities of the subject matter and the course, rate the overall effectiveness of this course?*	1	1	6	12	5	3	3.7
	Comments: "A lot more time then was thought had to be put in to designing such a simple water wheel" "This lab project allowed the students to become more familiar with design, proper sizing, and taking into account weather conditions. A small prototype was made, it's not quite to scale, but it's a good representation of what was designed and created." From the analysis of our project, it is safe to say that the forces acting on a wind turbine are very complex and time consuming. This design project inspired me in continuing the research in wind turbines in future". "Minor mistakes hidden in CAD model were clearly displayed in prototyping".							

5.2 Advice to anyone adding 3D printing to a machine design course

Desktop 3D printing is a tool for engineering educators can use to transform students' design concepts into reality with relative convenience. This state of the art technology helps educators to engage technologically savvy students and to facilitate their design effort. Some features of 3D printing (both positive and negative) identified during this study are highlighted below:

- 3D printers are easy to learn and use; students learned the basic operating procedures and were able to set printing parameters after a demonstration performed within a single class period.
- Students were able to integrate 3D printing into their 3D modeling skill set.
- Student's didn't have sufficient manufacturing skills and were hesitant to perform prototyping using traditional manufacturing; only one course offered each in manufacturing and machine design was not enough to prepare them to confidently use traditional manufacturing. 3D printing allowed them to create prototypes without traditional manufacturing.

- 3D printers operate relatively cleanly with no heavy machinery, no open cutting blades, and no rotating parts. The safety risk is minimal.
- Minimal supervision was needed from the instructor, and multiple machines could be run with the supervision of a single student.
- The 3D printing did not require a significant time commitment from the instructor because students could run 3D printing outside class time.
- The open source affordable 3D printers use only plastics (ABS and PLA), and have limited accuracy, surface finish, and possible wrapping in the longer parts.
- It takes a relatively long time to complete a part in 3D printing (hours) and students have a tendency to rush to 3D printing without verifying the accuracy of the CAD model, so they overlook simple faults in their design. It is difficult to detect and not possible to correct mistakes during the printing process.
- The overreliance on computers might be an issue. This could be addressed by requiring students to prepare 2D drawings for dimensional review. This might help to reduce the number of faulty designs and undesirable 3D printing runs.
- Good command of CAD modeling would positively impact project success.

6. Conclusion

In this study students acquired knowledge of design process and were able to design components for various energy generation technology devices. With the aid of 3D printers, students were able to prototype their design. The prototypes allowed them an additional avenue to analyze the motion and functionality of their designs, and to evaluate the accuracy of their CAD models as well as helped to realize different errors and mistakes they have made. In other words, the prototypes helped students to reinforce their knowledge of basic machine design: concepts mapping, practical constraints, force and stress computation, size and material selection, and the interrelationships of the factors. Students were engaged in building a physical object based on their own calculation and analysis. The 3D printer helped to close an existed loop of the design course by offering an effective prototyping method.

The integration of 3D printing into the design course helped to improve the rigor of the course in the areas of analysis, simulation, and prototyping. Along with design knowledge, students acquired the hands-on skill of operating 3D printers. They can use this skill in other classes including senior capstone design, and in future professional endeavors. Overall, student learning outcomes improved when 3D printers were used in the Virtual Machine Design course.

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