



Integrating CAD and CAM for Design-build Projects

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Abstract

This evidence-based practice presentation discusses design and build projects within an undergraduate, Engineering Graphics and Design program. Students are presented with a problem statement and parameters and asked to design a solution. Students utilize computer-aided design (CAD) and computer-aided manufacturing (CAM) software during the design and manufacturing process. Teams of two or three students sketch ideas, create 2D geometry in AutoCAD or 3D models/assemblies in SOLIDWORKS, participate in a pre-manufacturing design review, manufacture components using a 3D printer, CNC router or mill, and/or laser, assemble components, and provide a post-manufacturing design review. This presentation provides information regarding CAD and CAM tools, project workflow, and project observations, challenges and lessons learned. It is the intent of this presentation to provide resources for engineering and engineering technology educators to engage students in design projects that produce physical prototypes or design artifacts.

Introduction

A primary goal of many engineering educators is to teach students relevant knowledge and applicable skills that prepare students for a career in engineering or engineering technology. Jonassen, Strobel, and Lee [1] describe this preparation and transition as workplace transfer. The Pedagogy for Employability Group [2] suggests, when hiring graduates, employers seek the following attributes:

- imagination/creativity
- adaptability/flexibility
- willingness to learn
- independent working/autonomy
- working in a team
- ability to manage others
- ability to work under pressure
- good oral communication
- communication in writing for varied purposes/audiences
- numeracy
- attention to detail
- time management
- assumption of responsibility and for making decisions
- planning, coordinating and organizing ability

In order to receive accreditation from the Accreditation Board for Engineering and Technology (ABET), an engineering or engineering technology program “must have documented student outcomes that prepare graduates to attain the program educational objectives [3].” Highlighted below are several outcomes provided by ABET [3] for accrediting engineering

technology programs. Interestingly, and not surprisingly, these student outcomes are similar to the attributes specified as desirable by employers.

- an ability to select and apply the knowledge, techniques, skills, and modern tools of the discipline to broadly-defined engineering technology activities
- an ability to select and apply a knowledge of mathematics, science, engineering, and technology to engineering technology problems that require the application of principles and applied procedures or methodologies
- an ability to design systems, components, or processes for broadly-defined engineering technology problems appropriate to program educational objectives
- an ability to function effectively as a member or leader on a technical team
- an ability to identify, analyze, and solve broadly-defined engineering technology problems
- an ability to apply written, oral, and graphical communication in both technical and non-technical environments; and an ability to identify and use appropriate technical literature

Participating in design-build projects engages students in problem solving activities in an academic setting that mimic those of an industrial setting. Jonassen [4] suggests that learners need complex, ill-structured problem solving experiences. Design projects inherently contain ill-structured problem solving activities that produce a variety of solutions [4], [5]. A problem must have 1) an unknown entity in some situation, and 2) solving for the unknown must have some social, cultural, or intellectual value [4]. Problem solving requires the student to create a mental model of the problem statement or problem space, and progress into an activity-based manipulation of the problem [4]. Design projects provide an enjoyable and unique opportunity to learn in new ways and transfer knowledge [6]. Students that complete design projects learn and practice the skills sought by employers. Students gain first-hand experience in both hard and soft skills, while solving problems and creating physical artifacts.

Experiential learning techniques serve as the foundation for design projects. Two techniques that fall under the umbrella of experiential learning are problem-based learning and project-based learning [7]. Problem-based learning involves students working through complex or ill-structured problems by deciding what knowledge they need to apply to create a solution [1], [7]. Project-based learning involves some of the same aspects as problem-based learning, but will typically result in the creation of a physical design artifact that provides a problem solution. Problem-based learning is often open-ended engineering design projects that include learning significant design elements such as problem identification and formulation, design concept generation, and project management [7]. Jonassen et al. [1] assert “more classroom experiences and all PBL programs should engage students in resolving the complexities and ambiguities or workplace problems more consistently throughout the curriculum (p.147).” McClellan and Hyle [8] support this by adding, “the goal of higher education should be to facilitate learning through experiences.”

Design Projects

Automaton Project

An automaton is a mechanical device utilizing mechanisms to create repeated movements. One Merriam Webster [9] definition describes automaton as, “a machine or control mechanism designed to follow automatically a predetermined sequence of operations or respond to encoded instructions.” Wood [10] defines automaton as a “machine that contains within itself the power of motion.” Mechanisms used in automatons can include gears, springs, cams, pulleys, and linkages. When combined in creative ways, these mechanisms can create whimsical and mesmerizing movements. Designers have been creating automatons for generations. Some early and well know automatons include the *Digesting Duck* (1739), the *Flute Player* (1738), and the *Tambourine Player* (1739) by Jacques de Vaucanson and *The Writer* (1774), *The Draughtsman* (1774), and a *Musical Lady* (1776) by Pierre Jaquet-Droz [10].

Engaging students in manufacturing an automaton provides a unique opportunity to mix creativity with design. Students gain design experience, develop CAD skills, apply design for manufacturing and assembly (DFMA) principles, utilize manufacturing processes, consider materials, and learn to work with others. Consequently, these are essential qualities that employers seek when hiring designers and engineers.

The automaton project was implemented in a sophomore-level, parametric modeling and rendering CAD course in the fall semester of 2017. The lecture and lab course met three days a week and each class period was 110 minutes. Students utilized SOLIDWORKS as their primary CAD software for the course. Students had access to an Epilog Mini 18 laser engraver/cutter, an AXIOM AR4 CNC router, and various 3D printers including a Stratasys uPrint, Afinia H800, and FormLabs Form 1+. Students completed the automaton project in four weeks. Students were grouped into teams of three by random assignment. At least two approaches for the creation of student teams can be used. One approach is to use the randomly assigned method and another approach is the strategically assigned method. Random assignment is often used because of its convenience [1]. The opposite approach to randomly assigning teams is to strategically assign specific students to specific teams based on their individual skills. In this case, the instructor creates teams based on his or her internal assessment and will include a combination of the students’ hard and soft skills. It is important to keep the number of students in a team to two or three as having too many students in a group leads to members that do not contribute [11]. Students were given a problem statement or objective. The stated objective of the automaton project was to design and manufacture a functioning automaton. Prior to meeting with their team, students were given time individually to conduct preliminary research, brainstorm ideas, and create sketches of potential automatons. Afterward they met with their peers and discussed ideas as a team. The team generated one idea with which to move forward for design and manufacture. As a team, students assign the various tasks needed to transition from ideas and sketches into a 3D SOLIDWORKS model. Students were given three class periods to complete the preliminary design.

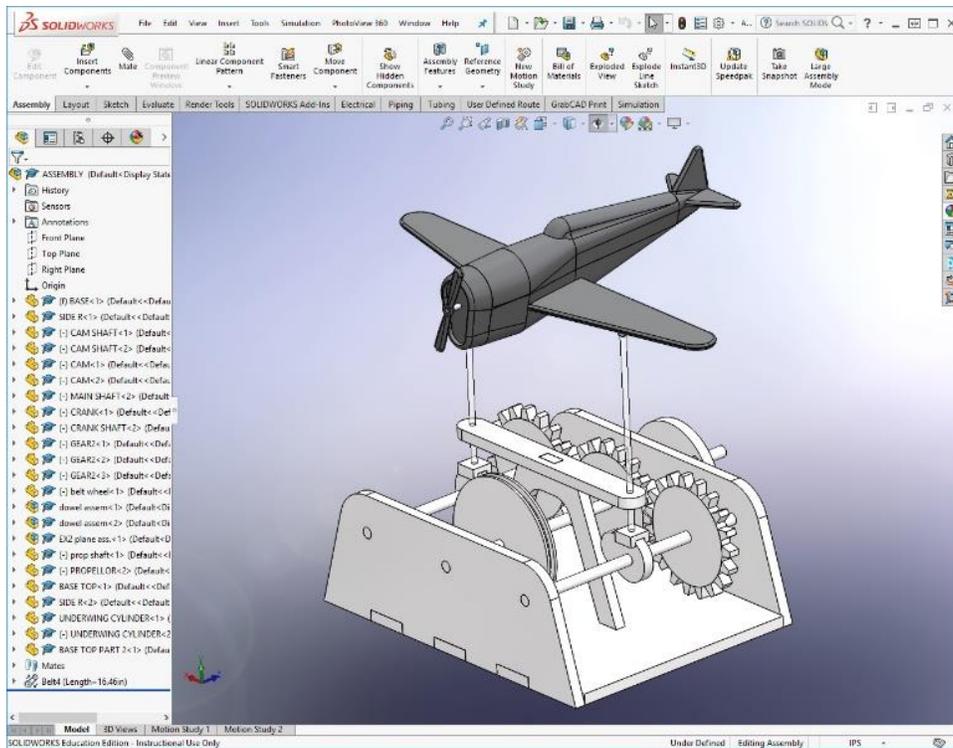


Figure 1. Screenshot showing CAD model of airplane automaton in SOLIDWORKS

After the three class periods, students participated in a preliminary design review administered as an oral presentation to the instructor and the class. The preliminary design review is a brief overview of the design and should address the project objective, materials being considered, manufacturing processes to be used, time of manufacturing and assembly, and estimated cost of materials. The preliminary design review presentation can include a combination of sketches, CAD screenshots or renderings, engineering drawings, photos or videos, or any media that clearly communicates design and manufacturing of the automaton project. The preliminary design review allows development of written and oral communication skills as well as peer evaluation. The preliminary design review also serves as another opportunity for the instructor to provide valuable input related to successful design and manufacturing [11]. It is recommended that the instructor ask guiding questions that lead students to the discovery of changes which facilitate the production of a functioning automaton. During the questions and comments period of the preliminary design review, typically at the end, students are encouraged to take notes related to changes that need to be made to the design. Students are given two additional class periods to make changes to their design and prepare for a final design review.

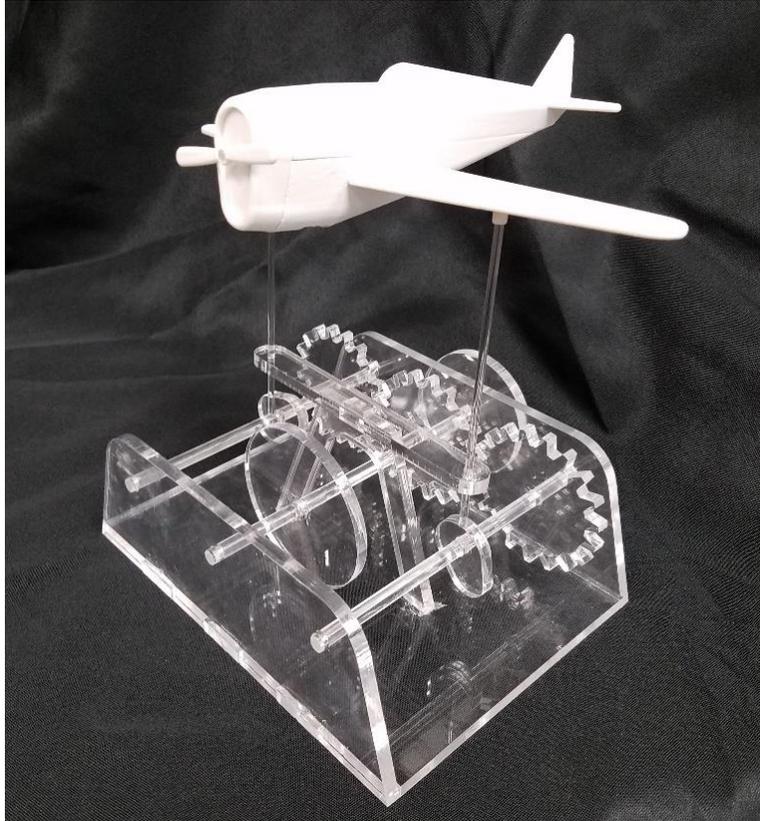


Figure 2. Physical model of airplane automaton

The final design review is similar to the preliminary design review, but should present a refined design that is ready for manufacturing. It is important to note, and an invaluable part of the process, that the final design may not be perfect. Students then progress to manufacturing and utilize laser engraving/cutting, 3D printing, and CNC operations, or a combination of these manufacturing processes, to produce their design. Students were given three class periods to complete manufacturing, assembly, and testing. At this point in the project students were allowed and encouraged to make simple modifications to their design based on data and feedback from the physical prototypes. Students were required to give a final presentation describing the entire design and manufacturing process.



Figure 3. Completed automaton projects

After completing the automaton project students were asked to provide reflection statements on aspects that were enjoyable, unenjoyable, and what they would do differently. Below are a few samples of student feedback.

1. What aspects did you find enjoyable?

“I liked that challenge of designing something that had a specific function and seeing it all the way through production.”

“The design process and the freedom in this assignment.”

“I found the complications that we had to face enjoyable.”

2. What aspects did you find unenjoyable?

“I had to redo my assembly twice which was annoying but it was my fault.”

“The time crunch at the beginning of the project. It worked out though.”

“It would be more enjoyable if we had another week.”

3. What would you do differently?

“Try to incorporate more mechanical movements into the design.”

“Have a more defined process, maybe a basic model to base things off of.”

“I would have finished my design sooner and ordered parts sooner.”

Additionally, based on participation in the automaton project, students were asked to rank the increase of their skillset. The 10 point Likert scale ranged from ‘0 – Did not increase’ to ‘10 – Significantly increased’. Table 1 below highlights the student rankings.

Table 1.
Student rankings of skills after automaton project

Statement	Ranking
Rank the amount that participation increased your SOLIDWORKS skills.	7.47
Rank the amount that participation increased your knowledge of design for manufacturing.	8.20
Rank the amount that participation increased your ability to effectively work on a team.	6.60

Note. n=15 students. Rankings are based on a 10 point Likert scale

In addition to the automaton project this course engaged students in a variety of reverse engineering activities where students disassembled mechanical products, measured items with scales and calipers, and created 3D parts, assemblies, and 2D engineering drawings using SOLIDWORKS. Students typically participate in at least one other design/build project. Based on an *IASystem*TM course evaluation the overall summative rating for this course has a median of 4.9 out of 5.0 ($n=13$) and a challenge and engagement index of 5.1 out of 7.0 ($n=13$). The overall summative rating “represents the combined responses of students to the four global summative items and is presented to provide an overall index of the class’s quality.” The challenge and engagement index “combines students responses to several *IASystem*TM items relating to how academically challenging students found the course to be and how engaged they were.” When asked to rank the amount you learned in this course a median score of 4.8 out of 5.0 was calculated ($n=12$). When asked to rank the relevance and usefulness of course content a median score of 4.9 out of 5.0 was calculated ($n=13$).

Table 2. below provides a brief summary of the timeline associated with the automaton project.

Table 2.
Project activities and allotted time

Activity	Class periods allotted
Research, idea generation, individual sketches, team discussions	1
Preliminary design creation (SOLIDWORKS)	3
Preliminary design review (oral presentation)	1
Final design creation (SOLIDWORKS)	2
Final design review (oral presentation)	1
Manufacturing, assembly, testing, design changes, and remanufacturing (3D printing, CNC router, laser cutting)	3
Final presentation (oral presentation)	1

Note. Class period length is 110 minutes

3D Printed Desktop Catapult Project

Over the last decade classrooms have drastically increased the use of 3D printing because of its ability to assist in teaching design and engineering concepts [12], [6]. Other educators have even implemented catapult or trebuchet projects in their classrooms [13], [14]. 3D printing offers an inexpensive and easy way for students to produce a physical prototype of their digital CAD model. Physical artifacts or prototypes are invaluable to connection of CAD skills and the ability to design successful products.

The objective of the 3D printed desktop project was to design a small, desktop catapult to launch a marble. The catapult project was implemented in a freshman-level, CAD course focusing on the use of SOLIDWORKS in the spring semesters of 2016 and 2017. The lecture and lab course met three days a week and each class period was 110 minutes. Students worked in teams of two. Students used two, 3" X .125" rubber bands as the energy source for launching the marble. The instructor informed students at the beginning of the project that final designs would be 3D printed using material extrusion technology. Material extrusion can also be known as Fused Deposition Modeling (FDM), a proprietary Stratasys term, or Fused Filament Fabrication (FFF), a term often used in the RepRap community. Consequently, students were encouraged to consider design methods for 3D printing, including build envelope size, material use, printing time, feature details, part orientation, and assembly. An initial design parameter required students to fit all catapult parts within a single build or print job, with a maximum size envelope of 6" X 6" X 6". Students used SOLIDWORKS computer-aided design (CAD) software to design their catapults. Students were required to create ideation sketches, design 3D SOLIDWORKS parts and create an assembly, produce a 2D SOLIDWORKS assembly drawing with balloons and a bill of materials, render a photorealistic image in SOLIDWORKS PhotoView 360, and animate the assembly and disassembly of the catapult.

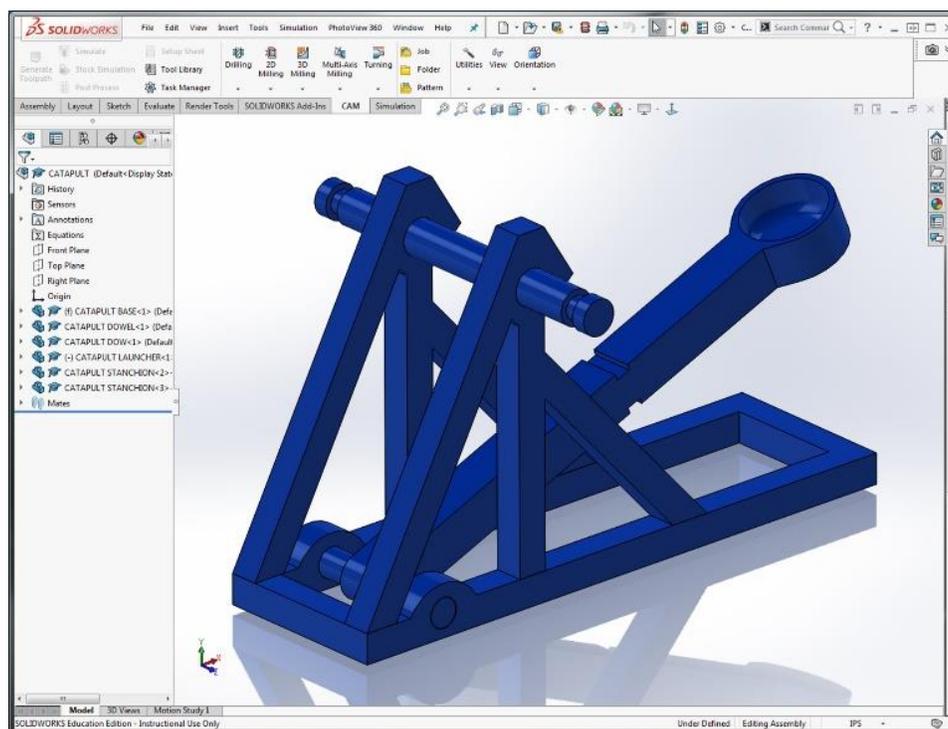


Figure 4. Screenshot showing CAD model of catapult in SOLIDWORKS

After all catapults had been 3D printed, students assembled the catapults and prepared them for launching marbles. On average, most teams launched marbles between 25 and 35 feet. However, one team launched a marble an average of 72 feet! Students were asked to rank their overall satisfaction and any perceived increase in their skillset. Table 3 reveals a high ranking, 8.50 out of 10, for overall satisfaction with the catapult project.

Table 3.

Student rankings of skills after catapult project

Statement	Ranking
Rank your overall satisfaction with the catapult project.	8.50
Rank the amount that participation improved your SOLIDWORKS skills.	7.58
Rank the amount that participation improved your design skills.	8.58
Rank the amount that participation increased your team work skills.	7.83

Note. n=12 students. Rankings are based on a 10 point Likert scale



Figure 5. Physical prototype of 3D printed desktop catapult

The 3D printed desktop catapults offer the opportunity for students to engage in a fun, tangible, and competitive project that builds CAD and design skills, increases knowledge of design for manufacturability and assembly methods, and promotes teamwork. Challenges associated with 3D printing desktop catapults include time and material for 3D printing. It is critical for the instructor to work closely with students to challenge design decisions and provide

feedback concerning manufacturability, assembly, and catapult performance. To assist in learning project management, it is recommended to create a timeline that highlights critical milestones.

After completing the catapult project students were asked to provide reflection statements regarding aspects that were easy, difficult, and what they learned about design. Below are a few sample student comments.

1. What was the easiest part of the catapult design project?

“Giving the design review presentation was one of the easier parts of the project.”

“Coming up with a design that was different from the others.”

“Working with my teammate.”

2. What was the most difficult part of the catapult design project?

“Carrying out the design properly and getting everything to fit.”

“Figuring out the tolerance for the holes, for the parts to assembly correctly.”

“Making things fit in the build plate.”

3. What did you learn about design during this project?

“I learned a lot about how things fit together in real life (it’s a lot different than SOLIDWORKS).”

“A knowledge of the materials being used is important.”

“I need to think more about the size of parts.”

This freshman level course teaches students the fundamentals of SOLIDWORKS parts, assemblies, and drawings. Students learn SOLIDWORKS by modeling a number of basic 3D parts ranging in geometric complexity from simple to intermediate, creating 2D engineering drawings based on ASME standards, and constructing several 3D assemblies. The parts and assembly assignments are taken from the *Technical Graphics Communications – 4th Edition* by Bertoline, Wiebe, Harman, and Ross and *The Beginner’s Guide to SOLIDWORKS: Level 1* by Alejandro Reyes.

Based on an IASystem™ course evaluation the overall summative rating for these courses has a median of 4.8 out of 5.0 ($n=22$) in 2016 and 4.8 out of 5.0 ($n=12$) in 2017. The challenge and engagement index was 5.4 out of 7.0 ($n=22$) in 2016 and 5.3 out of 7.0 ($n=12$) in 2017. When asked to rank the amount you learned in this course a median score of 4.8 out of 5.0 was calculated ($n=21$) in 2016 and 4.8 out of 5.0 ($n=12$) in 2017. When asked to rank the relevance and usefulness of course content a median score of 4.8 out of 5.0 was calculated ($n=21$) in 2016 and 4.9 out of 5.0 ($n=12$) in 2017.



Figure 6. 3D printed desktop catapults

CNC Cube Project

The objective of the computer-numeric control (CNC) cube project was to create a custom design to be etched or cut using a CNC machine. The CNC cube project was implemented in a sophomore-level, CAD course focusing on the use of SOLIDWORKS in the fall semester of 2016. The lecture and lab course met three days a week and each class period was 110 minutes. Students worked individually to create their design. Each student was given a cube of 6061 aluminum measuring 1.25" X 1.25" X 1.25". Students were informed that the CNC cube would be cut using a 1/16" square end mill using a Tormach PCNC 770 CNC mill. Students used SOLIDWORKS CAD software to design geometry to be removed from at least one face of the cube.

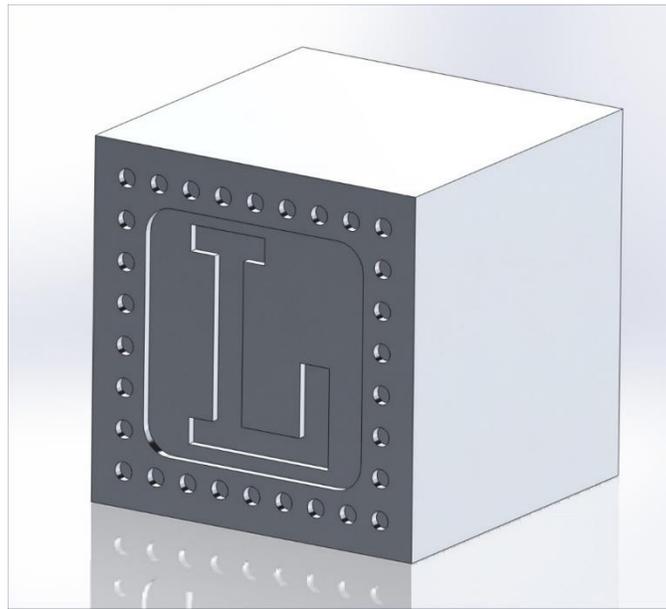


Figure 7. Screenshot showing CAD model of CNC cube in SOLIDWORKS

Students could choose to cut up to four faces of the aluminum cube. After geometry of the material to be removed was complete, students were required to generate the proper toolpaths using an add-in to SOLIDWORKS named HSM Premium.

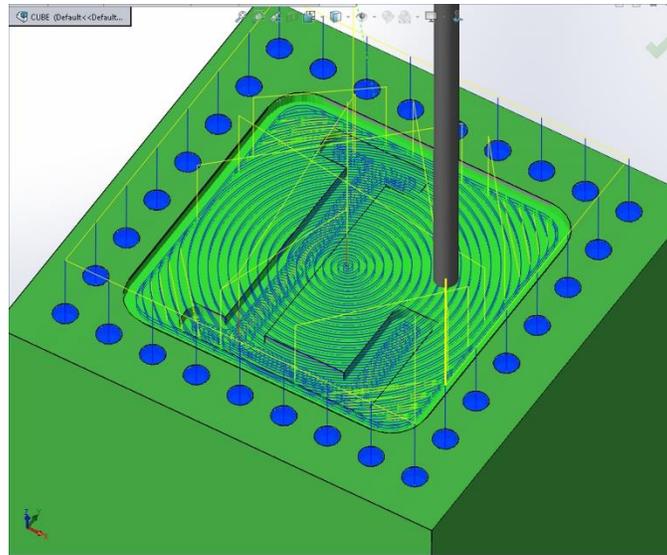


Figure 8. Screenshot showing HSM Premium CNC toolpaths in SOLIDWORKS

HSM Premium is computer-aided manufacturing (CAM) software produced by Autodesk. HSM Premium CAM software is an add-in to Inventor or SOLIDWORKS and is used to simulate CNC toolpath operations and export the appropriate machine's G-code. G-code is plain text language that instructs the CNC controller to perform desired motion and cutting to complete the cutting operations [15]. The green geometry shown in Figure 8 represents the aluminum cube and the blue circular and vertical lines represent the path of the cutting tool. Prior to using the Tormach CNC mill, students are required to meet with the instructor to review the toolpath simulation and closely inspect parameters such as spindle revolutions per minute (RPM), cutting speed and depth, travel speed, clearances, and manufacturing time. Figure 9 shows a completed CNC cube. It should be noted that the plunge rate was incorrectly specified in HSM resulting in a broken end mill and the student decided not to complete the hole pattern on the cube's perimeter. Some students decided to drill a small hole in the top, glue in braided steel wire, and attach an alligator clip to create a picture or note holder.

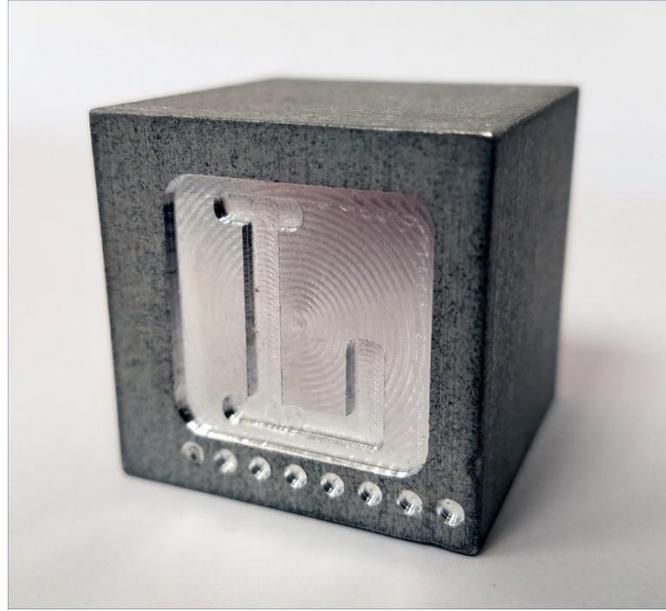


Figure 9. Completed CNC cube project

In addition to the CNC cube project this course engaged students in a variety of reverse engineering activities where students disassembled mechanical products, measured items with scales and calipers, and created 3D parts, assemblies, and 2D engineering drawings using SOLIDWORKS. Students participated in a variety of assignments and design-build projects during the course of the semester. Based on an *IASystem*TM course evaluation the overall summative rating for this course has a median of 4.8 out of 5.0 ($n=25$) and a challenge and engagement index of 5.3 out of 7.0 ($n=13$). When asked to rank the amount you learned in this course a median score of 4.7 out of 5.0 was calculated ($n=25$). When asked to rank the relevance and usefulness of course content a median score of 4.8 out of 5.0 was calculated ($n=25$).

Conclusion

Implementing and engaging students in design-build projects is an invaluable opportunity for students to increase skills in CAD, design for manufacturing and assembly, application of manufacturing processes and materials, and teamwork. Students understand design and apply knowledge transfer when digital CAD files are converted into tangible, physical products. The feedback and data students receive from inspecting manufactured geometries and relationships of produced features drastically impacts the amount they learn. Reduced pricing and vast availability of various CAD, CAM, and prototyping equipment provides educators opportunities to implement design projects in the classroom. Available online are a myriad of resources containing project ideas for STEM projects at all age levels. Educators can develop and implement their own design projects, seek ideas or design problems from peers, family, or friends, or work with local industries to develop design projects.

The author recommends allowing plenty of time to complete design projects. It is important not to rush, but instead allow time for students create, design, manufacture, assemble, reflect, redesign and remanufacture as necessary. A key component related to engaging students in design-build projects is allowing creativity, minimal guidance, and the opportunity for failure.

In most cases, students do not get the design and manufactured components perfect and functioning on their first attempt. Student reflection and discussion of the successes and failures of the project are the key to learning. A final written or oral presentation is recommended thus giving students a final opportunity to process what they have learned during the design-build process. Appendix A offers a rubric for assessing design reviews.

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Appendix A: Rubric for assessing design reviews

Category	Poor	0	1	2	3	4	Exceptional
Design objective	Does not discuss objective, does not understand design objective						Clearly states and understands the project objective
Ideation/Brainstorming	Does not include preliminary ideas or solutions, presents few or non-applicable solutions to solve design problem						Presents numerous, applicable solutions to solve design problem
Design for Manufacturability and Assembly	Does not describe part geometry and assemblies, provides minimal description of types of fit and feature relationships, gives weak rationale for design choices						Provides detailed descriptions of part geometry and assemblies, discusses types of fits and feature relationships, provides rational for design choices
Manufacturing Processes	Does not provide information about manufacturing processes, provides minimal understanding of process selection						Understands manufacturing processes, selects appropriate manufacturing processes. Provides rational for process selection, provides accurate manufacturing timeframe
Materials	Material list is not given, does not discuss selection, vendors, or pricing						Develops detailed bill of materials, selects appropriate materials, provides analyses of materials selection, includes vendor and pricing information

0 – Not achieved

4 - Achieved