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Incorporating Computer Aided Design and Three-Dimensional Printing in a First Year Engineering Design Course

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Abstract

This informational paper describes the methodology used to teach a hands-on, first-year engineering design class where Computer Aided Design (CAD) and Three-dimensional (3D) printing are introduced as tools to facilitate the creation, design and production of engineered products and systems. Additionally, students are provided insight into Computer Aided Manufacturing (CAM), design for manufacturing and embedded computer control. For several years, first-year engineering design was taught at this institution using the Lego® Robotics system as the vehicle for solving engineering design problems presented to each class. While that approach proved to be effective, it was desired to extend the concept of problem-based learning to encompass a variety of realistic scenarios while fostering creativity through enhanced communication and visualization enabled by CAD and 3D printing. The new approach adds two new learning outcomes and removes one from the earlier approach. Assessment of student performance is made primarily through individual assignments, quizzes, a final team project and an exam.

Two significant challenges have arisen with the CAD/3D-printing approach. The first is a compressed timeframe for instruction in the mechanics of using design tools due to 3D printing latencies. The second challenge is that additional human effort is required for the operation and maintenance of the 3D printers. These challenges have been addressed through liberal application of undergraduate teaching assistant (UGTA) efforts in combination with instructional videos. Instructional videos (generally 10 minutes or less) are provided for each topic covered during the first several lectures, to help students prepare for class. UGTAs provide individual support to students during class while new 3D modeling capabilities are introduced, help students outside of class by providing tutoring sessions, and have a large share of the responsibility for the operation and maintenance of the 3D printing lab.

This class has been met with great enthusiasm from students, instructors and administrators; and has resulted in many creative and surprisingly complex, meticulously implemented projects. An initiative was begun in the fall 2019 semester, where embedded control capability was incorporated into many of the existing projects by students with minimal programming experience. This has proven to have had a positive impact on making projects more realistic and on capturing student interest. This paper will provide an overview of our methodology in order to allow other institutions to develop a similar model.

Introduction

It is widely recognized among those engaged in engineering education that hands-on learning, particularly during the first year, is a highly effective pedagogical approach [1]-[5]. This paper presents an approach to providing hands-on instruction in a first- year engineering design course using CAD and 3D printing. It is desired to engage students with design projects that provide them with a signature experience in finding the connection between abstract theoretical concepts and physical phenomena. While this course includes instruction pertaining to skills normally associated with mechanical engineering (CAD), it is open to students from all engineering disciplines at Wayne State University.

For several years, engineering design principles were introduced at our institution using the Lego® robotics system. Transition from Lego® robotics to Computer Aided Design (CAD)/3D printing for the purpose of introducing engineering students to the design process began in the Fall 2017 semester. The impetus behind the transition was the desire to provide students with an earlier exposure to CAD, utilize technologies more closely resembling those used in industry, allow students to participate in developing realistic projects, and provide exposure to the design for manufacturing concept. Additionally, completion of this course has provided students with transferrable CAD skills which have reportedly had significant impact on helping students to obtain internships. In the current approach, the risks of premature fixation [6] and bounded ideation are mitigated by requiring the development of multiple concepts for each team's final project using an idea generation method known as design heuristics [6]. During concept development, CAD and hand-drawn sketches serve as tools to help students effectively translate the products of their imaginations to their teammates. As the semester progresses and project development transitions to detailed design, the enhanced visualization enabled by CAD helps in the creative process by improving the students' ability to assess new ideas and realize potential problems. Similarly, 3D printing helps with the identification of production related problems and helps prevent students from becoming disconnected from the realities of design in industry. This provides an avenue for introducing the concept of design for manufacturing.

To accomplish the desired goal, two focus areas are addressed: 1) Basic skills instruction focusing on providing competence with CAD and 3D printing; and 2) Engineering design process instruction through the completion of projects designed using CAD and implemented with the use of 3D printing.

Basic Skills Instruction (CAD and 3D Printing)
In-class instruction supplemented by on-line instructional videos, UGTA tutoring sessions/office hours, and UGTA classroom support [7] comprise the approach used in developing student competence in the use of an advanced, commercially available, CAD software tool provided by Siemens PLM Software called NX-12 [8]. Students learn to use CAD by creating three-dimensional models of complex individual components, creating two-dimensional drawings of those components, virtually assembling the components into a sub-system to ensure proper alignment, and creating an exploded-view drawing of the subsystem. Instructional videos (generally 10 minutes or less) are used to illustrate basic CAD operations such as sketch, extrude, revolve, mirror, pattern feature, etc. Additionally, for the purpose of building student confidence, short videos have been created which walk the students through most of the first 2 homework assignments, step-by-step. The target length for each video is 10 minutes or less.

Student competence in the use of the CAD tool is evaluated through a series of assignments and an in-class exam. The assignments consist of set of homework problems which build upon each other and are progressively more difficult; and an early individual project in which the students design a moderately complex object which is 3D printed. A final project is assigned to promote creativity and assess students' ability to synthesize knowledge and use it to solve a given problem.

Students are given the opportunity to experience the realization of their individual creativity through 3D printing as early in the semester as possible. Work on an individual project begins in the second week, which students can complete with a rudimentary understanding of the CAD and Computer Aided Manufacturing (CAM) tools. For this introductory project, each student designs and has a customized school logo 3D printed, which helps them gain intuition about size, print time, and material requirements of components. Additionally, this project gets students involved in 3D printing early in the semester, provides a vehicle for introducing them to the concept of CAM, CAM tools and design for manufacturing, and kindles a high level of enthusiasm which carries throughout the duration of semester. Examples of customized logos are show in Figure 1.

Figure 1. Examples of student designed custom school logos

Engineering Design Process

Team projects are used to provide hands-on instruction pertaining to engineering principles. Student teams are given the option to select from a list of approved projects, or to define one with instructor approval: a paddle boat and mechanical hand are two examples of Student defined projects. As students gain competence with CAD, instruction in the design process commences where, over the course of several sessions students are introduced to design process fundamentals, namely: creation of a problem statement; definition of qualitative and quantitative requirements; concept development; system design; component design; system integration and system test. As the design process steps are discussed in class, student teams apply them to their team projects. The general approach is to design a "real" system, and then to produce a scale-model "prototype". Examples of several recent projects are shown in Figure 2.

Figure 2. Examples of recent student projects

Teams collaboratively develop the problem statement, system requirements, concepts and top-level system design. The system design provides identification of required components and interfaces between those components, and generally consists of hand drawn sketches, CAD models and/or block diagrams. Based on the system design, each team member is assigned responsibility to design one or more of the components required for their respective project using the CAD tool. Using the same CAD tool, components are then virtually assembled to ensure proper fit with consideration given to clearances required in the context of 3D printing. This helps emphasize the importance of clearly defining and verifying interfaces between components which comprise the system. Consideration is given to the tolerances associated with the 3D printers, and students design interfaces with appropriate clearances in mind. Examples and demonstrations of 3D printed threaded fasteners, mating gears, and other interfacing components are used to help student understanding of relevant clearances.

Once satisfied with the individual components and the virtual integration, models are translated into a format suitable for the CAM tool. Students use the CAM tool to obtain an estimate of manufacturing time and material which are then used in calculating a cost estimate. After each team successfully completes a "milestone 1" design review, components are printed and assembled. Throughout the design process UGTAs serve as project managers, each supporting 2 or 3 teams helping students avoid pitfalls associated with 3D printing, ensuring an equitable division of responsibilities and tracking progress of tasks.

Students may implement embedded control by programming a microcontroller and integrating necessary hardware or selecting from a set of predesigned hardware (HW) and software (SW) "standard embedded control modules" (SECMs) [9]. Presently, SECMs include a micro controller board (μC), HW and SW for: motor control; Bluetooth (BT) interface to smart phone; joystick interface (I/F); and push button switch I/F. Table 1 shows some recent projects, where student-initiated projects are denoted by an asterisk.

Table 1. Examples of recent student final projects.

Project Name	Description
Bench Vise	Rotating base, jaws open to approximately 6 inches
Crane	Rotating arm and cabled hook, manually operated and implemented with bevel gears
Drawbridge	Manually operated-worm gear mechanism; Electronic implementation with SECMs
Electric Clock	Motor driven gearing/Geneva mechanism operating minute and hour hands
Elevator	Manually operated with handle, gears, pulley and cable
Ferris Wheel	Implemented with SECM (switches and servo motor, SW & μC)
Locks	Combination lock and key operated lock
Mechanical Hand*	Fingers with individual joints, palm and wrist. Fingers opened and close via a μC.
Pneumatic Engine	Two-cylinder air powered engine with pistons and crank shaft
Ratcheting tool	screwdriver and wrench. Student designed ratchet mechanism.
RC Car*	Body, chassis and wheels. μC programmed by students, utilizes BT I/F to smart phone
RC Paddle Boat*	Two motor-operated paddles, control Implemented with SECMs
Self-Watering Planter	Ferris-wheel-like mechanism, controlled by SECM (μC and motor)
Wind-up toy car *	Frame, wheels, gears, 3d printed spring designed by students

Recently completed projects include a 3D printed, 360° pivoting bench vise with a 6-inch opening shown in Figure 3.

A CAD developed virtual assembly used to ensure proper alignment and placement of components is shown on the left, while the right-hand image shows the completed 3D printed project.

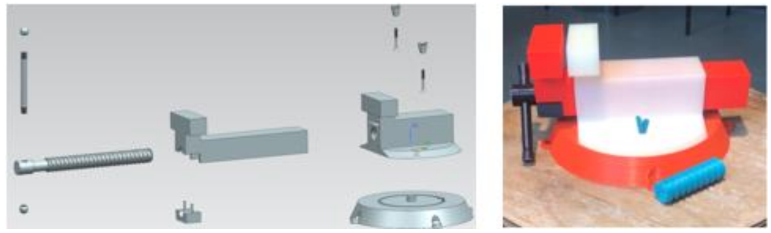

Figure 3. Pivoting Bench Vise with 6" opening

The wind-up car shown in Figure 4 incorporates a 3D printed flat spiral spring, chassis, wheels and complex gear mechanism. The car has the capability to move approximately 20 feet with the current spring. Alternative materials are being investigated for future work.

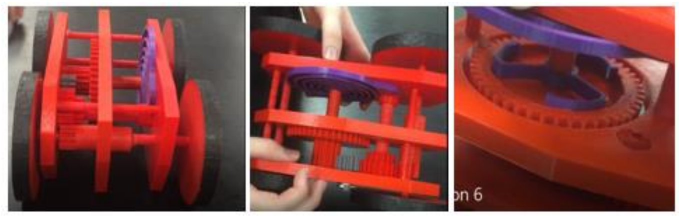

Figure 4. Wind-up car with 3D printed flat spring.

The remote-controlled 3D-printed paddle boat shown in Figure 5 is an example of a project using SECMs, incorporating a BT to smart phone interface, microcontroller, and two continuous rotation servo motors.

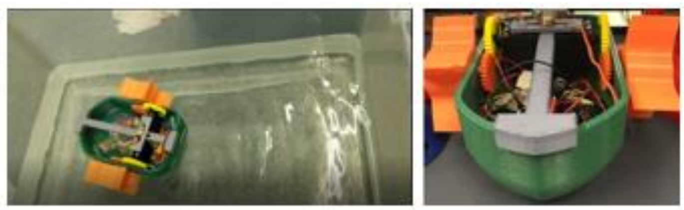

Figure 5. Paddle Boat Incorporating SECMs

Learning Outcomes

Implementation of the current approach incorporates two new learning objectives and removes one, as shown in table 2.

Table 2. Affected Learning outcomes and assessment

Learning Outcomes Affected by Current Approach		Assessment
Read and create engineering drawings and models	Added	HW, Q, P, Ex
Use plastic 3D printing to create functional objects	Added	HW, P
Develop and implement simple algorithms and programs	Removed	HW, Q, P

The assessment methods listed in table 2 are: HW-Homework, Q-Quizzes, P-Team Projects, Ex-Exam.

Future Plans

This course has been met with a high level of enthusiasm from both students and faculty. The students had the opportunity to be engaged in realistic engineering projects pertinent to their areas of research, and faculty have witnessed the outstanding work completed and sense of satisfaction demonstrated by class participants. Incorporation of SECMs to bring projects to life has been embraced by many students, and the development of new standard modules will continue in order to provide interfaces to a greater variety of electrical/electronic sensors and actuators.

Additionally, this course has demonstrated the positive impact of the use of peer mentoring. Support provided by UGTAs has far surpassed all expectations, as they have taken over most of the responsibilities associated with the 3D printing lab, provided most of the assistance on assignments, and provided valuable insights and ideas which have served to improve the content and delivery of the course. An important lesson learned has been the outstanding contributions made by undergraduate teaching assistants when they are given goals and constraints, provided the opportunity to take ownership in their areas of responsibility, encouraged to freely express their views, and are included in discussions pertaining to curriculum improvement and in the decision-making process. Going forward, it is expected that greater UGTA involvement will be incorporated into other sections of this course.

Acknowledgment
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