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Project-Focused Redesign of a First-Year Engineering Design Course for CAD and CAM in a Modern Era

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Abstract

The evolution and widespread presence of advanced computing has created avenues for incorporating more advanced modeling techniques into the classroom at an earlier stage of the engineering educational timeline. Since many students are now already well-versed in using technology in the classroom to enhance technical concepts, it is possible to guide students to more broad and advanced applications of computer aided design. Additionally, with the constant innovation of cheap, accessible rapid prototyping devices, it is now easier than ever to introduce students to manufacturing and prototyping to reinforce concepts and visualize the consequences of their design decisions. However, identifying outdated aspects of the course to be substituted with their modern counterparts can be challenging. In this paper, we describe the decisions made to create a more advanced design environment in an introductory-level engineering design and graphics course without losing critical engineering design foundations. This includes building a project-based curriculum focused on computer aided design of a product with considerations for multiple manufacturing methods, including 3D printing, laser cutting, and injection molding.

Introduction

The objective of pedagogical improvements in engineering education is to strive towards practical integration of theoretical concepts. For many types of engineers (Mechanical, Civil, Aerospace, ect.), computer aided engineering (CAE) software is an extremely powerful tool towards ideation, development, and implementation of complex design solutions. Computer-aided design (CAD) tools like Solidworks and Autodesk Fusion 360 provide real-time visual feedback of a design and allow the user to iterate based on part and assembly-level interdependencies. Computational tools based on the finite element method (FEA) help the designer to analyze the limitations of their design, predict failure modes, and optimize design parameters to achieve a certain performance. Computer-aided manufacturing (CAM) tools incorporate information about commonly used manufacturing processes like machining, injection molding, and 3D printing to provide additional information about the feasibility of a design. A seamless integration of CAE tools into the design thinking process can potentially reduce the cost of developing multiple physical prototypes by allowing engineers to rely on these virtual prototyping approaches to gain confidence in the solution.

The initial adoption of CAE in most undergraduate engineering curricula focused on browsing through the capabilities of the software and learning how to use them. However, over the last few decades, CAE tools, especially CAD and modeling software, have become much more user-friendly and intuitive. CAD has also become an integral part of the pre-collegiate level curricula for many students entering undergraduate engineering programs. The COVID-19 pandemic also forced both students and educators to adapt to online delivery and learning, often by creating tutorials and other innovative teaching solutions. Within this evolving teaching paradigm, first year engineering design courses provide a window of opportunity for educators to introduce CAE in a new way and help students utilize these tools to their fullest potential.

Teaching of CAE at UT-Austin

At The University of Texas at Austin (UT Austin), learning the foundations of engineering design takes place early in the undergraduate student experience, usually within the student's first year. For example, first year Mechanical Engineering (ME) students at UT-Austin are required to take the ME302: Introduction to Engineering Design and Graphics, a three credit-hour course. Traditionally, this course has focused on a lecture-lab format which involved learning how to use CAD software, preparing engineering drawings, and an introduction to potential opportunities within ME. However, the objectives of this course were not as well integrated and somewhat outdated. This paper discusses a redesign effort of ME302 to enhance the learning experience of this course. The proposed changes to the structure of this course generally imbibe the philosophy of hands-on learning and ownership of the idea-to-product phase which is backed up by student feedback.

The redesigned Introduction to Engineering Design and Graphics course focuses on several core learning objectives: (1) Ideation and idea evaluation, (2) Design visualization, (3) Design creation in various prototyping and manufacturing methods, and (4) Design evaluation in both experimental and simulated space. In order to achieve these objectives a new project-based format of this course was introduced that gives students the opportunity to design and create their own fidget spinners over a progression of design-focused assignments with room for creativity in a lighthearted product. At every step of the design process, students are encouraged to consider both their creative endeavors and the practical limitations of their design. In particular, they are forced to consider how their designs become limited by the manufacturing methods which they use to make their products, which include 3D printing, laser cutting, and injection molding that is assisted by CNC milled molds. Important considerations for these are the resolution of features possible in each method, minimum and maximum angles, the manufacturability of 3D features, mold draft angle, and many more. Students quickly learn which features are possible in one method versus the others, and which manufacturing processes are best suited for prototyping and mass production.

Updating the Teaching of CAE

The following sections outline the various changes to the class structure that have taken place in order to provide a more rigorous and engaging work environment. First, we outline the structure of the original class, with emphasis on the more outdated aspects of the class that were revised. This is followed up by an outline of the most recent version of the class, along with descriptions of various adjustments that were made since the first iteration of the changes to highlight challenges in the new curriculum. Finally, an analysis of how the updates to the course affect learning outcomes is presented.

Former Course Structure:

The course curriculum before the change was outdated and required significant updates to encourage students to build relevant skills for modern engineering. The course had three main phases before the modifications discussed in this study. In the first phase, students focused on hand sketching with pen and paper which was introduced to teach design concept development during product ideation phases. This skill had over 5 weeks of lessons and 21 assignments dedicated to it. While technical drawing skills can improve visual understanding of some of the critical elements of CAD software, these are also skills that can be developed with practice, devoting more than a third of the course time to them was not a good use of valuable in-class time.

The second phase of the class introduced SolidWorks CAD using a series of workbook assignments over the course of 8 weeks. These assignments were very detailed, but did not develop skills beyond a basic understanding of the functionality of the program. In particular, advanced features added to SolidWorks over the past 15 years beyond the basic 2D sketching, 3D modeling, and assembly were not explored.

The last part of the class involved a group-based reverse engineering project, where groups chose a device to take apart and rebuild as a SolidWorks assembly after modeling each component. This served as a fairly engaging challenge to modeling skills, as well as an introduction to products made using various manufacturing methods, but failed to introduce the challenge behind designing a product with manufacturing methodology in mind.

Updated Course Structure:
The updated course structure incorporates learning new skills with a semester-long independent design project. Every week, students attend a lecture dedicated to teaching and exemplifying the skills necessary for the week. Following the lecture, students have a weekly 4-hour, TA-led laboratory section that is split into a pre-lab consisting of tutorials for building the skills necessary to complete the laboratory assignments and actual work on the lab within the context of their design project. A schedule of the weekly topics covered can be found in Appendix A and arranged such that students simultaneously develop their skills in CAE and apply those new skills to the design of their project.

The design project chosen is a fidget toy colloquially known as a fidget spinner. This was chosen for the design project because it is a relatively simple mechanical device that still allows students a great deal of freedom and creativity in what the final product should look like while still imposing some constraints on their designs that they must consider when engineering their products. For example, they must consider fits and tolerances for incorporating bearings into their designs. Similarly, they need to consider how the manufacturing process places limitations on what spinner designs are feasible.

Lessons early in the semester target introducing the design process and CAE in the form of CAD. In the first few weeks, students complete SolidWorks tutorials to become familiar with the basic 2D and 3D modeling tools available for starting a design while also starting the ideation process for their spinner project. After familiarizing themselves with SolidWorks, students begin creating a 3D model of the main body of their spinner design and eventually create an assembly including the bearings and bearing caps critical to the design. The tutorials throughout this process introduce more advanced CAD topics like surface meshing for students that wish to create a more complex design. The most technically difficult CAD portion of the class arises when students prepare their design for injection molding production, where their solid body model must become a hollowed-out mold. In addition to the difficult CAD modeling, students must also be able to account for limitations introduced by the end mill size for CNC milling the mold, shrinkage of cooling plastic after injection molding, and press fit tolerances for bearing retention.

Introducing many advanced topics in the class served to provide context for the applications of their learning from this course into topics they will encounter more rigorously in the future. For topics like Finite Element Analysis, Geometric Dimensioning and Tolerancing, and Computer Aided Manufacturing, students are not expected to have a perfect understanding of the material but are asked to be able to explain the contexts and applications of their learning. In particular, these topics will be revisited in their third-year and fourth-year courses, but are useful in engineering clubs and other optional courses.

Fidget Spinner Project

Throughout the semester, students use their newly-acquired knowledge to continuously iterate a design for a fidget spinner. The following section outlines the design and manufacturing process taken over the course of the semester by highlighting the evolution of an actual student's project.

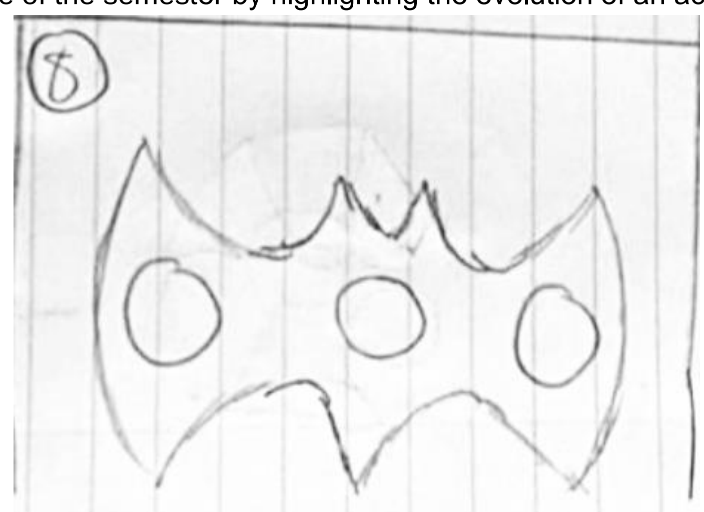

Figure 1. An example of a student-drawn spinner sketch for the brainstorming process

Students begin with a brainstorming session and submit a collection of at least nine different designs. This is meant to be a rough sketch of the basic shape so that students can get feedback on the feasibility of their design, including considerations for center of balance, manufacturability, and ease-of-design for a beginner-level CAD user.

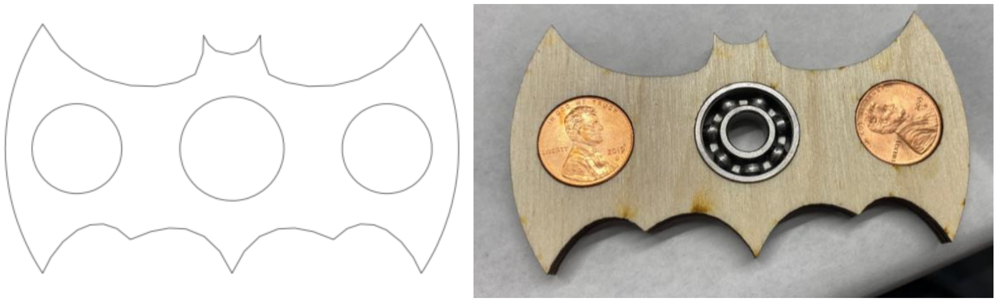

Figure 2. Left: A 2D SolidWorks drawing of a spinner outline to be used for laser cutting. Right: Assembled result of the laser cutting process.

Students then convert their hand sketches into a SolidWorks 2D sketch to practice using sketch tools in their designs. This sketch is also used to create their laser-cut designs. Designs are cut with no staff-made alterations to their submissions so that students can see flaws in their designs in real time. Since this is the quickest and most forgiving manufacturing process introduced in this class, students take their learning to adjust their designs and recut throughout their lab time.

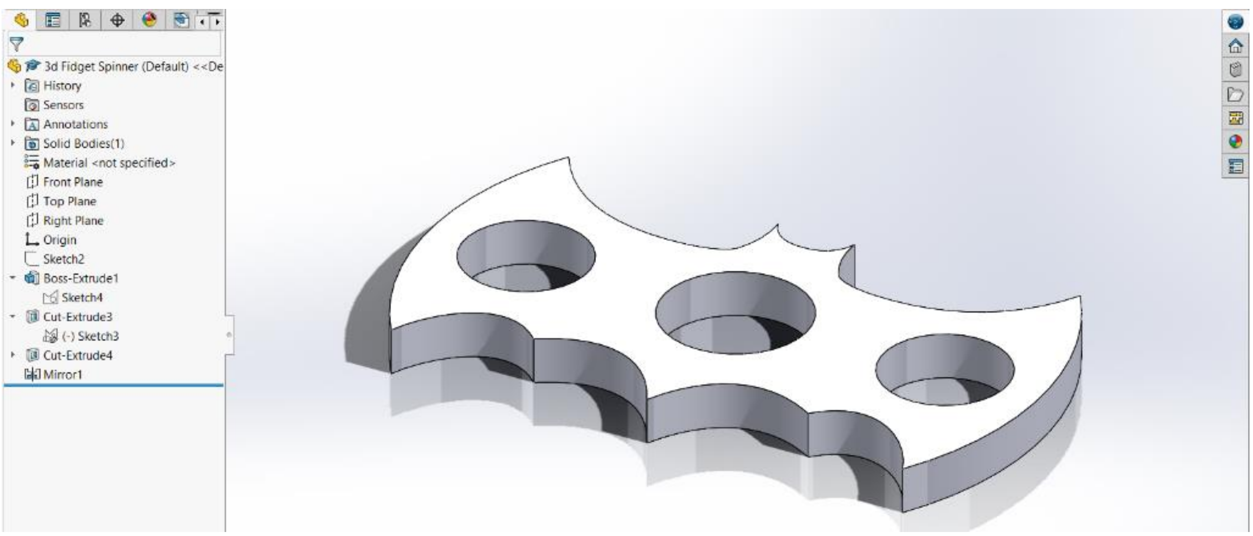

Figure 3. 3D SolidWorks model of the fidget spinner example

After creating the 2D sketch, students are then asked to 3D model their designs to become more familiar with independent use of the 3D features in SolidWorks. Students are encouraged not to simply extrude their 2D design and instead incorporate different 3D features in an iterative design. In the design below, the feature manager tree shows how instead of extruding the whole bat-shaped design, the student extruded half of the design, and mirrored it in order to reduce the need to define many measurements and relations in the base sketch and so that any design adjustments to the main sketch immediately get reflected in the other half. Holes were also cut as separate features to make adjusting hole size for different manufacturing processes easier. In this assignment, students are also asked to design bearing caps that serve as inserts into the bearings on which their fingers can hold the spinner to allow the bearing to spin.

Figure 4. Left: 3D printed additive manufacturing assembly. Right: SolidWorks multibody assembly.

Next, students 3D print their models to gain their first CAM experience with Cura for slicing their model and writing the g-code. They are also asked to print out their bearing caps to complete the full spinner assembly. Creating a SolidWorks assembly is the following assignment, pictured in Figure 4, and 3D printing helps visualize the locations of important mates. Since 3D printing is the most flexible of the manufacturing processes explored in this class, students are encouraged to keep their more complex design until this point in the class, but are encouraged to explore the differences in resolution between the laser cutter and various types of 3D printers. From this point forward, students are required to take CNC mold manufacturing into consideration.

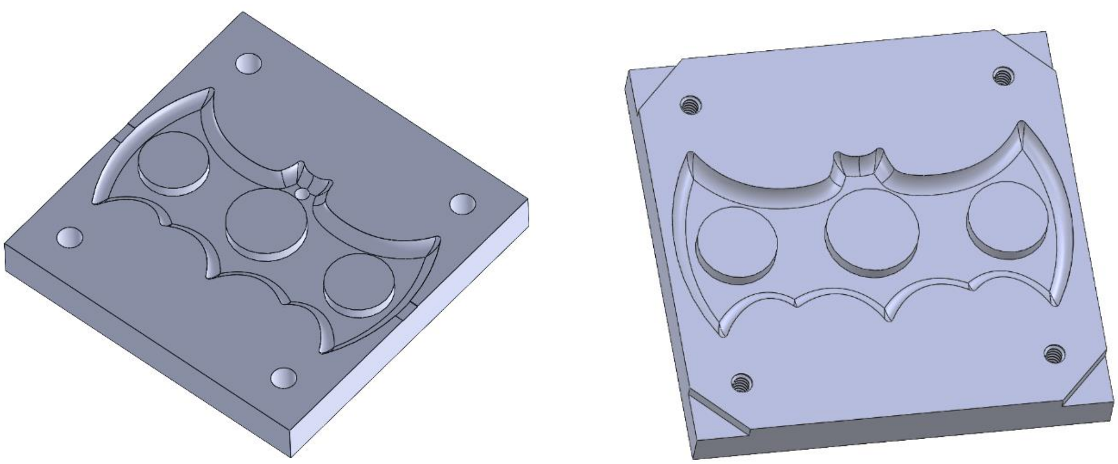

Figure 5. 3D SolidWorks models of fidget spinner molds to be used for injection molding.

Mold design CAD and CAM are the most challenging assignments of the class. Students are required to account for limitations of the milling process due to the size and shape of available tools and adjust their design accordingly. For example, the above design now features fillets to remove sharp edges that would make manufacturing difficult and product removal from the mold tedious. After completing the mold CAD in SolidWorks, students are required to use Fusion360 to create their mold CAM using a list of provided tools and the predicted usage and settings for each tool. However, in order to minimize risk to the machine, student CAMs are not used in the actual CNC milling process. Instead, after voting for which spinner will represent the lab section, the staff creates the CAM for the machine shop to machine.

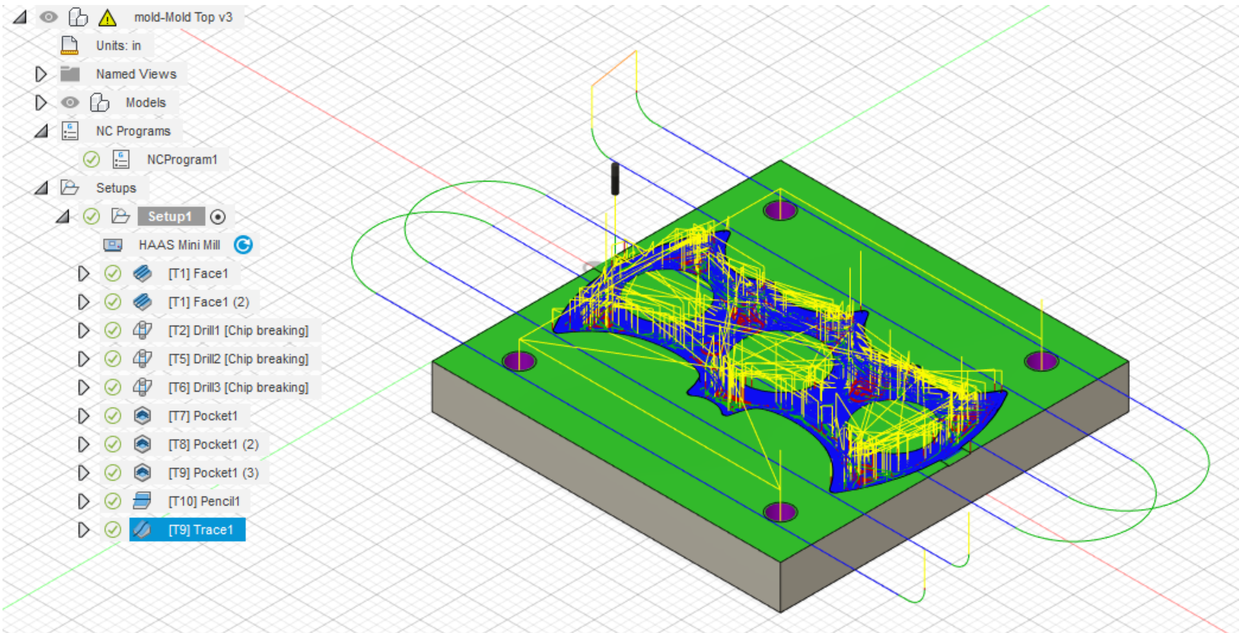

Figure 6. Fusion 360 simulated CAM of CNC milling manufacturing process

The mold is milled in a HAAS 3-Axis Minimill during one lab session. In this lab session, students are introduced to the milling process to gain exposure to the real-world application of their CAM and experience some of the CAM decisions explained in lab being used in real-time.

Figure 7. Finished CNC machined mold top plate, to be used in the injection molding machine.

While the molds are manufactured, students continue their SolidWorks education with Finite Element Analysis (FEA) and an introduction of Geometric Dimensioning and Tolerancing (GD&T). First, the spinner model is assessed for its ability to maintain an interference fit with the bearings and pennies without breaking. Using the shrink-fit connection to define the mates, students assess whether their spinners would survive the introduction of bearings and recommend adjustments to their designs based on their findings. Students are introduced to the topics of stress, strain, and material strength in order to evaluate their spinner's viability. While students are not expected to be able to do these calculations themselves, developing the understanding of how stress is distributed gives better context to the advanced simulation tools in SolidWorks.

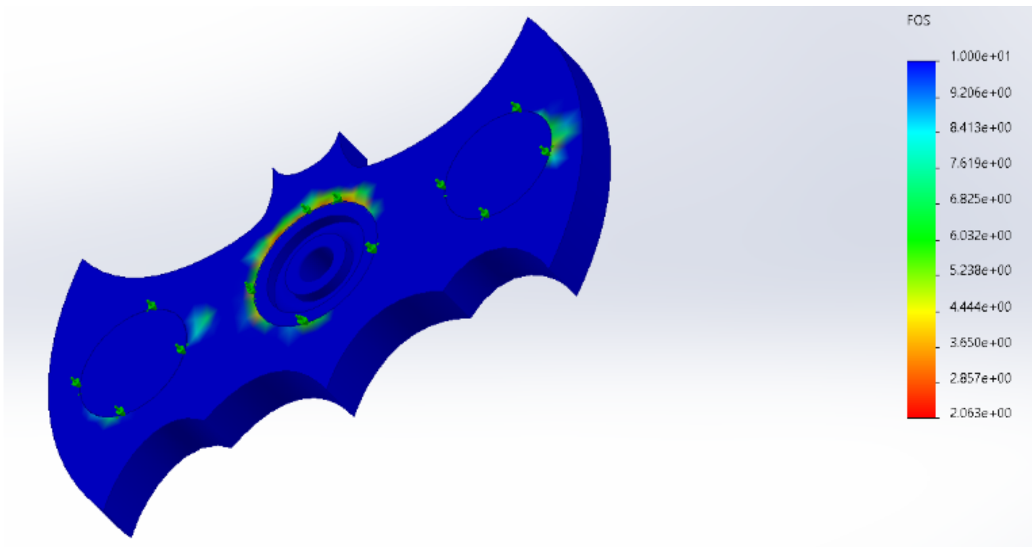

Figure 8. Finite Element Analysis of fidget spinner assembly

GD&T is introduced for their mold designs as an exploration of critical dimensions and functional requirements, as well as creating manufacturing clarifications for working with machinists. Students are required to dimension hole locations and flatness as well as to provide dimensional tolerances for critical mold and spinner features. The main body of the mold is often too complex for introductory dimensioning, so particular attention is given to mold features that would affect the efficacy of the mold. This particularly includes the holes through which screws will clamp the mold together, the location of the sprue hole, the flatness of the common faces of the mold, and the tolerance of the bearing and penny extrusions.

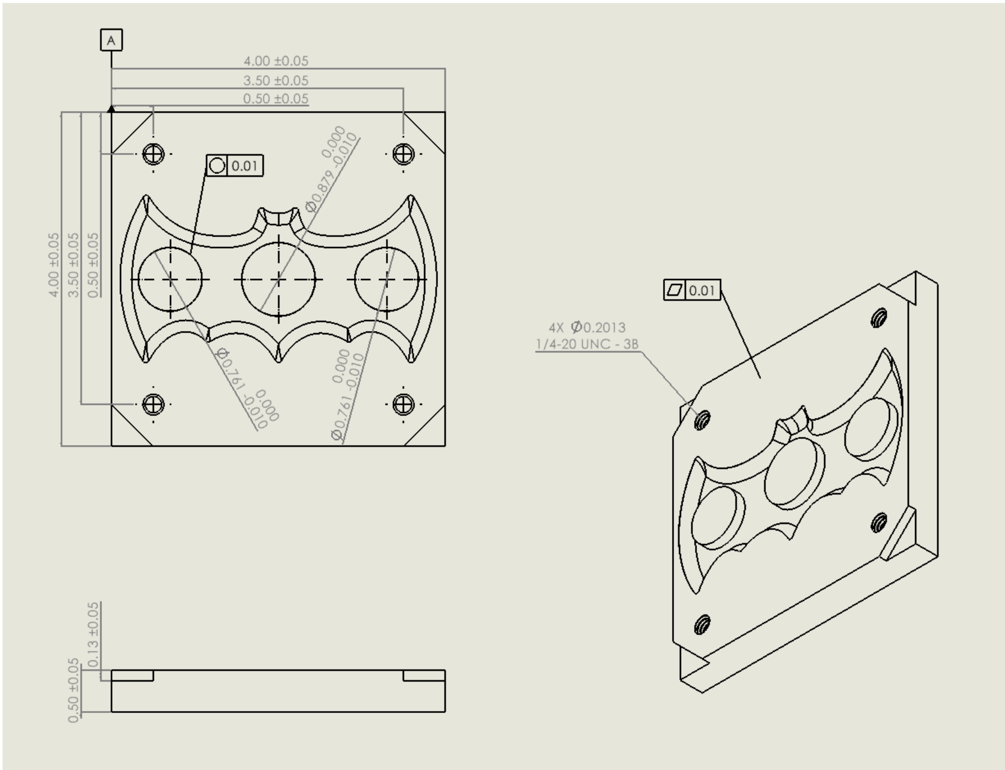

Figure 9. GD&T mechanical drawing of fidget spinner mold critical dimensions.

At the end of the semester when the molds are complete, students are then introduced to the injection molding machine. The majority of the lesson is in its function and applications, and students finally get to use the injection molding machine with the guidance of the staff to create an injection molded spinner. Every section is welcome to use molds designed by other lab sections and molds created in previous semesters.

Figure 10. Fully assembled injection molded fidget spinner

Finally, the last laboratory section of the semester is spent on experimentation. Spinners are mounted to a test setup that spins the design up to 1000 RPM and which uses a tachometer to track the reduction in rotation speed as a function of time that occurs once the spinner motor is turned off and the fidget spinner is allowed to freely spin on its own. Students are asked to plot their results and draw conclusions about their spinner's function and how to improve it. The spinner's performance in this test does not affect their final grade. Instead, students are asked to give specific changes to their spinner that would improve performance, particularly length of spin time.

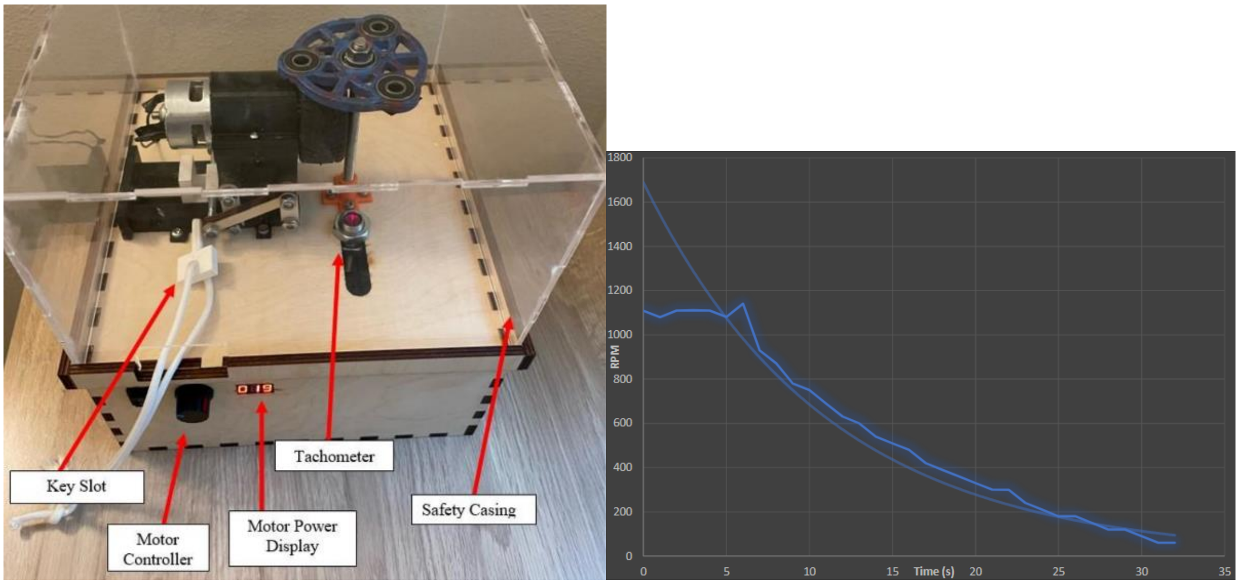

Figure 11. Left: Image of test setup used to evaluate spinner function. Right: Spinner testing results with exponential decay fit line

Conclusions

After several semesters of redesign, the new version of the course is now a fresh modernization of an outdated engineering graphics curriculum into a rigorous introduction to the use and application of engineering graphics through the lens of product design and manufacturing. Pre and post-semester surveys are being introduced to provide statistical support to the educational benefits of this updated class.

For those educators that wish to make similar updates to their curriculum, the following recommendations will help facilitate the process. The specific product and manufacturing processes outlined here may not be feasible at every institution, and many alternatives exist. For example, instead of the industrial medium-throughput injection molding machine used for this course, casting of parts using a two-part epoxy and 3D printed molds may be more feasible. The usefulness of incorporating the manufacturing into the class was to develop design with considerations for manufacturing, with the added bonus of increased student engagement for a physical take-home product. Additionally, manufacturing throughput isn't always high enough to be feasible for large classes, and accepting that CNC milling a mold for every student, or even for every group of students, simply did not provide a high enough increase in learning to justify the stress put on the instructional staff. While requiring 4-hour lab sections made classes long enough for the assignments and labs that required extended work or production times, shorter classes throughout the week would be equally effective for most assignments. SolidWorks and Fusion360 are also not the only engineering graphics programs that would be effective for the course. While some of the most advanced functions of SolidWorks may not be replicable by other programs, Onshape, Sketchup and Autodesk Inventor are cheaper alternatives capable of achieving a majority of the same learning objectives.

Overall, the new course is a friendlier and more engaging way of introducing advanced engineering graphics and basic engineering design concepts to a technologically advanced student body. Hopefully the documentation of this experience can help educators take inspiration for updating their own classrooms.