Failure Mode: An Engineering Capstone Case Study of Educating Despite Failures

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Abstract

In the modern engineering curriculum, the highlight of the students' careers is the capstone class where they get to show off their abilities. However, the greatest learning tool they experience is failure. Capstone projects can be challenging. In this paper, a case study of five teams working on the same project in a competition modality are tasked with constructing a coil gun. Each team is faced with different challenges including exploding components. Despite the setbacks, each team felt that they learned a great deal and would do the project again given the opportunity.

Keywords

Senior Design, Capstone, Failure, Constrained Design, Coil Gun

Introduction

The capstone experience has been a part of universities for nearly two centuries [1]. The notion of it being a culminating opportunity to "cap off" a degree was introduced in the 1900's and became a stable part of the engineering curriculum in the late 1900's to early 2000's. The Electrical and Computer Engineering (ECE) Department at the Missouri University of Science and Technology (formerly known as the University of Missouri – Rolla) made Senior Design a part of the curricula in 1995. The key ingredient to the ECE senior design course was giving the students the chance to select their own teams and projects. The wide variation in team abilities and project scope made it necessary to evaluate the students on following process and procedures and not on the successful completion of the project. This grading method has led to some very ambitious projects that were doomed to failure yet taught the students more about the process of engineering than any success they may have had in their regular lecture courses.

The goal of the capstone course is to integrate knowledge, concepts, and capacities [2]. The student should be knowledgeable in their chosen field, able to develop a concept, and implement the concept to some degree of success. According to National University [3] the six essential components to the success of a capstone project are: introduction, literature review, methodology, discussion, conclusion, and recommendations. The team must scope their project in the introduction, research solutions, discuss possible solutions and implement, evaluate the results, and revise to come up with recommendations. The capstone class will teach the students Creative Thinking, Critical Thinking, and Oral Communication [4]. Brooks, Benton-Kupper, and Slayton concluded that assessment of capstone performance is on the reflection and contribution by each team member [5]. These ideas for a capstone class are the foundation for the ECE Senior Design course sequence at Missouri S&T (Senior Design is a two-semester sequence in which the first semester focuses on the design and organization of the project and the second semester implements the concept).

Typically, each team is allowed to pick their project independently and no two teams could do the same project. However, in Fall 2023 the instructor introduced a slight wrinkle in that teams were allowed to select a coil gun project in which they would be in direct competition with the other coil gun teams. Of the 19 total senior design teams that semester, five of the teams decided to take the challenge and join the competition. The competition was judged on muzzle velocity of the projectile, safety of the gun, and appearance (the coil gun will be used for recruiting and needed to have style!). Wikipedia has a nice explanation of what is a coil gun and is a good starting point in researching the design [6].

The coil guns had a few specifications limiting the total capacitance, voltage limit, power source, barrel length, and projectile. Beyond these, the teams had full autonomy to design their guns, and each team came up with a slightly different gun.

Senior Design Semester I – Research and Design

At the onset of the project, each team, as well as the instructor, had very little knowledge of coil guns. However, the specifications for the design needed to be specified. After discussions with other faculty in the power field it was decided the specifications for the coil gun would be as follows:

1. A maximum of 32,000 μF of capacitance,
2. Upper limit on the capacitor voltage of 500 V,
3. Powered from a standard 120 VAC, 15 A wall outlet,
4. Maximum of two-foot barrel length,
5. 5/8-inch carbon steel ball bearing projectile (provided by instructor).

The specifications gave the students the opportunity to design a gun that would launch a projectile a good distance, yet not likely to be lethal should someone get hit accidentally.

The teams were then tasked with researching and designing their coil guns. The teams selected a faculty advisor to help them with the design. Additionally, there were a couple of subject matter experts available to help with the overall concept. The main design components were the coils, charging circuit, triggering circuit, and safety components.

Each of the teams got off to good starts. One of the subject experts, Chris Wolfgeher a retired instructor from the Naval Academy with prior experience with coil guns, was able to orient them into what they were up against in the design of the coil gun.

The coils were the first challenge the teams faced. What wire to use, how many layers, length, and even the number of coils to use were all questions that needed to be answered. This was the first area of divergence with the teams. While all the teams selected multiple coils, the number varied from two to four coils. Some of the teams did only cursory research into coil design, while others did full simulations to optimize the coil performance. In parallel to the coil design was the selection of the capacitors. The capacitors dictated the power level each coil would be delivered. Capacitor selection ranged from a single, large capacitor, to 32 small capacitors that were evenly distributed to the coils.

The charging circuits required less research than the coil design and were generally successful for each team. Most of the teams selected a bridge circuit that used either direct wall power or a transformer boosted voltage to direct-charge the capacitors. One team used a specialty made charging IC that did a great job; this was the same team that had 32 capacitors. Every team was able to charge their capacitors to the rated voltage of the capacitor.

The teams integrated safety components into the design. These included limiting and discharge resistors, safety shields, isolation circuits, and power shutoffs. Again, each team was able to make their designs relatively safe with the caveat that only qualified personnel were allowed to operate the guns.

The component that turned out to be the most challenging, yet one of the simplest in concept, was the triggering mechanism. The triggering mechanism had the task of energizing the coils from the stored capacitor energy in a controlled manner. All the teams elected to use a microcontroller to fire the coils in sequence. Most did it based strictly on a timed sequence, while others used sensors to trigger the sequence. Most of the teams used power MOSFETs while one team used a solid state (thyristor) relay.

During the research and design phase the teams were well prepared from their ECE course work. The learning objective for this phase was to discover and plan in preparation for the construction of the coil guns. All teams did well.

Senior Design Semester II – Construction and Testing

The second semester of the two-semester Senior Design sequence is focused on the implementation and testing of the project design. This phase of the project is where most of the learning happens. The ECE curriculum has multiple layers of hands-on experiences, most of these are short term assignments and are generally well defined. Senior Design is the first opportunity the students get to work in a multi-discipline team (Electrical Engineers, Computer Engineers, and occasionally Computer Scientists) on an open-ended project. As a side note, some of the students are on university competition design teams. It is obvious who these students are in the organizational skills they bring to the project.

As this is the significant experiential learning opportunity for most of the students the main learning objectives are in the areas of good construction techniques and, more importantly, deliberate, focused testing. This is, however, where the wheels start coming off.

The first task that all the teams started with was the construction of the coils. Having wrapped coils before, the instructor gave the suggestion of using some form of power tool, either a drill, lathe, or coil winder, to construct the coils. All the teams took this advice and constructed their coils successfully.

Teams then worked on various parts of the circuitry. The charging circuits, as mentioned previously, were all successful. The main differences were in the overall voltage output from the circuitry and the speed of charging. In general, the teams designed their charging circuit to the limit of the capacitors that they acquired. None of the teams exceeded the 500 VDC specification, however, a couple teams where in the 400 VDC territory. The complexity and cost of the charging circuit were directly proportional to the voltage output level desired.

Equally successful were the safety measures that each team implemented. They all quickly realized that if the capacitors failed to discharge during firing operation, there was a potentially dangerous situation with high voltage capacitors and no way to dissipate the voltage. All the teams elected to discharge the capacitor through a power resistor, some just did it more spectacularly than others. One team had a large blade switch that they would close if the capacitors did not discharge that would produce a large arc when closed.

The timing of firing the coils was accomplished by all the teams using microprocessors. Each team had a Computer Engineer or knowledge of microprocessors that made the process fairly easy. The largest design consideration was in selecting to either use a timed sequence or to use a sensor to detect the location of the projectile. Using a sensor allowed for more flexibility in when to trigger the coils but required more programming skill to reduce the latency in the triggering. The success of this part of the project was not easy to judge since the trigger timing depended on the coil being able to be fired from the capacitor voltage.

The last part of the circuitry was the trigger mechanism. As mentioned, most of the teams attempted to use power MOSFETs to trigger the coils. None of the teams were successful. Conceptually, the MOSFET made sense as a trigger as it could be turned on quickly, thereby reducing latency, and shutoff just as fast to maximize the acceleration through the coil. Every attempt at triggering using a MOSFET led to the destruction of a MOSFET. The only team to successfully fire their gun used, instead, a thyristor-based solid-state relay. A couple of teams attempted to convert to the relay but were unsuccessful at firing the gun. This, however, may be due to several conditions that will be discussed in the next section. This point of failure in the design of the gun also led to a breakdown in the learning objectives. The students didn't show an understanding and instead of a regimented approach to dissecting and solving the issues it became a, "let's try anything to see if it works" approach.

Issues

The failure modes of the project were from the coil design and trigger circuit. The issue with the coils was in not using enough wraps to get the magnetic flux high enough to induce motion on the projectile. A couple teams only did a single and two layers of wire wrap. This was not nearly enough. A minimum of 5 layers with 10 or more being the best balance in construction time, cost, and weight.

The issue with the coils could have been caught earlier with a proper testing scheme. Most of the teams attempted to get the trigger working first before testing the coils. A simple blade switch, although lossy and producing a large electric arc, could have been used to test if the coil and capacitor combination would be able to propel the projectile. There was a known issue with the projectile that only one team eventually discovered. The projectile was a steel ball. An iron ball would have been better, and an iron rod would have been better still. The projectile moves by having a magnetic field induced. However, when the ball rolls, the field changes direction requiring the field to be reestablished. Since the ball was steel and not pure iron, the ability to create the magnetic field is reduced. A rod would not have rolled so that the field strength would have been much greater allowing higher accelerations of the projectile.

By far, however, the use of MOSFETs was the biggest issue of the design. What was discovered was that the specifications given by the manufacturers is far greater than what will be seen in practice. Designers that specialize in using MOSFETs know this and design for it. Additionally, the coil gun is a worst-case situation. To get a large magnetic field, a large transient voltage is needed. The shock of the large transient has two consequences. First, the current is very high and can burn out the MOSFET (Figures 1 and 2 show the result of a high current pulse through an underrated MOSFET).

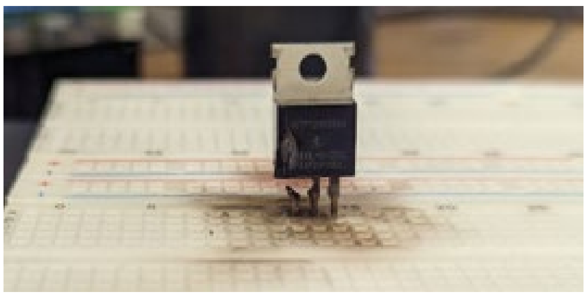

Figure 1: Aftermath of MOSFET when the current exceeded the specifications.

Figure 2: Transient test result of a power MOSFET.

The other consequence was that the impulse would cause the circuit to “ring” with oscillations. The circuits are naturally underdamped to get the transient pulse. The ringing would cause an additional failure in that the current would exceed the reverse bias limit and the MOSFET would internally fail and cease to function. While not as spectacular, this was the primary failure and caused the greatest number of dead MOSFETs.

A failure that was not anticipated was the failure of the circuit boards and solder points. The transients could not only burn up MOSFETs, but even when a strong enough MOSFET was used, the high current would find additional failure points. Several of the teams did not consider the effects of current on circuit board traces and the solder points. These could lead to the same spectacular fails as an exploding MOSFET. Figure 3 shows the result of a failure in a solder point.

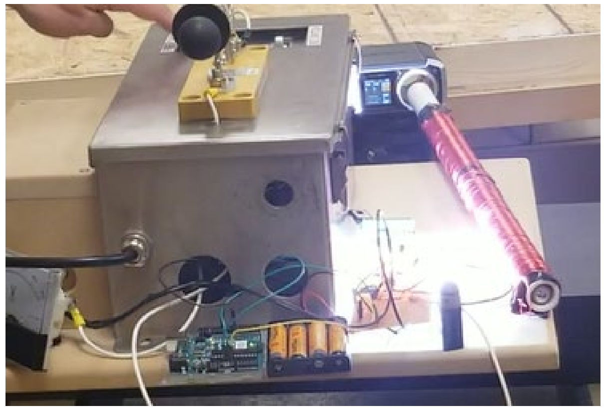

Figure 3: Exploding solder point caused
by the current transients.

Another team had properly sized the circuit board traces, had good solder points with high current solder and still had an issue with the transient currents. This time, a diode exploded most likely due to a manufacturing defect. Figure 4 shows the explosion and aftermath of the diode.

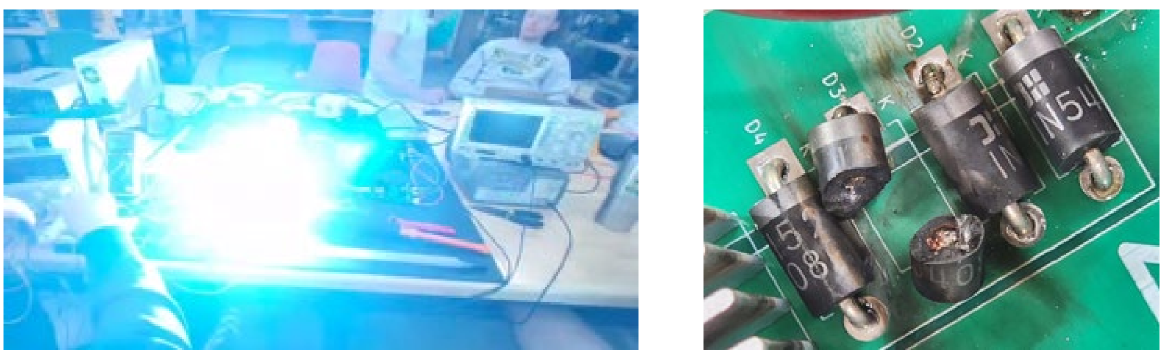

Figure 4: Exploding diode due to current transient.

As far as learning outcomes, the trigger was the most disappointing. The teams did talk with each other, but instead of working toward how to solve the MOSFET problem, they stove-piped into their individual teams. Primarily due to it being a competition, the teams did not want to share insights to fix the problem. However, after two and three failures of the MOSFETs, the teams should have looked at pooling resources to find a solution or look at alternatives much earlier. However, this also turned out to be the most impactful. From this the teams learned the importance of a testing plan and to seek help and alternatives much quicker than they expect. The result was that the school of hard knocks will eventually educate, but you can avoid it with some forethought.

Student Feedback

Feedback from the student participants was elicited. Unfortunately, most of the students that participated graduated, so it was harder to get feedback. Two of the students did, however, return the following:

Student 1:

"The coil gun project in Senior Design was unlike any other project I had the privilege of contributing to during my education. It gave me the opportunity to apply many of my classes all in one place and to work with fantastic students and professionals in the area. Although our end-product was not successful, I still learned a lot by doing the project and it remains one of my most memorable experiences from Missouri S&T."

Student 2:

"Working on this project was a phenomenal opportunity to get outside my comfort zone, in the realm of electronics. A typical electronics project, such as an Arduino build, has much lower power requirements and much lower switching speeds than my team attempted to work with in the construction of our coil gun. Because of this, many new challenges were introduced that we hadn't directly dealt with before. I would say that was the most beneficial aspect of this project, in the sense that engineering is all about tackling problems that you don't, at first, know how to solve. Dealing with exploding (expensive) components, MOSFETs frying, and tight deadlines may have led to an unsuccessful coil gun, but certainly taught me the importance of many aspects of the engineering process such as planning for potential failures and gathering data through testing."

Results, Conclusions, and Lessons Learned

As much as the students learned during the project, the instructor learned just as much. This was the first time the instructor had attempted a project so far outside his comfort zone. It was not possible to anticipate all the issues that were faced given his level of knowledge in the field. For some of the issues, even experts that were consulted were mystified why the guns were still failing. No team was perfect, but one team did manage to get their gun to fire.

For the students, they definitely experienced the life cycle of a functional prototype. The teams had to interview professors and subject experts to find out what a coil gun does and how it does it. They had to research design options and critically analyze the design choices. They discovered the practical, physical limitations of working with material and devices. They all learned the benefits of a testing plan and how to use the plan to accelerate the successful completion of the design. As far as a teaching tool, the coil gun project was a resounding success, even though 80% of the guns did not successfully fire.

Things that the instructor would do differently if he were to repeat the project includes using an iron rod instead of a steel ball bearing, providing the capacitors so that there was less variability, and providing solid state relays for the triggers. These three changes would have led to an increased success rate and a better competition. The iron rod would have led to a more impressive launch compared to the steel balls. The capacitors were a function of how much money the team was willing to put into the project. The higher rated capacitors would then have forced all the teams to more carefully consider how to charge the capacitors. And, most critically, the solid-state relay was the only trigger technology to have shown that it would have led to more than one successful coil gun.

In conclusion, the coil gun project was a successful senior design project. It provided an opportunity for the students to demonstrate all the principles that define a capstone project. They learned a great deal about prototyping and to watch out for the pitfalls. Even the instructor learned about the level of detail needed before attempting a project of this complexity.

Acknowledgments

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The course instructor would like to specially acknowledge each of the teams that took part in the case study (listed in the Biographies Section). Their willingness to push through adversity was inspirational. And, in case you were wondering, Team Velociraptor was the overall champion of the competition – Congratulations!

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Biographies

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Team Gauss Gurus: Matthew Duff, Ian James, Martin Melinder, Gabe Schoenberger, Gabriel Snyder

Team Kinetic Antenna: Grant Brinker, Brady Davis, Maxwell Ryan, Evan Seabaugh, Alexander Wortmann

Team Railgun A: Justin Amaro, Spencer Clubb, Collin Jasper, Mir Kian Shafe, Daniel Wiseman

Team Gaussinator: Joshua Andreyev, Joseph Breen, Beau Bryant, Bailey Fisher, Jacob Slavick

Team Velociraptor: Elijah Gross, Micah Johnson, Carter Schaper, Mick Von Feldt