Northeastern University
College of Engineering

Cornerstone of Engineering I & II
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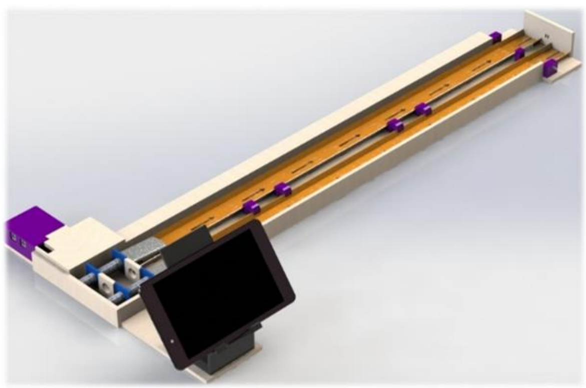
Project 2: Museum Exhibit



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Report Submitted: **December 11th, 2019**

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Professor O' Connell
Northeastern University – College of Engineering
Room 365, Snell Engineering Center
360 Huntington Avenue
Boston, MA 02115

Dear Professor O' Connell ,

This report was prepared for the purpose of detailing our efforts to build a prototype for Project 2, the museum exhibit. It is intended for Professor O' Connell but is open to all eyes. The topic of this report is the engineering process that our team underwent to build the prototype, as well as overarching lessons learned from this experience. A quick introduction to our prototype: we constructed an interactive race track, where users choose two of four electromagnets to race against each other, with the hope that the experience will teach them about the function of electromagnets, what determines the strength of an electromagnet, and the overarching future uses of electromagnets in clean transportation. The report is split into individual and group sections. Individual sections were completed independently by each team member and compiled into the report. The primary sections are as follows: Introduction, Background, Methodology (individual sections); Final Design and Results (group sections); Discussion/Analysis, Conclusion, Recommendations, Lessons Learned (individual sections). All other sections are group sections. The introduction sections will cover the general context of our work, including the problem statement, intended client and stakeholders, as well as the scope of this report. The background will go over the background research that each member completed regarding our topic. The methodology section will explain our design process as we went through the project, from the perspective of each team member. The final design will provide a detailed technical description of the final prototype. The results section will discuss both quantitative and qualitative test data. The discussion/analysis sections will make a case for why our prototype should be advanced into the next stage of development. The conclusion sections will discuss how the prototype met design constraints, requirements, and expectations. The recommendations section will put forward a list of changes that can/should be implemented if this prototype were to be furthered developed or if another team attempts a similar build. The lessons learned section will step away from discussion of the project to explain how the overarching learning experience was from this project, for each team member. The report includes detailed information in the appendices as well, which is referenced throughout, and provides more in-depth context for the entire project.

Thank you for your time and we look forward to your review of our project.

Sincerely,

Sidharth Annapragada, Trevor Giardine, Giona Kleinberg, Demitri Kokoros

ABSTRACT

The presented problem involved designing and constructing an interactive museum exhibit that was educational and interactive. The purpose of this problem was to utilize the engineering design process to encourage an informative education on a topic pertaining to building a sustainable future. The exhibit had to fit within a client's size requirement, utilize a rapid-prototyped part, be easily transportable, and be a universal design so a diverse group of users can engage with it. Our solution to the problem was an exhibit featuring an interactive GUI which would control various types of electromagnets that propel cars down a racetrack and records their travel time. The design featured a physical demo and included a standard tri-fold poster with information on electromagnetism. The combination of an informational, visual, and tactile helped make this exhibit a success because it provided users information in a clear way while also letting them physically see the effects differences in electromagnets have on the overall functionality of the magnetic car. This was a valid solution as that it was entertaining due to the racing component while also educational because of the posters and descriptions.

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SIDHARTH ANNAPRAGADA

1.1 INTRODUCTION

Problem Statement

The problem is that the client needs a portable, educational, and entertaining exhibit that can inform kids about the issue of electromagnetic clean transportation. This is important because giving them this exposure, which they might not otherwise receive, can help inspire them to help solve such problems. Currently, available designs featuring electromagnetism and racing are miniaturized electric train sets and gravity car exhibits respectively. These can be improved by combining the two concepts into a portable exhibit that pairs customizable electromagnetic powered cars with a racetrack. The users, middle-schoolers, need an engaging and educational experience that will inspire them to help solve these problems in the future. Our solution will reach a large magnitude of children and educate them about the issue of clean transportation and electromagnetism, through portability, interactivity, competition, and engaging features.

The portability of the exhibit is particularly important as the client is a travelling museum that has both space and transportation constraints. Therefore, the exhibit must be able to be set up and deconstructed in a reasonable time frame and be able to be stored in a fixed container.

The term "engaging" refers to both active and passive components of the exhibit. These styles of engagement are intended to increase post-use recollection of the exhibit. An example of active engagement is the competitive aspect of the races. An example of passive engagement is having bright colors and sounds.

The term "educational" also refers to both active and passive components. Both styles are intended to simply expose users to the concepts of electromagnetism and its applications for the future of transportation. An example of active education is the deliberate informed selection of different magnet types. An example of passive education is the informational write-ups that can be read through while using the exhibit.

Stakeholders

The intended stakeholders for this project include the client: the Museum of Science – Boston travelling program; and the users: middle to high school students with limited exposure to previous museums, and a cursory knowledge of STEM. The client approached Professor O' Connell to develop the first line of prototype exhibits for a new travelling museum, who in turn assigned each of eight teams to develop prototypes.

Pertinent topics in engineering

For this design, the main theme was focused on teaching about a scientific concept or engineering achievement that related to a future STEM problem in our world. This project focused on the future of clean electromagnetic transportation systems to combat the rising threat of climate change. Our focus was on educating the users about how electromagnets work followed by their future applications.

Scope

This is the final technical report for this project. It will cover our entire design process, from background research and problem definition, to our iterated implementation process. Once the design process is thoroughly described, the report will discuss the final design and performance.

1.2 BACKGROUND

The problem in question was building two electromagnetically propelled race cars to race each other, while allowing the users to choose different types of magnets in order to explore what affects the strength of the magnetic field. Additionally, the exhibit had to explore the future societal impact of this technology. Therefore, my background research focused on two things: electromagnetism, race timing, constructing electromagnetic propulsion systems, and similar exhibits that exist on the topic; and electromagnetic transportation systems as the future of clean transportation. Finally, I conducted research into universal design and some ethical concerns regarding the safety of the project.

RESEARCH

My specific research began with a quick refresher on the physics of electromagnets. I referenced Resnick and Halliday's "Fundamentals of Physics" for this [1]. This allowed me to recall the basic functionality of electromagnets and gave me the mathematical tools I would need, as well as the insight, in order to start designing the different electromagnets. Next, I researched a few simplified explanations of electromagnets and electromagnetism, in the context of a museum exhibit, in order to gain insight into how we could educate children on the subject. For this, I referenced "Magic of Magnetism" [2]. This source discussed the content of an old exhibit at the Boston Museum of Science, that was done in collaboration with Northeastern that involved magnetism and electromagnetics. I did not personally conduct research into other versions of this exhibit, but my colleagues did.

I continued my research with a brief look into the future of electromagnetic transportation systems, which have the potential to reduce carbon emissions. I referenced "The History (And Future) of High Speed Rail" to get an idea of the history and future of this technology to reinforce my own understanding about the future impact of electromagnetic propulsion for the future [3].

I also conducted research into universal design considerations. This resulted in adding a few characteristics to our problem definition and solution, that incorporated a few of the seven universal design principles. We used these principles to inform design parameters, such as font size and the interface angle, throughout the design. [4, 5]

Finally, I conducted some research into the safety of these devices, a potential ethical concern. I found that the major risk was a burn risk if the magnets were left on for too long. Electrocution risk was minimal to nonexistent. To this end, I added overtemperature protection and short magnet on times to the design requirements.

1.3 METHODOLOGY

This is a chronological account of our design process for this prototype.

PROBLEM DEFINITION

Our design process started with laying out a team contract. Following this meeting, where team goals and rules were established, we conducted extensive client and user research, in order to determine factors that our client would need, what similar clients have done in the past, and to determine what elements would best engage and educate the user. We used this research to reframe the problem statement to emphasize the key elements we wished to address with our design.

SOLUTION GENERATION AND DECISION

Following our redefinition of the problem, we met and conducted a brainstorming session. The purpose of this session was to ultimately produce a concrete idea for the project. We began by generating a list of around 15 themes to address, that met the design requirements. We used our client research integrated into a brainstorming session to generate this list. After we generated a list of themes, we switched gears and used a rank order comparison to assess which elements of engaging users were most important. We generated the list of engagement elements using the user research. We then created a list of around 20 exhibit ideas using more general brainstorming, again based upon both our client and user research. Finally, we narrowed this list to four options through discussion, and applied a Kepner-Tregoe decision analysis, using our rank order from before to choose Electromagnetic Racers as our project topic. See Table ___ in Appendix B for the details of the analysis.

IMPLEMENTATION: PREPARATION

This phase of implementation primarily involved conducting more research, updating our problem statement for the new specific project topic, and drafting initial design sketches. Each team member conducted research into the topic, then created a design sketch. A decision analysis was applied to combine the best features of each sketch into a final design concept sketch. See Table 5 in Appendix B for details of the analysis. My concept sketch is depicted here:

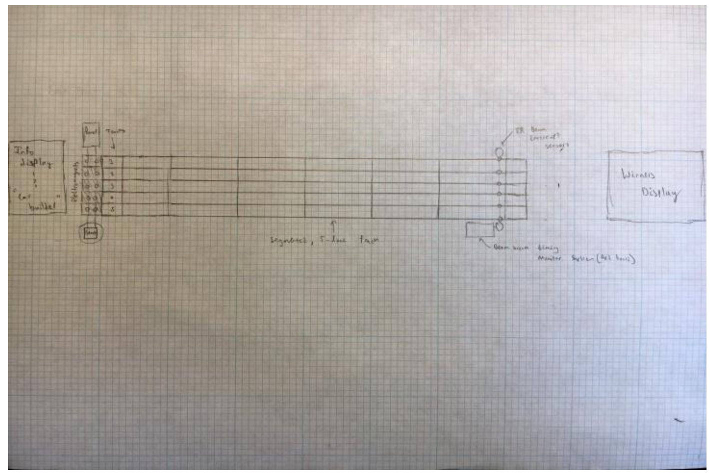
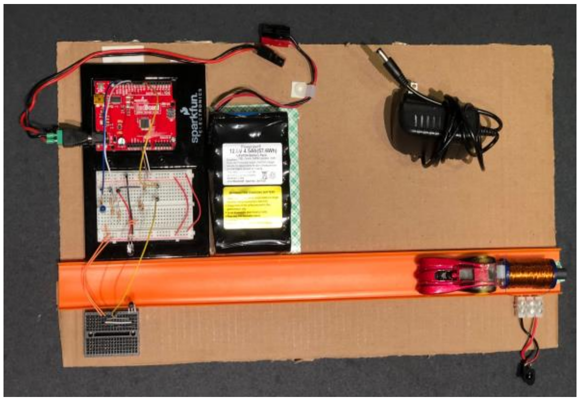


Figure 1. Sid's Design Concept Sketch

IMPLEMENTATION: INITIAL CONCEPT

Based on the concept sketch, work began on constructing the initial demonstration of our topic. This involved three main elements: getting a magnet and power supply, getting a car and track, and setting up a sensor to detect the car finishing. One team member focused on getting a functional magnet that could work with a donated power supply, as well as building the IR sensor setup, while the other members focused on finding track, a car, a permanent magnet, and a cardboard frame for the initial demo. This phase primarily involved exploring the various challenges we would face in constructing the final exhibit, as well as demonstrating a cardboard concept of what our exhibit would look like. Figure 31, from Appendix G shows this model. It is included here for convenience:

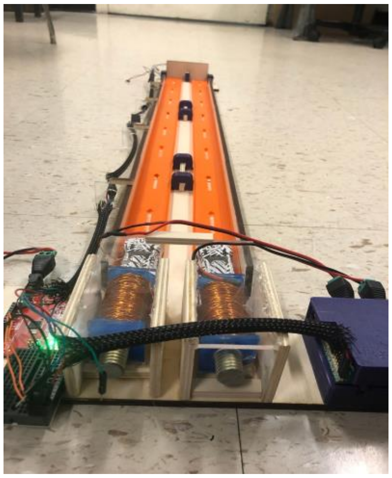


EVALUATION: INITIAL CONCEPT

Based on the demonstration, it was determined that the primary challenges we would face were building a strong enough magnet, powering it, and generally constructing the full exhibit. See the results section for quantitative and qualitative test results for each evaluation phase.

IMPLEMENTATION: PROOF OF CONCEPT

The primary focus of this phase was transitioning to a full-scale version of our exhibit, and implementing at least the basic functionality of the final exhibit as a proof of concept. This primarily involved designing and constructing custom electronics for the magnets and sensors, building stronger magnets, upgrading the power supply, and finally constructing the full-scale track and frame. Figure 33 from Appendix G depicts this model, and is shown here for convenience:



EVALUATION: PROOF OF CONCEPT

We evaluated the proof of concept performance and determined that our main concern was ensuring that the system was fully functional and consistent.

IMPLEMENTATION: CONCEPT FINALIZATION

We finalized the major functionality of the exhibit and began working on getting the full system consistent and functional. We also began building aesthetic components and finished an interactive GUI. Figure 37 in Appendix G shows screenshots from this finalized GUI.

EVALUATION: CONCEPT FINALIZATION

Based upon the feedback from the gallery demonstration, we determined that we needed to work on consistency, building the rest of the magnets, aesthetics and the poster, and redoing the GUI.

IMPLEMENTATION: PENULTIMATE PROTOTYPE

We improved the GUI, poster, and aesthetics, and further improved consistency, reconstructing parts that needed to be reconstructed.

EVALUATION: PENULTIMATE PROTOTYPE

Based upon our feedback from the gallery demonstration, we determined that final testing and consistency improvements, code bug fixes, a clearer interaction scheme, the final magnet types, and data logging were the final items we needed to work on.

IMPLEMENTATION: FINAL PROTOTYPE

For the final leg of implementation, we focused on finishing constructing the magnets and implementing user feedback. This included making interaction clearer, with labels and pictures included in the GUI and on the parts, as well as adding a touchscreen interface to make the GUI more obvious.

Evaluation: Final prototype

The final evaluation phase of our project involved presenting it in a public exhibition. We received feedback from peer judges, who critiqued the final prototype and we also gained more observational data of user interaction, which all contributed to the recommendations/future work section in this report. Please see the results section for quantitative and qualitative test results for each evaluation phase.

Individual Contributions

I led the initial phase of problem redefinition and solution decision and contributed to the idea for our final project during Milestone 1. Generally, I contributed to the implementation phases, doing the electronics and the final implementation of the GUI. I also contributed most of the CAD and an equal share of the construction with my teammates. I also was in charge of testing and getting the project fully functional and consistent.

TREVOR GIARDINE

1.4 INTRODUCTION

PROBLEM STATEMENT

This project addresses the need for an educational and entertaining exhibit that can inform kids about the issue of clean transportation from a traveling museum. This is important because giving them this exposure, which they might not otherwise receive, can inspire them to help solve such problems. Currently, available designs featuring electromagnetism are miniature electric train sets and gravity car exhibits. These can be improved by combining the two concepts into a portable exhibit that pairs customizable electromagnetic powered cars with a straight racetrack. The users, middle schoolers, need an engaging and educational experience that will inspire them to help solve these problems in the future. Our solution will reach many children and educate them about the issue of clean transportation and electromagnetism through portability, interactivity, competition, and engaging features.

The educational component is an open-ended solution. That is primarily due to the ways in which different people process and obtain information. There should be both hands-on, visual, and traditional information given to the users through different facets such as a poster or graphic and the components themselves. Regarding portability, all components of the exhibit must fit within a clear tote container and be light enough to be physically moved by a person or from an available mechanism (wagon, hand truck, etc.). All of this is required to successfully complete the exhibit for the client.

STAKEHOLDERS

There are several stakeholders in the production of the museum exhibit. These include the users and the traveling museum. Both are important to understand due to their significance in the decisions made by the group. The stakeholders helped direct the group through our decision making due to the role of implementing the exhibit

The users are middle schoolers (preteens). The reason we created our project is because the middle schoolers who would be accessing the exhibit haven't readily had accessibility to a museum or to educational exhibits. When coming up with ideas for what project to make, we orientated ourselves to the preferences and hobbies of middle schoolers to create something that would appeal to them. This proved most important in first steps of the project as we were trying to determine what we wanted to do and how to implement it based off of what we know about the preteen age group.

Figure 2. Picture of the Museum of Science, Boston [6]

The other stakeholder in our design was the traveling museum itself. This was important since the stakeholder determined the overall size and components used for the exhibit. Such constraints resulted in a change in decisions in the how the group intended to race cars and how the users would interact with the exhibit considering there needed to be an educational component. The educational component set by the traveling museum resulted in the use of a comparison chart to help determine the best idea that would be both educational and fun. The group had a lively debate over the best possible way to combine the two with the clear goal of satisfying the travel museum by creating a popular exhibit.

PERTINENT TOPICS IN ENGINEERING

In order to inform the users on the issue of clean transportation, the group looked for a topic that would be educational while being entertaining and meeting a societal need. The issue that we mutually agreed on was clean transportation. The team knew first-hand the effects of poor air quality on our respiratory health and the issues with traffic around the holiday season. This led us to research possible forms of transportation that would cut back on our carbon footprint while also moving people faster and safely. This led the team into the realm of electromagnetism, where we investigated the potential to implement it here in the US.

ELECTROMAGNETISM IN THE UNITED STATES

Electromagnetism has been something studied throughout the world for the approximately the last two hundred years. Since its origins, the uses of electromagnets can be found in everyday objects such as heaters and electronic devices. The future of the technology is in the transportation industry. The current project is to build a maglev train that would connect the northeast corridor from Washington DC to New York City.

Figure 3. Northeast Maglev Train [7]

The construction of this service would be beneficial to the economy due to the amount of people required to build the tracks. The economic benefits would be substantial since maglev trains run on power, not fuel, which is far cheaper to produce and pay from the grid. Since maglev trains have less friction, they move significantly faster and would be an upgrade over the Amtrak system. The amount of rides taken per day would increase, therefore decreasing the cost of travel between major cities.

SCOPE

The scope of this engineering project covers all of the stages of the engineering design cycle. Due to the task presented, the group started out with a problem that had to be addressed and researched potential solutions. Then, the group developed possible solutions to the issues and selected the best one. The group subsequently built a prototype of the exhibit for the client and tested it until it was proven to work. Once it worked, the group improved the design and worked on the final prototype to be presented at the Expo. Following the Expo, the group was able to reflect and evaluate their project from the feedback.

1.5 BACKGROUND

Before delving into the project, the group had to better understand the problem better. This can be broken down into the research of the problem, how ethical the problem and project are, and whether this exhibit would be considered universally friendly.

When evaluating the research into the problem, they focused on better understanding our client and user. By understanding both better, the group could better address the problem and make an exhibit that was built to be successful.

RESEARCH OF CLIENT

The client, the traveling museum, required extensive research to understand. For the purposes of this research, the client is the Museum of Science in Boston. The Museum of Science has a high a standard of quality and motivation, which was reflected in the construction of the exhibit.

The Museum of Science states that its primary mission is to "play a leading role in transforming the nation's relationship with science and technology". They acknowledge the technological revolution due to the rapid development of new technology that "reshape[s] our lives and world" [8]. Also, the museum's mission to promote active citizenship, inspire lifelong interest and appreciation of science and engineering, and encourage kids to pursue a better understanding of the modern world is evident in the exhibits. Based on these goals, it is evident that the museum is in search of impactful exhibits targeted toward children [8].

The museum strives to keep with current technological and educational trends to keep the exhibits engaging for users. Secondly, the museum wants to develop outside connections by networking with communities and other museums to diversify their exhibits and generate more ideas. Lastly, they would like to focus on integrating science and math curriculums into their exhibits [8]. This will emphasize the importance of the country's future and draws in students from all over [9]. Out of the exhibits we saw, the best exhibits were interactive, competitive, dynamic, bright, and colorful.

After looking at the Smithsonian Guide [10], the four components users care about are: the ideas, the personal, the objects, and the physical. The idea aspect involves visitors seeking conceptual and abstract thinking. As for the personal aspect, visitors seek a connection with the exhibit. Finally, visitors hope to stimulate their senses through visual, touch, and auditory elements. Some additional factors include having a clear target audience, the use of graphics, and incorporating technology with the exhibit. Also, it is key to find a way to dense information in an eye-catching and attractive way [11].

HISTORY OF THE PROBLEM

There are a few factors that have caused traveling museum exhibits to struggle. First, it is possible to make an exhibit overwhelming. This could mean it is too dynamic, presents too much information, or is distracting and hard to understand. Additionally, too many interactive stations could disrupt people from getting a chance to understand the exhibit fully. Lastly, exhibits that add interactive elements need to ensure that the point of the exhibit is still clear. Sometimes kids may be distracted if the interactive elements don't directly tie into the topic of the exhibit. Exhibits can struggle if they try to do too much at one time [12].

When examining the restrictions of the project, the design group realized the importance of targeting engagement factors for the users. Our intended audience is people of preteen-age with a middle school education or lower. This greatly narrowed our options since higher-level material needed to be simplified to the point where they could understand it and benefit from such concepts. A goal that the group prioritized and that the University at Albany advises is to keep the exhibit fun. “If adolescent students don’t see how science relates to their lives here and now, they lose interest pretty quickly; thus in higher performers, a confluence of factors comes into play to keep the broadest spectrum of kids engaged and successful in tackling middle school science” [13].

One consideration the group had when evaluating our users was the fact that people within this age group often have very short attention spans. “The attention span of the average middle school student is 10 to 12 minutes, and there is little evidence that their brains can be trained to develop a longer span” [14]. Therefore, any exhibit of ours requires something that is quick and engages meaningful information in a short amount of time. Therefore, something like bullet trains is an intriguing path for us to follow due to the fact it is hands-on and fast. Due to the dense amount of information that explains how it works, we would need to present a watered-down version, so they understand it before moving on. Additionally, “…providing visual prompts to ignite curiosity is powerful for all students, and especially for those who regularly engage in social media or are reluctant readers. Visual stimuli are less threatening than text; when compelling images are used as prompts, teens are more willing to risk making observations and inquiries that align the content with their interests” [15]. Therefore, the exhibit will need to provide lots of graphics to accompany the physical exhibit in order to engage the users who are performing the task.

Another issue the group raised when researching the potential users of our exhibit is how the viewers will interact with each other. Considering the age group, we researched the possible implications of the possible interactions between these users. When examining their age and academic level, “…from fourth to fifth grade there was a sharp reversal in the ranking of the two characteristics mentioned as important most frequently by pupils. Fourth graders ranked "nice/friendly" first, and fifth graders ranked friendship group membership first. Girls emphasized being "nice/friendly" first, and classroom behavior more than boys; boys emphasized smartness and talent/interests more than girls” [16]. Considering the socialization and values of the age group, there are multiple facets in which the exhibit could utilize those beliefs best. In a research project it was found that having a competition of little importance, quick duration, and a clear goal are vital in making the most effective exhibit, because “…when taken together these three features we could conclude that the most healthy and beneficial competitions are those that are undertaken for exclusively symbolic value (e.g., “good job you won”, “polite applause for the winners”, etc.), short, and characterized by all participants feeling like they have a chance to win, and have the process and quality of work being given conspicuous value” [17]. By including a competitive element, there are multiple facets—like hands-on, visual, auditory—for which users could take the information and task with them. Competition, if done in the fashion stated previously, is included, it can make the exhibit more intriguing and desirable for the target audience.

As noted, before, the way in which users often engage with the users is to offer an incentive, regardless of performance, to stimulate their participation in the exhibit.

“Next, we consider competitive incentives, which offer a more convex link between performance and reward than piece-rate incentives, and consequently might have a stronger effect on effort levels (Lazear and Rosen 1981), and thus on (creative) performance” [18]. If we provide a small incentive for completing our task, it would further improve what the participants got out of the exhibit since they are more likely to retain information in order to obtain the prize. By making it uniform across all aspects and allowing kids to construct something freely to tackle the task, the creativity and interaction with the exhibit further emulates the process of learning hands-on while also getting something more than just knowledge out of the deal.

Lastly, the role of colors has been something studied for the better part of the 20th century. As kids develop, the role of color is vital in their perceptions of what they like and how they perceive an exhibit. It has been found that

"…young children love to play with colorful toys and older children express themselves in many ways with color. Color psychology techniques used in a child's environment will bring out the best in them personally and also support their emotional and physical growth" [19]. Since color is such a big factor in what is deemed

'interesting' and that older children express themselves with different colors indicates that color is an important way to attract this age group to our exhibit. Since there is an emphasis on flashy colors, "…research shows that color is an important feature and characteristic for teenagers when they make purchasing decisions to buy clothing, electronics, shoes, backpacks/handbags, watches and school supplies" [20]. Therefore, it is important the exhibit contains elements that engage the senses in order to attract more participants.

Ethics

One factor we investigated was whether or not our exhibit was ethical. We had to create an exhibit that didn't do harm to the profession, demonstrated a benefit to society (prototype or research), and was of our best work. These principles, which come from ASME's Code of Ethics [21] focus on how whatever is created must solely be beneficial in both physical and educational retrospect and needed to demonstrate our capabilities. Our group had experience with electromagnets so collectively the group had faith it would be able to build off the known knowledge. We also consulted the Boston Museum of Science's Code of Ethics to inform our trajectory [22].

Our group was researching something that could benefit society in the long run, while also helping current research into maglev technology. As the exhibit progressed throughout the project, the group found no ways in which this research and technology would be detrimental to society. When looking at how the current rail system can be redone, there was no room for human displacement and the costs and energy necessary to operate it was significantly cleaner than current modes of transportation, the group thought it was the best way for us to demonstrate engineering with educational intentions.

Universal Design

Lastly, we had to ensure that we would make a design that meets the Universal Design considerations. The essence of universal design is accommodating a wide range of users. This means the exhibit must be physically and intellectually accessible, in a way that is equitable and flexible for all. There are seven major considerations in this regard, based upon the Center for Excellence in Universal Design's criteria: equitable use, flexibility of use, simplicity and intuitiveness of use, perceptible use, the safety of use, physical ease of use, and physical accommodations for use [5]. There are two primary elements to our exhibit. The first is interacting with the user interface, where they learn the basics of electromagnets. The second is placing the electromagnet in position, moving the car into position, and activating the exhibit. For the user interface, we will focus on a minimalistic and intuitive design to ensure instructions are understood clearly. The interface will also be placed and positioned in a way that is easily accessible and will feature tactile, audio, and visual feedback for use. The primary challenge for the UI is designing an intellectually accessible system. For the placement of the car and electromagnets, the primary challenge is creating a physically accessible system. To this end, connectors for the magnets will be chosen to allow for ease of use, and the magnets will be positioned within the ideal 11-inch reach range. Similarly, the cars and track will be designed for reset ease (likely with a latch mechanism and instructions for reset). There are specific details to work out for both the physical and intellectual accommodations, but this is a general outline of our plans [4].

The first principle is “Equitable Use”. It entails providing the same or equivalent means of use for all users, avoiding segregating or stigmatizing users, provisions for safety, security, and privacy, and finally, it must be appealing for all. Within our design, this means making sure table heights and reach is appropriate for all (27” and 11” respectively according to MOS), making sure that colors are neutral (color scheme of pale blue and white, like our presentation theme), and ensuring safety. In terms of, initiating the exhibit, these will be considered.

The second principle is “Flexibility in Use”. This entails providing choice in methods of use, accommodating left and right-handed users, facilitating user accuracy and precision, and finally providing adaptability to the user's pace. For this design, this will mostly involve considerations during UI design as well as designing the start button, magnet connectors, and a car placement system. The entire exhibit will be operable at the pace of the two users racing. However, it is designed to provide individual timing, so single users can operate it independently of a race if needed. In terms of user methods, defaults will be provided, so users need not interact if they would not like to.

The third principle is “Simple and Intuitive Use”. This means removing unnecessary complexity, being consistent with expectations and intuition, accommodating literacy and language skills, arranging information consistent with importance, and providing appropriate feedback and prompting after task completion. The first will be a design goal that we will strive towards during work. We will attempt to make the exhibit’s purpose and function clear so expectations match results. We will try to minimize the need for a high level of literacy during the learning phase and will attempt to minimize language on the UI so that it is intuitive to use. The flow of the UI and interaction will be arranged in ascending order of importance in terms of learning. Feedback will be based on the competition results and on the electromagnet; selection made by the user. This will culminate the learning experience with an explanation of what aspects of the magnet resulted in the given performance.

The fourth principle is “perceptible information”. This entails providing the same information in multiple formats (visual, verbal, tactile). This also involves starkly differentiating between essential and additional information. Essential information will be made “legible” for all levels of literacy. Elements of the exhibit will be clearly differentiated so that instructions will be clear to follow. Finally, the exhibit will be compatible for people with various sensory abilities.

The fifth principle is “tolerance for error”. This entails an arrangement that minimizes hazards and errors, with warnings in place for hazardous items. Fail safes must be integrated and encourage focus in tasks that require vigilance (discourage lack of vigilance).

The sixth principle involves reducing physical effort. Everything will be situated such that operating forces are reasonable, repetitive motions are minimized, sustained effort is minimized, and a neutral body position is able to be maintained.

The seventh and final principle is “size and space for approach and use”. This means that a clear line of sight to elements must be maintained for sitting and standing users, reach for seated and standing users is comfortable, variations in hand size and grip are accommodated for, and adequate space is provided for assistive devices.

1.6 METHODOLOGY

This section covers our engineering design cycle and the process used to make the final prototype.

PROBLEM DEFINITION

When beginning Project 2, the group was given a problem from a traveling museum. The initial problem statement, in short, was to create an educational exhibit that demonstrates engineering principles. The group first looked at what the given constraints were for the project and consulted the client for the exact restraints. The engineers had to make an exhibit that fit within a bin and was light enough where they could carry it. In the first engineering meeting, they discussed potential ideas and how they were going to make something that was both fun and educational. That led us to the research phase to understand the user and client. A result of the research correlated with what the group found by visiting the Museum of Science by finding competitive exhibits to be the most informational. This led to competitive to be one of the top characteristics for our solution when doing a rank-order chart.

RESEARCH AND DECISION

The next client researched was the users themselves. The team researched how children develop into preteens and the culture that they grow up in. This led to the need for stronger aesthetics due to the preference preteens have for prettier things. This wasn't as high of a priority when evaluating just the museum, but it increased significantly during the comparison due to the importance it could have in drawing users. The exhibit needed flashy colors and a clean exhibit to help garner interest in the exhibit.

Once the elements were found (see Appendix B)—such as being competitive, tactile, sensory-stimulating, and gratification—the engineers began coming up with potential exhibits that would fulfil these. Some of the ideas the group came up with were like other groups, such as wind and the shaker tables. The group idea was racing, with the electromagnetic component being the most enticing. All the ideas met the criteria desired, while also meeting the limits set by the museum.

Figure 4. Brainstorming Session for Milestone 1.

The team selected the top three ideas off of a majority vote: racers, turbine, earthquake table. See Appendix B for details. After delegating for an hour, the windmill exhibit scored the most points in our analysis comparison. However, the group found this to be misleading due to the probability of another group wanting to do something similar. Due to the knowledge of electromagnets, the group went against conventional logic and selected the electromagnetic racers. We then created initial design concept sketches and performed a decision analysis to choose which one to move forward with. My design sketch is depicted below:

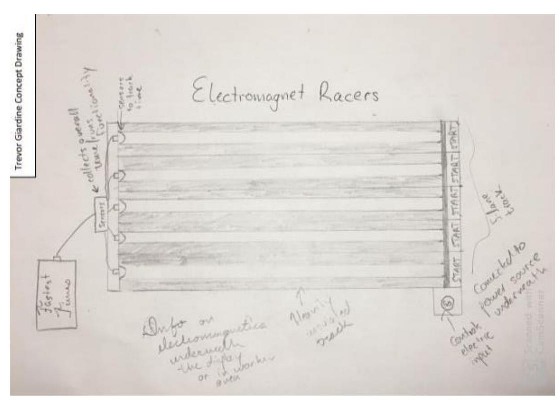


Figure 5. Trevor's Concept Sketch

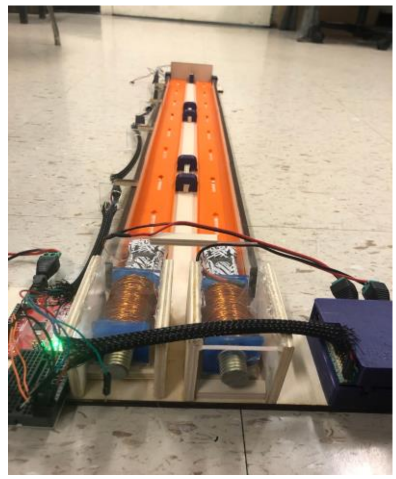
Initial Prototyping

Now that the group had finally chosen a solution to making the exhibit, the team their attention to how they would implement this. The engineers knew from the beginning that they would be using the magnetic repulsion as the force that shot the car. They initially wanted the kids to make their own cars but the idea was later scrapped due to the inconsistencies with 3D printing components. Generic Hot Wheels tracks were obtained for the tracks that the cars would race down. The engineers wanted to make different types of electromagnets with key differences. They knew they had to use the Redboard to at least run the GUI, with a separate component to race the magnets.

Construction of the first prototype was two Hot Wheels tracks on a tiny piece of cardboard. The group knew the complexity of the circuitry and electromagnets was hard, so they used a small 5V power source initially. A pair of identical electromagnets were constructed and built for the prototype. The team ran everything on an Arduino and the cars were purchased Hot Wheels which had magnets glued on to them. Figure 31, from Appendix G shows this model. It is included here for convenience:

Prototype Improvement

This model was modified for improvements following its presentation. The team opted for a laptop charger to power the electromagnets to provide more current to the coils. They constructed a 36” track for testing. Next, the engineers created a baseplate for the track to rest upon with a puzzle piece design. In order to keep the tracks apart, 3D-printed arches were made to separate the tracks. (see Appendix C for models/layouts). This was subsequently followed by a guardrail on the side to make it even tighter to lock the tracks into place (small tolerance). Figure 33 from Appendix G depicts this model, and is shown here for convenience:



This model was modified for improvements following its presentation. The group opted for a laptop charger to power the electromagnets to provide more current to the coils. They constructed a 36” track for testing. Next, the engineers created a baseplate for the track to rest upon with a puzzle piece design. In order to keep the tracks apart, 3D-printed arches were made to separate the tracks. (see Appendix C for models/layouts). This was subsequently followed by a guardrail on the side to make it even tighter to lock the tracks into place (with a small tolerance). A PCB was designed and soldered to shoot the electromagnets. The cars continued to have tape on them to attach the magnets to the cars. This was completed prior to the first demonstration at the gallery walk.

Feedback and concept Revisions

Following the gallery walk, the issues found were consistency, making a pleasant looking GUI, and making the whole exhibit look better.

The engineers initially explored shooting the electromagnets down a slight incline to increase the speed and consistency of the cars. Due to the printing inconsistencies, electric tape was used to attach the magnets to the back of the cars. This led to more time to be spent on the base. They decided to cover up the wires and laser cut pieces that fitted with the guardrails. This made the design look much larger and more professional.

The GUI became the focus after this and the first presentation. The GUI was completely redone to simplify the instructions and provide more visuals and information. Besides the simplification, there was very little else done the exhibit. They worked hard to make sure that the cars would be always centered by having better instructions. Additionally, the hyperloop was implemented for aesthetic appeal. The new houses were made for the electromagnets and the circuit board housing was labeled.

FINAL CONCEPT

Following the second gallery walk, the hyperloop was removed due to inconsistencies with the racers. The GUI got further simplified with a new reset function. Lastly, planned to laser cut new pieces of wood for the wire housing and Redboard housing. The poster and GUI had more research inserted into them. This was all done leading up to the Expo. The progress of the final design can be noted in Appendix C. For details of the functionality, refer to the final design section.

GIONA KLEINBERG

1.7 INTRODUCTION

PROBLEM STATEMENT

The problem is that the client needs an educational and entertaining exhibit that can inform kids about the issue of clean transportation. This is important because giving them this exposure, which they might not otherwise receive, can help inspire them to help solve such problems. Currently, available designs are miniaturized electric train sets and gravity car exhibits. These can be improved by combining the two concepts into a portable exhibit. The users, children need an engaging and educational experience that will inspire them to help solve these problems in the future. Our solution will reach a large magnitude of children and educate them about the issue of clean transportation and electromagnetism, through portability, interactivity, and engaging features.

STAKEHOLDERS

The stakeholders in our exhibit's success include the client who is requesting the design. It is necessary to make sure the design is cheap and within the $100 budget set as well as make sure it accomplishes the goal of the client which is to promote learning of a topic related to a new future. Another stakeholder is the users who will be interacting with the exhibit. It is necessary to make sure the exhibit is not only visually appealing but also fun for the clients. Those operating the exhibit must also be accounted for by making the exhibit easy to assemble, disassemble and simple to operate.

PERTINENT TOPICS IN ENGINEERING

This exhibit also resides under a larger theme of addressing future applications of engineering and sustainability. It is important that the youth are cognizant of the problems of our society and the importance of engineering new solutions to those problems. It is just as important to protect the people on our planet as the planet itself. Sustainable engineering designs will help to contribute to solving society's problems without creating or worsening other environmental problems. Electromagnets have large potential as a permanent solution to the search for sustainable and clean transportation.

SCOPE

This report covers the entire engineering design cycle with respect to the exhibit designed and constructed. The design process is followed from initial brainstorming, throughout its construction, to final results and a finished design.

1.8 BACKGROUND

CLIENT RESEARCH

Client research was conducted with the following conclusions. Exhibits should be impactful, modern, and educational to fit with the museum's goals. They should contain interactive and dynamic elements to better engage students and involve an intellectual and personal connection. They must maintain focus on one topic, and not attempt to do too much at once and be safe and accessible for all. However, the foremost purpose of these exhibits is to inspire and ignite a passion for math or science in the future generation of kids. (reference client research)

USER RESEARCH

User research was also conducted and came to the following conclusions. The users would be most engaged by quick, meaningful, interaction, with a competition of little significance and a clear goal, all accentuated by sensory engagement. Small incentives are the best way to engage children of middle school age. It is a primary objective to utilize this information to keep children engaged as that is an important requisite for effective learning.

UNIVERSAL DESIGN AND ETHICS

Research was done on universal design and ethics in order to ensure our exhibit met all current standards. Information gained is summarized in the following. The essence of universal design is accommodating a wide range of users. This means the exhibit must be physically and intellectually accessible, in a way that is equitable and flexible for all. There are seven major considerations in this regard, based upon the Center for Excellence in Universal Design's criteria: equitable use, flexibility of use, simplicity and intuitiveness of use, perceptible use, the safety of use, physical ease of use, and physical accommodations for use. There are two primary elements to our exhibit. The first is interacting with the user interface, in order to learn about the material, choose an electromagnet and name the vehicle, as well as get feedback after the race. The second is placing the electromagnet in position, moving the car into position, and activating the exhibit. For the user interface, we will focus on a minimalistic and intuitive design, with multiple language localizations if possible, so that instructions, information, and use is eased. The interface will also be placed and positioned in a way that is easily accessible and will feature tactile, audio, and visual feedback for use. The primary challenge for the UI is designing an intellectually accessible system. For the placement of the car and electromagnets, the primary challenge is creating a physically accessible system. To this end, connectors for the magnets will be chosen to allow for ease of use, and the magnets will be positioned within the ideal 11-inch reach range. Similarly, the cars and track will be designed for reset ease (likely with a latch mechanism and instructions for reset). There are specific details to work out for both the physical and intellectual accommodations, but this is a general outline of our plans.

ADDITIONAL BACKGROUND INFORMATION

Previous attempts to solve this problem were successful however it became clear that more success was possible. Past electromagnetically themed museum exhibits have either poor design or are unable to hold the interest of the user long enough to convey material effectively. Our design strives to create a balance between these historically challenging sides of electromagnet exhibits. Poor designs usually failed to meet expectations due to too much complexity, a lack of learning elements, or a non-tactile nature that discouraged learning.

1.9 METHODOLOGY

STAGE 1: PROBLEM OVERVIEW AND SOLUTION GENERATION

The engineering design timeline for this project began with the assembly of Team 6 and a meeting to establish a team contract (Appendix A) dictating terms, policies and work quality for the group to adhere to. Extensive research was done to understand the attributes of a successful exhibit as well as how best to convey a concept and encourage learning among the users. The team was presented with the problem and entered the brainstorming phase in order to generate possible solutions to the problem. The decision was made to do an exhibit on electromagnets due to their importance as a tool for engineers of the future which fit the theme and qualifications of our project. This solution was chosen from around 20 different exhibit ideas generated based upon our research and narrowed down through initial discussion among team members and a Kepner-Traego analysis with our team's perceived goals for the exhibit. See Appendix B

STAGE 2: SOLUTION DECISION

At this stage, each team member created a unique design for the electromagnetic racing exhibit and created initial sketches of their design in AutoCAD. A mentor was consulted and a thorough discussion led to the decision to implement a combination of the four designs in order to incorporate the strengths of each. The solution plan was solidified by a more complex AutoCAD sketch of the design. Decisions were made to include a guided user interface with the exhibit and to have multiple varied electromagnets in order to demonstrate their properties through comparison with each other. An image of my design concept sketch is shown here:

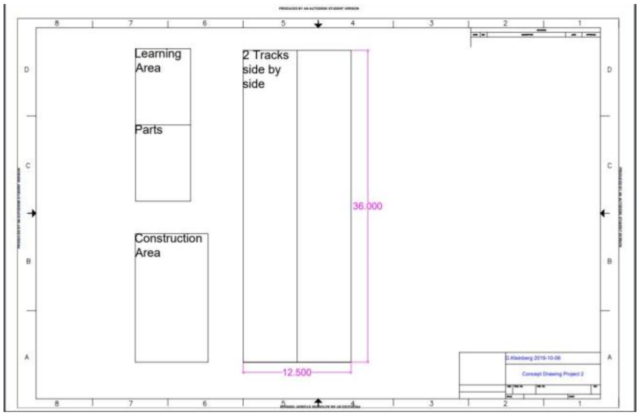
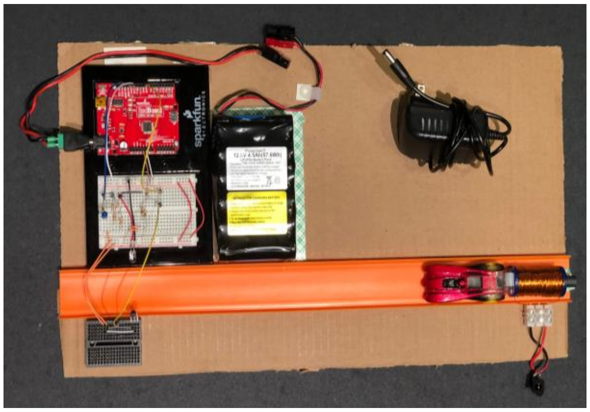


Figure 6. Giona's Design Concept Sketch

STAGE 3: PROOF OF CONCEPT

This stage primarily consisted of the construction of a circuitry test in order to ensure the solution's viability. The prototype from this stage is depicted below. A laptop charger was used to run current through a preliminary design of one of the intended coils to launch a car down a short, straight track into a break-beam sensor that was wired to an LED that powered on when the sensor read as low. The test proved successful. Additional research was done to plan for incorporating universal design requirements into the final exhibit to be implemented at a later stage. Figure 31, from Appendix G shows this model. It is included here for convenience:

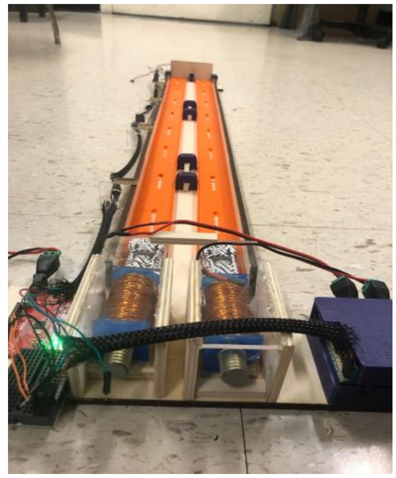


STAGE 4: PROTOTYPE CONSTRUCTION

The fourth stage consisted of a large amount of construction, primarily on two copies of the first electromagnet, baseplates in order to house the track, electromagnets, and electronics. Work was done on creating a custom PCB to reduce the need for large amounts of wires and control the power output to the electromagnets. Working code was created for the guided user interface in order to control the exhibit. The baseplates made were laser-cut into a puzzle piece design in order to fit the transportation constraints of the project. 3D-Printed parts were also made to house the PCB, sensors and in order to connect the puzzle piece design together when the exhibit is set up.

STAGE 5: FINAL CONSTRUCTION AND GALLERY WALK

Construction continued in this stage replacing materials used for prototyping with more permanent materials and replacing band-sawed wood with laser-cut wood. A picture of the prototype is shown below. The long connection line from the user interface to the red-board to the PCB to the electromagnets was successfully established for the first time. The user-interface was updated with teaching components and overhauled aesthetically. Code adjustments were also made in order to accommodate two new electromagnets that were made with thicker wire and less coil revolutions. . Figure 33 from Appendix G depicts this model, and is shown here for convenience:



STAGE 6: GALLERY WALK AND TESTING

This stage comprised of conducting extensive testing on the exhibit through participation in a Gallery Walk with other exhibits and collecting feedback as well as contacting third parties from a diverse set of backgrounds to answer questions. See Appendix D. Additional testing was conducted in a nearby college residence hall where the exhibit was set up as it would be during final testing and passerby were enticed by candy canes to test the exhibit. This testing provided many comments used in order to make the exhibit more intuitive. We decided to do extensive testing in order to ensure the decisions made were successful and to search for possible points of improvement.

STAGE 7: FINAL TESTING

This final stage primarily involved a large-scale testing of our exhibit to an extensive audience at a design expo that was organized to replicate the museum environment this design was constructed for. Data was collected based on user inputs and actions and recorded by our team. Since the last stage, two new magnets were constructed to complete a set of four electromagnets. Casings for the wire on the side of the track were redone and laser cut for a more refined design. The casing for the red-board was also laser cut and reinstalled. Electromagnets were labeled by their respective letters using a sheet of acrylic and the hyper-loop was abandoned due to complications it caused by bending the tracks. This decision was made because our team believed accurate results and consistency were more important than the aesthetic benefits the hyper-loop provided.

INDIVIDUAL CONTRIBUTIONS

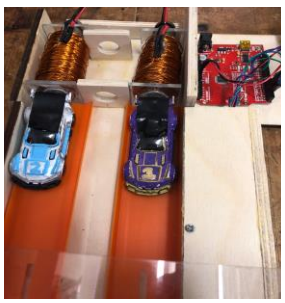


Figure 7. Close-up picture of electromagnet holders and beginning of track that I worked on.

I contributed to the project by undertaking the entire initial prototyping of the user interface as well as the code within it that provided teaching elements and connected the GUI to the red-board. This same code was used to turn on the electromagnets and receive and display signals from the break-beam sensor in the form of car times for each track. Additional contributions included constructing two of the final electromagnets which were both copies of Coil B - The Rifle. I worked on general construction for all prototyping phases most notably in designing the 3D-printed pieces that appear in the center of the exhibit as part of the locking system between base plates when setting up the exhibit. General construction I worked on also included wood pieces to cover wiring, aesthetic elements such as the flag as well as the woodwork for the electromagnet holders and constraints at the beginning of the track. I provided feedback used in troubleshooting as well as a large magnitude of solutions to minor problems surfacing throughout the construction of our final design. Ideological contributions were also made during each stage of the design project. My ideas, such as the implementation of a reliable setup to hold the electromagnets in place or the logic necessary for the code to the user interface were critical to the final design.

DEMITRI KOKOROS

1.10 INTRODUCTION

PROBLEM STATEMENT

The client needs an educational and entertaining exhibit that can inform kids about the issue of clean transportation. This is important because giving them this exposure, which they might not otherwise receive, can help inspire them to help solve such problems. Currently, available designs are miniaturized electric train sets and gravity car exhibits. These can be improved by combining the two concepts into a portable exhibit. The users, children need an engaging and educational experience that will inspire them to help solve these problems in the future. Our solution will need to fit on a 36"x28", be transported safely in a large plastic bin, and built with a $100 budget. The exhibit will reach a large magnitude of children and educate them about the issue of clean transportation and electromagnetism, through portability, interactivity, and engaging features.

The primary objectives of this project are to create an educational STEM museum exhibit that can be transported easily from one location to the next. More specifically, it should teach children about clean transportation and why that is important.

The constraints are mainly on the size of the exhibit, as the table size and transport bin are relatively small. Additionally, the $100 budget will ensure the exhibit is cost-effective and does not become overcomplicated.

The main function will be a race between two cars powered by electromagnets. They will be timed to add a competitive component to the exhibit.

STAKEHOLDERS

The client is a new traveling museum program that will take exhibits to locations where these resources are not typically available. The Museum of Science in Boston states that they, "would like to promote active citizenship, inspire lifelong interest and appreciation of science and engineering, and encourage kids to pursue a better understanding of the modern world." [8]. Based on these goals, it is evident that museums in general are in search of impactful and inspiring exhibits targeted toward children.

More specifically, the users will mainly be children under 18, who do not have the ability to visit museums or access these types of STEM learning tools. When targeting children, it's important to consider the visual appeal of the exhibit, interactive components, and level of complexity. There is the chance that some users will be adults, and for that reason it is key that the exhibit is simple yet has learning opportunities for all ages. The client wants an educational exhibit, while the users want something fun. It is our task to find a balance between the two when designing our project.

PERTINENT TOPICS IN ENGINEERING

The primary learning goal is to give kids a better understanding of physics and forms of clean transportation. In terms of the Bloom's teaching taxonomy, we hope that this project will allow kids to apply the information we feed them to the exhibit, create their own form of an electromagnetic vehicle, and evaluate the pros and cons of maglev transportation [23]. The design involves racing cars on a magnetic track, with the option for kids to interchange a certain part of the car to improve it. They will also interact with an interface that has information about electromagnetism. This will ensure they learn about the importance of physics and how magnets can change the direction of the transportation industry in the future.

SCOPE

This is the final technical report for this project. It will cover our entire design process, from background research and problem definition, to our iterated implementation process. It will include detailed CAD drawings and wire diagrams for each step of the project. Once the design process is thoroughly described, the report will discuss the final design and performance.

1.11 BACKGROUND

RESEARCH

For our research, we focused on one real-world implementation of electromagnets, which is the Maglev train. The basic layout of a magnetic track involves three different types of loops. One loop must create a magnetic field that allows the train to hover above the rails, another must keep the train horizontally balanced, and the last must propel the train forward. This is all done using magnetic attraction and repulsion. As explained by one source, "Imagine the box with four magnets -- one on each corner. The front corners have magnets with north poles facing out, and the back corners have magnets with south poles outward. Electrifying the propulsion loops generates magnetic fields that both pull the train forward from the front and push it forward from behind" [24]. In traditional maglev systems, input power transfer is key. This is the transfer of electricity that powers the train's levitation and propulsion coils, as well as other electrical components on the train [25]. Electromagnetic induction is what allows for this transfer of electricity. The magnets pass through coils which induct and generate electricity [26]. The levitation aspect eliminates friction, allowing for extremely high speeds. Maglev trains are considered clean transportation because they run on magnet powered electricity. The high speeds due to no track friction also increase travel efficiency. Japan has developed a maglev that reaches speeds up to 375 miles per hour [24]. The United States' Department of Transportation conducted a risk assessment of these trains in 1990 and determined them to be very safe, despite concluding that stopping could become an issue [27]. Even so, this was before all the upgrades in technology that have been implemented in the maglev design. Due to the fact that electricity is a clean energy, the trains are extremely environment friendly. This is the biggest upside of transitioning to this form of transportation. The downsides are its extremely high cost, and the requirement of demolition in order to clear paths for the rails within a city.

ETHICS

There are not many ethical concerns with our exhibit's design or its topic. First, dealing with electricity is always a risk. Therefore, we must make safety a priority and not sacrifice any safety measures for design improvements. This means keeping the strength of the power source around 5V, which is what is provided by a standard laptop. We also ensured the magnets were safe to be handled by users. Secondly, we would like to make sure we do not implement things that our outside our abilities. We do not want to unintentionally make our project flawed. We also discuss clean transportation and energy in our project. We see these teachings as ethical because it is important that the environment is protected going forward.

UNIVERSAL DESIGN

It is crucial to accommodate a wide range of users. In order to accomplish this, the exhibit must be physically and intellectually accessible for as many people as possible. There are seven major considerations covered in the Center for Excellence in Universal Design's criteria: equitable use, flexibility of use, simplicity and intuitiveness of use, perceptible use, the safety of use, physical ease of use, and physical accommodations for use [5]. This includes following the size and layout expectations, safety expectations, and maintaining a reasonable level of complexity.

1.12 METHODOLOGY

PROBLEM DEFINITION

First, the team contract was drafted and the initial meetings were scheduled. We completed both client and user research during this phase, during which we identified the goals and expectations of those groups. This helped us develop our first problem statement, which was then revised at the next meeting.

SOLUTION GENERATION AND DECISION

At our first major brainstorming session, we started by writing every idea on the white board, regardless of how plausible the ideas were. We then cut down a majority of ideas based on which seems impossible. That left us with our three best ideas; Turbines, Racers, and the Earthquake machine. A Rank-Order comparison was then used to weigh and determine the importance of various design aspects. We proceeded to implement a Kepner-Tregoe decision matrix on the remaining ideas, incorporating these ranked design features. See Appendix B for the referenced charts. Although the racers were ranked third in the final tally, we decided it was close enough to choose the topic that interested us the most. This is how we landed on the topic of electromagnetic racers.

IMPLEMENTATION: PREPARATION

Next, each group member brainstormed their own ideas for the electromagnetic racer exhibit. This included individual research and a rough design sketch, shown as Figure 8 below. This allowed us to finalize our problem statement before beginning construction.

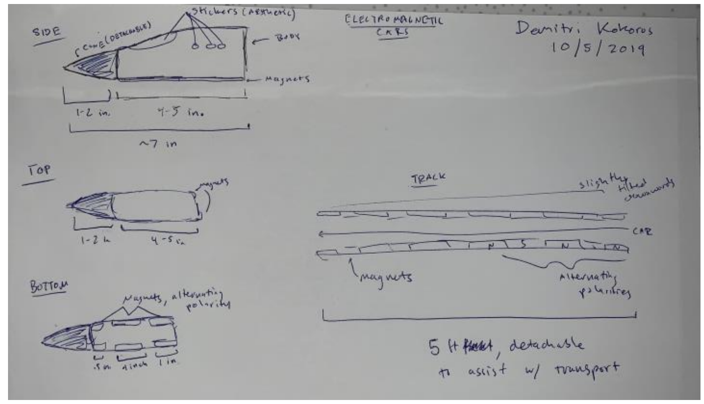


Figure 8. Demitri's Concept Design Sketch

IMPLEMENTATION: INITIAL CONCEPT

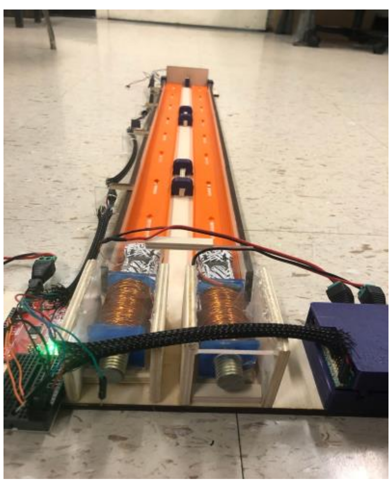
During this phase, we began constructing the cardboard prototype as an initial concept. It was mainly composed of placeholder pieces and cardboard. The goal was to show the cars can be launched down a track using electromagnetic forces, and that the IR sensors can work. Figure 31, from Appendix G shows this model. It is included here for convenience:

EVALUATION: INITIAL CONCEPT

Based on our initial concept design, we determined the biggest challenges would be generating enough power with the magnets and building consistent magnets. We identified that the connection with the Red Board worked well and that the sensors also worked as intended.

IMPLEMENTATION: PROOF OF CONCEPT

For the next phase in our building process, we were tasked with create a proof of concept. To show that all major design components can be implemented, we incorporated the PCB into the prototype. We switched our power supply to a laptop charger and incorporated a button as the launching mechanism. We also upgraded many components from cardboard to wood, in order to prepare for the final phase. We decided to continue testing only two electromagnets, because of how time consuming it was to construct each one. Lastly, the first test was conducted (see Appendix D). The test involved launching the cars ten times and recording the results. This was used to determine the consistency of the launch mechanism and magnets. . Figure 33 from Appendix G depicts this model, and is shown here for convenience:



EVALUATION: PROOF OF CONCEPT

This phase forced us to evaluate which aspects of our exhibit would require the most focus going forward. We determined these aspects to be the consistency of the launch and better wiring. We also planned to implement magnet holders on the back of the car.

IMPLEMENTATION: CONCEPT FINALIZATION

As we began working towards the final exhibit, we coded a rough GUI and could now launch the cars using the interface on the laptop. A few aesthetic changes were made, including re-cutting the wooden components. One pair of new magnets were created, using the thick wire. Most importantly, the second official test was conducted using different combinations of magnets. Four combinations were tested, seven times per combination (see Appendix D). This was meant to determine whether magnet pairings would be an issue and if we had improved the consistency of the magnets.

EVALUATION: CONCEPT FINALIZATION

After presenting our project and receiving feedback from the class, we had a clear idea of what to improve. People wanted to see more aesthetics added, consistency improved, more magnet options, and a more cohesive GUI. We also realized a poster would be needed in order to better convey our teachings.

IMPLEMENTATION: PENULTIMATE PROTOTYPE

For the penultimate stage of building, we primarily focused on developing the GUI and ensuring it could launch the cars as well as display the sensor readings. We also worked on the aesthetic elements, keeping in mind peer feedback. We laser-cut almost every wooden piece and crafted a mechanism that properly stopped the car at the end of the track, in line with the sensors. The poster was worked on and the rough contents and its layout was completed. The final test was run, once again testing four magnet combinations. Due to overall high consistency, only five tests per combination were conducted. Also, we used our feedback plan to collect further data by communicating with various sources. We them set up our exhibit in the lobby of Stetson West and asked random students to rate certain design aspects. This helped us develop a strategy for improving key components.

EVALUATION: PENULTIMATE PROTOTYPE

After this building phase, it was clear that the GUI had bugs that required attention. Additionally, it was determined that the exhibit required much more thorough instructions. Finally, it was agreed upon that we would tackle the extra credit, which involved coding something that could collect data as the exhibit was active.

IMPLEMENTATION: FINAL PROTOTYPE

Aside from cleaning up aesthetics, we spent a majority of our time building the final two magnets. It was at this point that we decided to only have one magnet per type, rather than pairs. In short, we did not have the time or tools to have eight magnets in total. Also, the circuitry was finalized, and the wiring was covered.

EVALUATION: FINAL PROTOTYPE

Our project appeared to be received well at the design expo. We had many visitors and interactions with the exhibit were smooth. We determined the strength of the magnets were not at the level we had hoped, however there was no chance to further improve upon that.

INDIVIDUAL CONTRIBUTIONS

I conducted the client research at the beginning of the design process. I also did individual research on our topics of clean energy and electromagnetism. I presented the group with my own sketches of a possible design, which convinced them to use a straight track rather than curved. I designed three different versions of the car mounted magnet-holder in SolidWorks (see Appendix C). I printed two of these magnet holders, however for each version the tolerance did not allow for a usable fit. Due to the lack of time and vouchers, we did not have the chance to print the final version or implement the magnet holder. I also constructed one of the thick wire magnets, which required using a drill to wrap wire around a hollow core. I helped debug the main issues in the code which prevented the sensors from reading both times at once. I went into the loop and rewrote the chunk of code that was recording the times. I re-cut and glued the side pieces which covered the wiring. I also helped install the hyperloop, which was not used on the final project due to design flaws. I built the framing for each magnet and glued them into place. I completed most of the memo write-ups for our group. Lastly, I completed roughly 50% of the poster content.

SGDT: MAGNETIC RACERS

1.13 FINAL DESIGN

The overall interaction with this exhibit involves working through the instructions and information in the graphical user interface, supplemented with instruction from the poster and operator. The User essentially chooses their coils, then races them against each other, then evaluates their results, and is finished interaction. Reference the figure below for a visual depiction of this interaction. The section is continued on the next page.

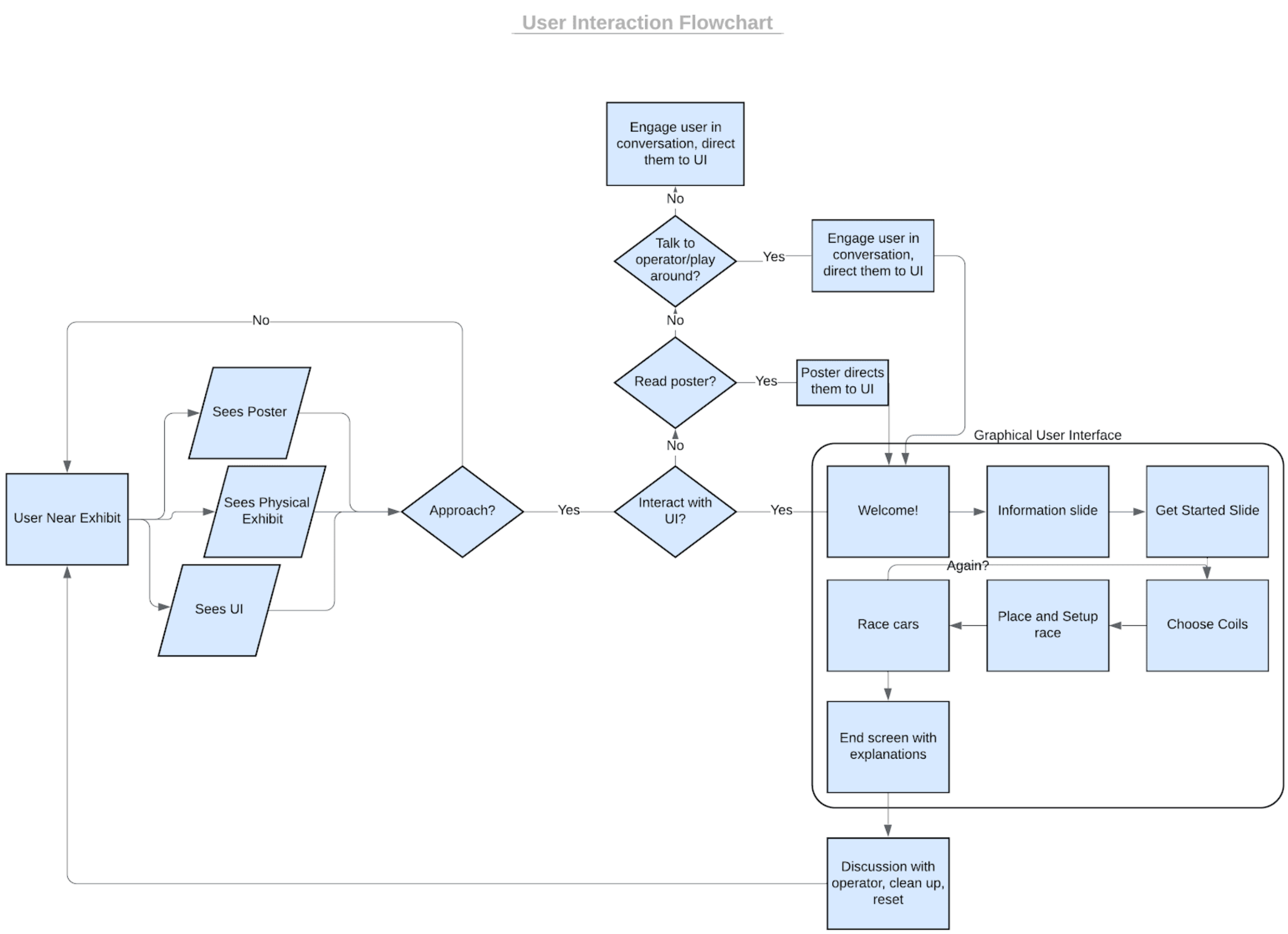


Figure 9. User interaction flowchart

There are four primary components to this project: the physical construction, the GUI and code, the sensors, circuits, and power, and the magnetics. The report will go into detail on each section, in the order listed.

Physical Construction

The exhibit is primarily made from three connected wooden bases, with guard rails on their sides. There are “centerbar connectors” on each wooden base piece, as well as a puzzle piece cut on the ends, that hold the bases together. The puzzle piece cuts interlock and a wooden bar through the centerbar connectors holds the base pieces together. The base pieces were laser cut, and the centerbar connectors were 3D printed. Note that all purple parts were 3D printed. Two segmented orange tracks lie constrained between the centerbar connectors and the guardrails. There is a brake system on the end piece, which includes a wood end cap, sponge impact absorbers, and a recessed track segment to catch the recoil from the car impact. The timing sensors are mounted on the end piece, and the magnet slots and circuitry are mounted on the start piece, encased in wood and a 3D printed case. A cable connecting the sensors at the end to the start circuitry runs along one edge of the case and is hidden by a wood cover. A 3D printed mount holds the interface in place. A labeled figure is to the right, to help make sense of the various components. Reference Appendix C for detailed CAD drawings, and Appendix G for more photographs.

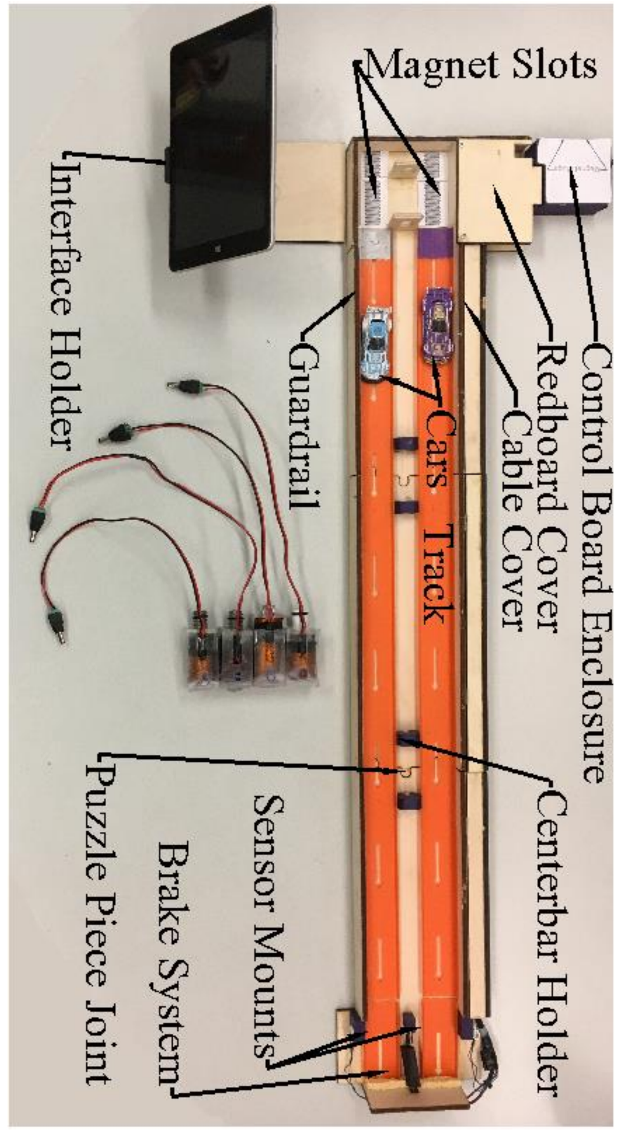


Figure 10. Labelled Physical Components of Final Prototype.

GUI and Code

Please refer to the flowchart pictured above for the flow of the GUI, as well as the images of the GUI to the right. This section will detail the process by which the GUI was created and its functionality, as opposed to the overall flow. The GUI was created in MATLAB App Designer. It consists of a series of "panel" objects. Each panel contains an "artboard" image, created in the GUI prototyping software "Adobe Xd". Overlaid on this image are images of the various buttons, with the callback "image clicked" enabled. This allows code to execute when buttons are pressed. Panels transition between each other when specific buttons are pressed. This transition is an animation produced by gradually moving the panel into the viewport over a fixed "transition time". When the start button is pressed (the "Race Cars" process in the flowchart), the first magnet is turned on for 50 milliseconds. Then the first magnet is turned off and the next one activated (at approximately the clock rate of the Redboard, 16 MHz). After another 50 milliseconds, the second magnet is turned off, and the timing loop is activated. The loop will end if either both cars reach the end or three seconds have passed. If a car is detected, the loop will record the time and update a text label displaying the time for the given car. A reset button was implemented to reset this panel if the user wishes to run it again. A count of all "misfires" where the car does not reach the end is also kept. The average times for each car was logged. Note that the figures to the right are duplicates of Figure 37 in Appendix G and are included for reading convenience.

SENSORS, CIRCUITS, AND POWER

There are two main circuit boards working with this exhibit: the Redboard and the Control Board. The Redboard handles interaction with the GUI, including turning the magnets on and detecting the digital signal from the timing sensors. It also provides power to the Control Board. The Control Board is responsible for powering the magnets, through two MOSFET assemblies. It is also responsible for driving the timing sensors, which are two IR "breakbeam" sensors, with two emitters and receivers straddling the track. Driving the sensors involves a 555 timer to generate a 38kHz signal for the emitters, which is the carrier frequency that the IR receivers are sensitive too. When a car interrupts this signal, the receiver detects the absence of the signal and pulls its output high. The Redboard is powered by the laptop interface, and the magnets receive power from a laptop power supply at 19.5V, 9.23A current-limited. Please reference Appendix F for the schematic and wiring diagrams. A simplified wiring schema is provided below to help visualize the system.

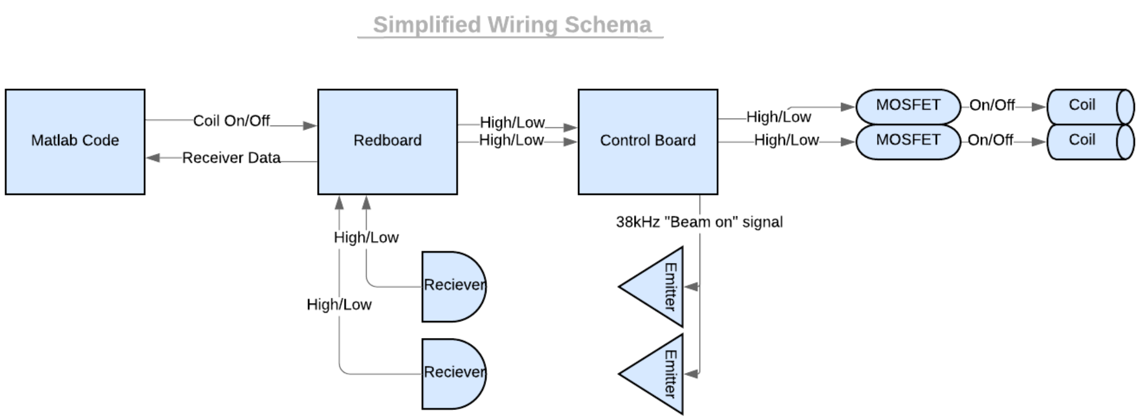


Figure 11. Simplified Wiring Schema

MAGNETICS

There are four different types of magnets, with varying characteristics. There are two copies of each type, for a total of eight magnets. The first type is called “Coil A”, the second is “Coil B”, the third is “Coil C”, and the fourth is “Coil D”. A quick synopsis: Coil A and B are cylindrical, with thin and thick wire respectively; Coil C and D are rectangular and ring-shaped, both with thin wire. The coils were wound with enameled copper wire, which was found not purchased. Coils and B have a steel core, with acrylic square capping off the wire. They have a male barrel jack header connected, to plug into the circuit board. Coils were wound using a drill, and the wind count was approximated. The core for Coil C was a piece of rectangular steel keystock. The core of Coil D was a 3D printed plastic cylinder, with small pieces of rectangular steel inserted in order to boost the strength of the magnet.

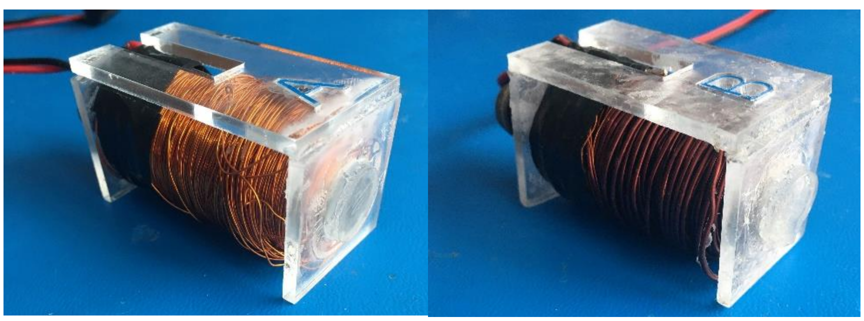
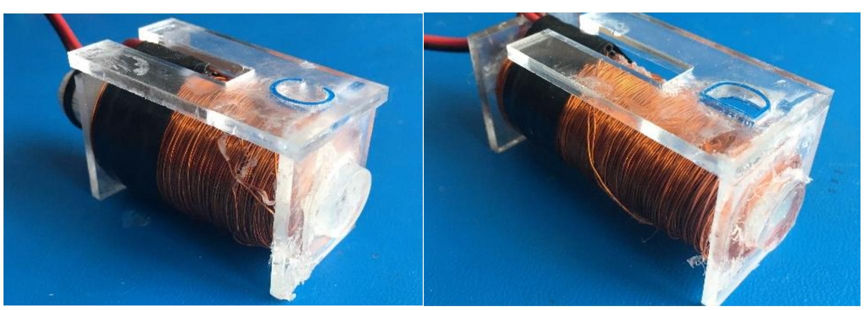


Figure 12. Electromagnets A through D.



1.14 RESULTS

The track measures 38.25” long, 10” wide, and 7” tall when the hyperloop is attached (2” without). During the construction process, three official tests were conducted (see Methodology). The results of the tests are shown in Table 6, in Appendix D. The first test was conducted on 11/10/19. Ten trial runs were conducted, with a success rate of 30%. A successful launch is determined by the car reaching the end of the track in under 3 seconds. Furthermore, 40% of the tests were misfires, while the remaining 30% did not launch. The second test was conducted on 11/20/19. It resulted in a success rate of 43%, or 12 successful launches, on 28 test runs. The percentage of misfires was 25%, while the amount of complete failures came out to 9, or 32%. The final test was conducted with 15 test runs. Out of these 15, only 1 was a misfire and 0 failed to launch. This means the final test had a success rate of 93%. When displaying the final project in the Northeastern Stetson West Lobby, we polled 19 people on their thoughts. The average ease of use rating was 7.2/10. The average rating for aesthetics was 9.5/10. They came in rating their knowledge of electromagnets at an average of 4.2/10, and left rating it at 7.7/10. After conducting our feedback plan, we collected the following qualitative data: When asked what the initial reaction to the exhibit was, a non-college student, Cheyenne, stated, “It looked a little intimidating because there were wires everywhere. The electromagnets looked like they were going to shock me”. Trevor’s father suggested, “more information about the electromagnets would benefit the exhibit” when asked how the learning experience was. When prompted with the question, “What changes would you suggest improving this exhibit?”, Cheyenne suggested, “hiding the wires so the exhibit is not so intimidating”. The gallery-walk provided several evaluations of our exhibit. One comment claimed the exhibit “looked fragile” and questioned its durability. Another comment said that while it was “very clean and organized”, it should be completely user operated. On the exhibition day, roughly 15 people visited and fully interacted with our exhibit. Furthermore, over 10 people came up to our exhibit and left without interacting with it.

SIDHARTH ANNAPRAGADA

1.15 DISCUSSION/ANALYSIS

The prototype met all design constraints and requirements: it was easily assembled, disassembled, stored, and transported. It was under the $100 budget. It had myriad and layered educational components, intertwined with engagement components to reinforce learning and retention. It met the design goals of inspiring and exposing users to electromagnetic propulsion technology.

Based upon the results of testing, it seems that the design was relatively engaging and informative for users. The final iteration of the prototype was relatively consistent, such that all the magnets were able to launch the cars to the end of the track most of the time. The main weakness, based upon qualitative observations, was that the exhibit simply did not catch the eye. General users would simply walk past our table. Once they stopped however, we found that the exhibit was relatively engaging and informative. During interaction, a drawback was that some users became intimidated and would be hesitant to interact.

Compared to current solutions, such as the gravity racetrack at the museum of science, and electric train sets, this exhibit tackles the more nuanced and integrated problem of educating about electromagnetic propulsion.

Compared to other prototypes in our cohort, this project is also unique in its topic and theme.

1.16 CONCLUSION

The final design met design constraints. It was able to be constructed and deconstructed into a container within 30 minutes. It met requirements for an educational exhibit, containing both active and passive components educating users about electromagnetics and their future applications. It also met the “engaging” constraint, containing multiple active and passive engagement components.

Performance was satisfactory. The final prototype that was showcased had generally favorable user comments. They seemed to be relatively engaged and informed by the exhibit. The performance of the exhibit in terms of consistency was also satisfactory. Quantitatively, consistency was lower than during testing, however it was still at sufficient levels for the exhibit to be engaging.

Similar design efforts should take care to choose an adequate power supply, and carefully wind and construct the magnets. Care should also be taken to position and constrain the magnets movement, to improve consistency. Reference the next section, Recommendations, for more details on this subject.

1.17 RECOMMENDATIONS

There were three main components to this design: the magnetics, power supply, sensors, and circuitry, and the physical exhibit. All three aspects could be improved significantly, especially for putting forward a final product. Additionally, aesthetic elements could be improved and some added.

There were two primary flaws with the magnetics. One was a minor flaw, and the other was an unforeseen problem, which also involved the power supply. The first flaw was an issue with the construction of the magnets. Essentially, the metal core material damaged the wire wrapped around it, once the winds became tight enough, reducing the strength of the magnets. This is solvable by insulating the core material from the wire with a thin, smooth, and cushioning material, such as tape. This was done for every coil except coil A, where the flaw existed. The construction of the magnets was a significant hurdle. In the future, automating the process with a coil winding machine, and using proper materials, as opposed to scrap materials, could vastly improve the exhibit, resulting in more consistent and accurate magnets, with the exact electrical characteristics needed for the rest of the system. The unforeseen problem involved the resistance of the coil being so low that it tripped the overcurrent safety features of the power supply. This was solved by increasing the resistance of the coil. However, the coils resistance was still too low to be run in parallel and increasing it further would have reduced the strength further. Hence, a programmatic fix was made, where one coil would be turned on for 50 milliseconds, followed by the next coil, in order to not trip the overcurrent protection.

Therefore, an improvement to the power supply would be a custom design. Designing a custom AC-DC linear regulated power supply, which could deal with the necessary currents and voltages, directly interfaced with the other control circuitry would improve the performance of the exhibit and remove the need for the fragile and inconsistent “quick fixes” that were applied. Adding transient voltage suppression as well as other protection to the magnet and sensor control circuitry would also be an improvement.

In terms of the physical exhibit, improvements could be made to the electronics and sensor housings, insulating and protecting them better, as well as concealing them in the frame. The track could be extended for a more exciting race, the electromagnet placement could be made better by changing the tolerances, instructions, and general system of positioning, and the learning components such as the poster could be miniaturized and permanently affixed to the exhibit. Finally, changing the connectors for the sensor cable to more reliable connectors would make the exhibit more reliable and a plug-and-play solution, where the magnets simply click into place and have an electrical connection, without needing to be placed then plugged in with a long wire would make the exhibit easier to interact with.

Based upon our qualitative observations, we found that it would have been useful to add certain aesthetic elements to draw users into the exhibit. This includes dynamic LED lights, buzzers/sounds, actuation, and static aesthetic elements to add height and draw the eye. Static elements may include a racetrack flag, as well as elements to add height to the exhibit itself.

1.18 LESSONS LEARNED

Contributions

Between Milestone 5 and 6 I primarily contributed construction and technical work. I spent the majority of my time working on debugging the system. This entailed ensuring that the IR sensors, and their associated cable were acting reliably, ensuring that the circuitry was working reliably, getting the new sets of magnets functional, testing the consistency of the magnets, rewriting the GUI code, cleaning up the craftsmanship with new laser cut parts, helping construct holders and cases for the electronics and magnets, and helping with the aesthetic components. Between Milestone 6 and 7 I continued testing and improving consistency. I built two new types of magnets. I also got the touchscreen interface working and made the GUI clearer to use.

Resources

Our team was over budget, though the final BOM cost was slightly under budget. Personally, I spent around $50-70 on the project. In terms of time, I spent around 130 hours, primarily between Milestone 3 and 7. This project has taught me a few lessons about resource and time management. In the future, I think that planning out the bill of materials in conjunction with the MCAD will be something I do differently. I did do that properly with the ECAD, and hence did not run into budget, materials, or time problems. Additionally, I have found that spending too much time awake was damaging to my physical and mental health, and reduced my performance working on the project. I think that in the future, I will adjust my working hours, in order to better accommodate sleep.

Reflections on Learning

I think that this project was a good experience on really digging deep into a systems design. I have done a lot of engineering work before, and on my own, but this was yet another excellent long-term project to sink my teeth into that involved mechanical, electrical, firmware, software, and marketing design. Though I did not necessarily gain any significant knowledge or new skills, besides perhaps more hands-on experience with electromagnetics, the experience was invaluable for my system design skills.

Reflections on Working in a Team

This project was a learning experience for working on a team. It helped me learn that asking for help is important and was one of the few instances where working in a team was mostly enjoyable. I haven't yet overcome the challenges we have faced as a team, but I am learning from my mistakes. I think that I made a significant mistake in not asking for help with technical aspects of the project and I think I have a problem with hubris and being managed that I need to work on. I have always been a technical leader when working on teams, and this was also the case on this team. I am a pretty hands-on leader and prefer to do most of the work myself, another thing I need to work on. I also had multiple clashes with another individual on the team, which was unique in my history of teamwork, and was an interesting problem to deal with. I see my biggest asset to the team being my technical knowledge. If I could go back and start over, I think that I would have emphasized a clear leadership/organizational structure, and asked for help a lot more. If there had been more time, I would have liked to get equipment to wind better quality coils, rebuild some of the coils, and design a custom linear regulated AC-DC power supply to power the coils and avoid many of the issues we faced.

TREVOR GIARDINE

1.19 DISCUSSION

After a lot of our testing and construction, the final design was finished. The final design had to fit within a storage bin and be carried. The design that the engineers came up with consisted of electromagnetic racers that ran on Hot Wheels tracks which were attached to a wooden plate. This design used a PCB and Redboard to operate and consisted of 4 different types of electromagnets (one of each). The complete model can be seen in CAD in Appendix C and G. A touchscreen interface was introduced to run the GUI and the four different cores were labeled clearly. The final exhibit featured all wirings outside of the plugs covered up for aesthetic and safety precautions. After presenting at the Expo, the group received positive feedback regarding the exhibit due to the information presented and the hands-on approach. The group received many top scores, which was a result of the overall look and presentation of the material of electromagnets.

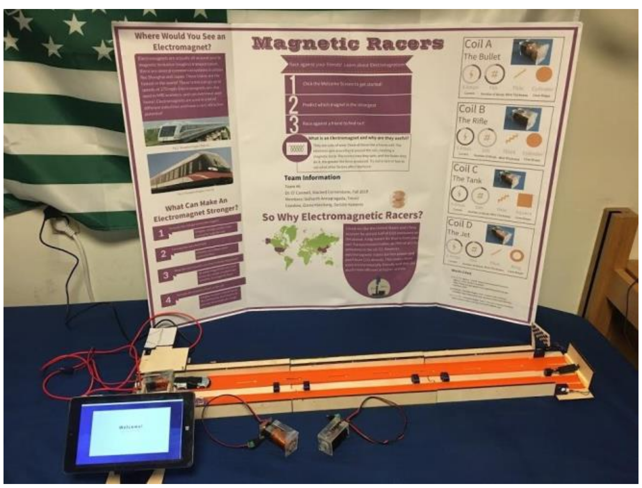


Figure 13. Picture of fully set up exhibit with poster.

The group had to revise the design multiple times. Some things the group liked about the design was the puzzle piece design, PCB, and the touchscreen interface. These components worked well for what their purpose was and showed the technical skill required to make an exhibit. The engineers were, however, critical of elements such as the magnet holders, electromagnets, and the hyperloop. Those issues restrained the project a bit because the magnet holders couldn't be 3D printed properly so tape was used, which took away from the overall effect of the car. When presenting, issues with the tape led to additional drag on the cars. The electromagnets were generally weak, and some electromagnets couldn't get to the end of the track. While the exhibit functioned properly, the group had to switch out one of the coils because one electromagnet was not working (there was a spare). This took away from setup time and hindered the group from presenting calmly.

When the Expo took place, the project performed admirably. Users said they learned what makes a stronger electromagnet and they were able to use their own hands to make judgements and try trial-and-error practices to learn. The exhibit educated people while also letting them have fun. The exhibit received several compliments on the color scheme and felt everything was presented clearly.

Compared to other exhibits at the Expo, this exhibit was one of the stronger ones due to the educational component being good with an interactive element. While it was not as hands-on as the Wind Turbine and Shaker Table exhibits, it provided more information into what made a good electromagnet which led to better understanding of the concept of electromagnetism and clean transportation.

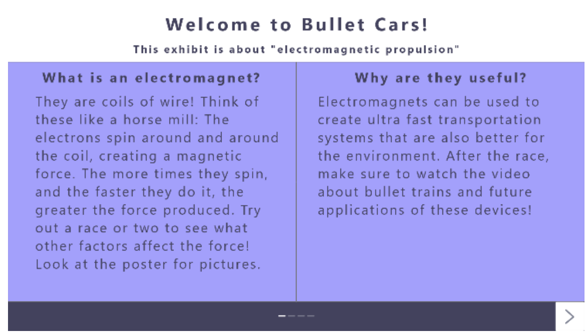


Figure 14. GUI Information Screen.

Since the client wanted an educational and interactive, the group met these requirements based from the responses they received. They received many praises for their idea and the execution of their solution performed well when demonstrated. They received compliments on their professionalism and understanding of the topic. This made the group one of the top exhibits following the Expo.

1.20 CONCLUSION

After all of this, the Expo was a success for the group and the project was well-received. The final project met all the requirements set by the client as that it was educational and engaging while being portable and easy to use. This was huge for the group's success at the Expo since they were able to demonstrate the progress made since the early prototype (see Appendix G) and were able to introduce more educational components to the exhibit.

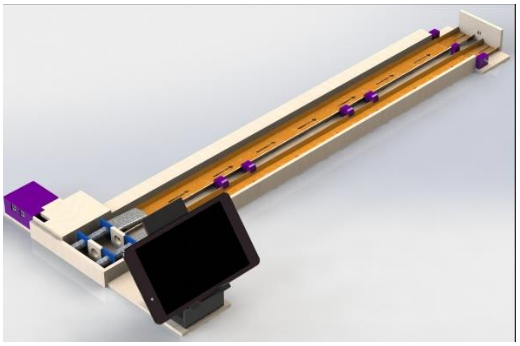


Figure 15. Final Solidworks Design.

The final design consisted of two tracks on a plate with a touchscreen GUI to operate the electromagnets. The exhibit featured a poster and a GUI which contained information on electromagnets. The exhibit featured elements where the users would personally select and predict what electromagnet they felt was the best. The exhibit received praise from staff and wandering students as that they felt it was a great topic to research/learn about, interactive, and they were left with information afterwards. The key takeaway most people had was what made a better electromagnet. While some people skipped right to the demo, most users waited long enough to get some information regarding electromagnets from the poster and GUI and then made an informative decision about what electromagnet they felt was going to be faster. The most complaints received was that some of it was a bit confusing due to the magnitude of the topic, but felt the instructions were clear and presented accordingly. The project performed well when the users used it and it was enjoyed by many.

While users felt the exhibit performed its best, the group disagreed based off of the speeds which the electromagnets were shooting in earlier testing. Before, the cars consistently made it to the end with less misses, while at the Expo there were more misfires. Additionally, since the speed of the cars was lacking overall, the group felt it was more of an educational piece due to the clear physical differences in performance of the cars based from the electromagnets. Users gained insight into the power of electromagnetism and understood the coils better after interacting with the exhibit.

Some of the criticisms the group had regarding the exhibit was that they felt they had to redesign multiple components multiple times due to errors in cutting (FYELIC was problematic) from bandsaws and the laser cutter being weak. The group would be a bit more careful if they could do it again and would want to make sure that all pieces were cut with a laser printer for accuracy. The group, if they continued this project, would have worked on making the electromagnets much stronger in order to make the speeds of the cars significantly faster. The faster speeds would have made the exhibit for entertaining while still maintaining the educational component. The group would have invested more money and time into some of the materials like the PCB and wires and would have a larger track if the table was different.

1.21 RECOMENDATIONS

After committing 102 hours to this project (see Appendix J), I had some regrets about the project and things I would have liked to implement.

When initially figuring out the components for the project, I wish the group had come up with the idea to make a full-size electromagnetic track. This would have simplified a lot of issues that they had throughout the project and the engineering cycle. Due to the unpredictability of the magnets and the fact they didn't have a good way of winding the coil around the steel/iron rods, it led to poor performances in early testing due to the unpredictability. The magnetized track wouldn't require the electromagnets to be the force driving the reaction.

Another regret was that we didn't reach out to any companies regarding electromagnets. This could have gotten the project some stronger magnets and they might have been willing to assist in making the exhibit better by having even more electromagnets. This would have been helpful in finding a way to wind them up better and it would have been good to have professionals commenting on the design while also giving constructive criticism. I also wish they had reached out to a physics or ECE professor earlier on because when we talked to Professor McGruer, his information would have been more useful in the earlier stages of the design process when the first electromagnet was made.

Another regret we had was we didn't make an official interface housing. They had difficulties getting a touchscreen for the project and it made it hard to have a consistent model to build around. This made it hard for us to have the motivation and tools to make housing due to the various size laptops owned. If the team had more time, we could have found someone who would openly let us borrow their computer, but the group waited too long where they had to use a tablet that ran Intel Atom to run MATLAB. Usability was an issue over the course of the project because the differences in laptops really had an impact in how the GUI ran and how they could display the information to the users. This was one of the motifs throughout the project and seemed to hold them back a lot as they tried to produce multiple components such as the timers, break beam, and launchers. They were disappointed to not have enhanced the display and processing speed for a synced experience for the users.

There wasn't a whole lot that I wish had happened different with the project. The group performed very well, and the exhibit received lots of positive feedback. This made the project feel gratifying since the only details or changes that they wish had been done were just improvements of the components used for the final design.

1.22 LESSONS LEARNED

CONTRIBUTIONS

My role in the group escalated toward the end of the design process as the exhibit approached the Expo. I took initiative and became the lead writer on all the memos and was in charge of information research and visuals. I worked a lot on the educational aspects, such as the poster, information cards, information for the GUI, and making the whole experience easier to understand. I contributed a lot to the aesthetics (such as the hyperloop) and devised the braking system and suggested the ideas for the Hot Wheels tracks. The work performed ate up a lot of my available time and is the reason why I am the leader on the hours sheet (see Appendix J).

RESOURCES

The group met the maximum budget of $100 by spending $66.86). This left the group with more wiggle room for last-second purchases but still hindered their ability to obtain a touchscreen laptop. I personally spent around $65 ($15 actually used) on the project because a lot of the components he purchased were later returned because they weren't used. My key purchases were some of the plastic for the hyperloop and a lot of the attachment elements (which were later returned). If the team had a larger budget, they would have invested in a touchscreen monitor that would connect and mirror the laptops.

REFLECTIONS ON LEARNING

I learned a lot about coding, circuitry, and what goes into a project like this. Coming in with no experience in coding, I was able to learn some Arduino and MATLAB features which were helpful. I also learned a lot about how to solder and how a PCB is put together (which is simple yet hard!). As a group, we realized the amount of effort required to go into a class like this and worked diligently to make it a tolerable level of work. While we were often stressed, we learned he needed to work efficiently and stay on track with the design process. We definitely learned a lot about how this project works and really understood the design process as the group redid elements.

REFLECTIONS ON WORKING IN A TEAM

The group had a lot of dynamic. Issues were that the group members preferred individual work which made it hard to collaborate (ex. memos). It made it hard sometimes because stuff couldn't get done when it was desired to be completed. The group had several conflicts throughout the timeline (see Appendix H), especially in Milestones 4 and 5. I had to act as a mediator at times due to the frustrations of various group members with one another. The group knew the issues with group work with people they didn't know coming in, so it was no surprise there were issues at time. The group struggled with accepting criticism which made the work environment toxic periodically. I was the one who broke up intense arguments and tried to keep the peace. The group didn't handle adversity well. This led to more individual or selective work meetings where the only one or two members would meet instead of the whole group depending on the given task for the day. Overall, the group was decent for the project but would not be one that the group would work with again.

GIONA KLEINBERG

1.23 DISCUSSION/ANALYSIS

RESULT ANALYSIS

Data collected from the final testing of the exhibit produced great results. See Appendix D for specific results. The project accomplished all specific goals set for it and met all non-quantitative goals sufficiently. Users reacted well to the exhibit, enjoyed it, interacted independently with it and learned about electromagnets in the intended manner as proven by the data collected through all testing done. Based on these results, it can be concluded that our exhibit would be successful as a travelling museum exhibit with the purpose of educating users about sustainable energy methods. The design does what it is intended to efficiently and well therefore it can be interpreted as a success.

QUANTITATIVE GOALS

The design meets all constraints including size constraints, functionality constraints, and budget constraints set by the client. The design fits within a maximum footprint of 28” x 36” when setup, includes educational text, includes interactive components and costs less than the budget of $100 (See Appendix I). It contains many rapid-prototyped parts as well such as the PCB case or break-beam sensor holders. The design also accomplishes all required functions of the project as an exhibit. The exhibit is easy to use and can be operated completely independently after setup without a facilitator. The exhibit is interactive and accomplishes its goal of teaching users about electromagnets while still fitting the transportability requirements of fitting within a small plastic tote. Balancing all requirements of the project without sacrificing goals is one of the largest strengths of this exhibit.

NON-QUANTITATIVE GOALS

Many goals of the project did not have quantitative magnitudes associated with their success but were met to the best of our team’s ability. The aesthetics of the design were accounted for during all stages of the design process with a layout that was appealing as well as functional. Laser-cut wood and 3D printed parts as well as the painted cars contributed to a refined design that appeared complete and professionally. Learning was accomplished greatly. Based on the results from our final testing, almost everyone who interacted with our exhibit left with increased knowledge of electromagnets and their applications. The design also attracted many users due to its tactile design that was fun to use. Due to these qualities of the exhibit, the design was able to effectively meet all non-quantitative goals set for it and exceed expectations.

1.24 CONCLUSION

DESIGN PERFORMANCE

The design meets all constraints including size constraints, functionality constraints, and budget constraints set by the client. The design fits within a maximum footprint of 28” x 36” when setup (See Appendix C), includes educational text, includes interactive components and costs less than the budget of $100. (See Appendix I) It contains many rapid-prototyped parts as well such as the PCB case or break-beam sensor holders. The design also accomplishes all required functions of the project as an exhibit. The exhibit is easy to use and can be operated completely independently after setup without a facilitator. The exhibit is interactive and accomplishes its goal of teaching users about electromagnets while still fitting the transportability requirements of fitting within a small plastic tote. Due to meeting all of these requirements and also effectively teaching the users about electromagnets, this design can be considered a success.

FUTURE DESIGNS

Similar exhibit development in the future which aims to educate users about sustainable energy should choose a topic that is less complex or plan for a larger commitment of resources. A large amount of time and money was spent attempting to make the electromagnets simple to operate and functional, however, this time could be better spent on other aspects of the exhibit if a topic was chosen that was more conducive to a museum exhibit environment. This issue could also be solved with a secondary design made in advance of a machine to aid in wrapping the coils. In order to ensure the electromagnets would be consistent and functional a large amount of time was spent carefully winding them. It would be much more resource-effective to spend time designing such a machine than individually wrapping each electromagnet by hand and a drill. With the implementation of this machine, more electromagnets should also be made to further aid the teaching component of the exhibit.

1.25 RECOMENDATIONS

Similar attempts to solve the proposed problem should spend more time on initial research of their prospective design. Lots of time was wasted due to picking a topic with an unpredictable and hard to control nature. In order to make the goals of the project easier, topics should be picked that would better function in a museum exhibit setting. Devices such as electromagnets with necessary exposed wires and inconsistent natures require much more resources in order to turn them into a reliable, safe exhibit. Preparations should also be made for which materials each intended aspect of your project will be made of and an estimate of their cost in order to make sure the intended aspects will not exceed such a budget. Wood should be replaced with stronger, durable materials such as plastic. More work should also be done in order to ensure the circuitry of the project is not exposed or in danger of being damaged by the rigorous environment of a museum setting. Given more time, more aesthetic and learning elements should be included as well as additional electromagnets to further the variability of options.

1.26 LESSONS LEARNED

CONTRIBUTIONS

I contributed to the project by undertaking the entire initial prototyping of the user interface as well as the code within it that provided teaching elements and connected the GUI to the red-board. This same code was used to turn on the electromagnets and receive and display signals from the break-beam sensor in the form of car times for each track. Additional contributions included constructing two of the final electromagnets which were both copies of Coil B - The Rifle. I worked on general construction for all prototyping phases most notably in designing the 3D-printed pieces that appear in the center of the exhibit as part of the locking system between base plates when setting up the exhibit. General construction I worked on also included wood pieces to cover wiring, aesthetic elements such as the flag as well as the woodwork for the electromagnet holders and constraints at the beginning of the track.

RESOURCES

Our group came under budget and utilized our budget as much as possible. Resources were always obtained from free and discounted sources if available and materials were used based on a cost to effectiveness ratio. See Appendix I I bought the poster board and a few other materials for the project. A large amount of time was spent on the project with a considerable amount of it spent testing. See Appendix H. A large amount of the time I personally spent on the project was towards developing the GUI and on construction. Resource management in the future will place a higher focus on prioritizing time as a resource to ensure that large amounts of time are not wasted and the design process is more efficient.

REFLECTIONS ON LEARNING

I learned a lot from this project about the engineering design process. I learned about managing resources and working with a team on a scale that was new to me personally. I had to teach myself how to create an interface using a MATLAB app and connect it to a red-board. I learned about the functions and properties of electromagnets and break-beam sensors. I also learned how to 3D-print a part as a rapid prototype from a Solidworks model. The greatest lessons learned in this project involved seeing a design go through the engineering design cycle from start to finish and appreciate the work it takes in order to do so.

REFLECTIONS ON WORKING IN A TEAM

This project shaped our team working skills considerably. Feelings of frustration and lack of motivation proved to be the biggest challenges to overcome for our team throughout the project. We overcame these problems by attempting to put them out of mind and continue working until the problems were solved. We learned that complaining or identifying problems does not help to solve them. We utilized a third-party task management website called Trello to organize these problems in order to put them out of mind until they were necessary to solve. Our team still needs to work a little towards delegating work among members and managing time by avoiding procrastination. My personal leadership style is perfectionist which can often be perceived as controlling. I recognize my desire to input ideas even when I am the one being managed and doing so has allowed me to control myself and make sure everyone has a chance to be heard equally. The biggest asset to our team was our team's synchronized nature. Our personalities resonated with each other well and led to a good working environment. Given more time, our team would have liked to add more magnet options and more teaching components.

DEMITRI KOKOROS

1.27 DISCUSSION

To start, nearly all the constraints of the project were met. The exhibit fit on the table however it barely exceeded the 36”x28” size requirement by ¼” length-wise. This was a necessary sacrifice as it allows for the attachment of a wooden board to block the cars from falling off the track at the end. We determined the extra length did not affect the track’s ability to fit on the table. Additionally, the track was detachable and easily fit safely into the plastic bin. The detachable features made it extremely portable and allowed for an efficient set-up. Finally, we remained under the $100 budget. For this reason, I believe that based on meeting the constraints, our design was very successful. Furthermore, our results from the weeks leading up to the final day of testing were highly inconsistent. This was likely do to the inconsistencies in magnet production. After several important changes were made (see Methodology), the project began to see steady improvement. The final day of testing however, indicated that we have produced a highly consistent exhibit. As Table 6. Quantitative test data for evaluation of magnet consistency after running 15 tests with various electromagnet combinations, we encountered only 1 misfire. When racing two of the same electromagnets, they finished in a tie 70% of the time. This data shows that the launching mechanism was consistent and both the interface and circuitry were performing as intended. This was important for our goal to show users the potential applications and practicality of electromagnets. After observing how consistent they are, they are hopefully convinced that they can be used for transportation. When racing the stronger electromagnet against a weaker one, the stronger won only 63% of the time. This is much lower than it should be, even taking into account the variability of a handmade magnet. We were not able to reduce this error; however, despite this weakness in our exhibit, it did add a more competitive element to the race by making the best electromagnet harder to determine. Another issue is that this slightly detracts from the learning goal of understanding electromagnets, but I believe the poster and interface help achieve that goal in addition to highlighting the benefits of clean energy. The 83% increase in the average rating of electromagnet knowledge before and after interacting with our exhibit indicates that our project was successful in teaching users. The feedback plan helped us identify the biggest issues with our exhibit. It showed that our main problem was a lack of detailed instruction. We also realized that covering the circuitry and wiring was necessary. People were not sure how to interact the exhibit. Over 15 people fully interacted with our exhibit at the expo, which we felt was an impressive amount. However, over 10 people seemed to acknowledge our exhibit and move on without interacting with it. I think this could be due to the lack of lights and flashy aesthetics. Overall, were told by Dr. O’Connell that the exhibit was “well received” and therefore believe that it was successful and well-designed.

1.28 CONCLUSION

Overall, the exhibit performed well. It was fun, competitive, aesthetically pleasing, and attracted users with its racing theme. We applied the skills that we have developed over the course of this semester, such as the engineering design process, various software, and using workshop tools. multiple It was designed with the constraints in mind despite hanging ¼” off the edge of the table, and with a focus on balancing entertainment and education. The topics of electromagnetism, clean energy, and transportation were thoroughly relayed through both the interface and the pasteboard. Unfortunately, some people did not feel the exhibit was worth interacting with. Despite that small amount of disinterest, we received over a dozen visitors at the expo. For this reason, I believe confirms that our exhibit was successful.

1.29 RECOMENDATIONS

If given more time, multiple aspects of the project could have been improved upon. The wooden side walls of the track are not perfectly cut, as we did not have the time to laser cut them and were forced to resort to the bandsaw. Furthermore, it would have been possible to better contain the wiring with a better cut wooden box. Additionally, we ran out of 3D print vouchers and could not print the magnet holders. This forced us to use tape, which was much less aesthetically pleasing. We spent a lot of time winding the electromagnets, which took time away from other components of the projects such as adding lights on the track. Due to the low budget, the electromagnets couldn't be purchased, and winding by hand was not easy to accomplish as carefully and to the quality we would've liked. If time had permitted, I would've liked to add a ramp feature to increase the speeds of the cars. It is crucial to fully understand electromagnets before beginning this project, because there are many small details that impact the design as a whole and its overall function. A lot of time was wasted making incorrect assumptions about the magnets. For example, we did not account for the difficulties of launching two different magnets simultaneously (with one power source). It was an issue with the how the resistance of a wire makes the current behave. This led to some overengineering in making sure it would be possible to make it a fair race. To make this a commercial product, it would be necessary to make the magnets very easy to use and safely enclosed in a casing. Additionally, consumers need to be able to run the race without the interface, so the launching system would need to be changed to a switch or button. Lastly, it would be interesting to develop an application of some sort that could connect to the track wirelessly and record race times.

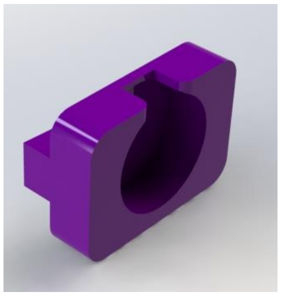


Figure 16. Magnet Holder 3D Model. Attaches to back of car and holds permanent

1.30 LESSONS LEARNED

CONTRIBUTIONS

I conducted the client research at the beginning of the design process. I also did individual research on our topics of clean energy and electromagnetism. I presented the group with my own sketches of a possible design, which convinced them to use a straight track rather than curved. I designed three different versions of the car mounted magnet-holder in SolidWorks (see Appendix C). I printed two of these magnet holders, however for each version the tolerance did not allow for a usable fit. Due to the lack of time and vouchers, we did not have the chance to print the final version or implement the magnet holder. I also constructed one of the thick wire magnets, which required using a drill to wrap wire around a hollow core. I helped debug the main issues in the code which prevented the sensors from reading both times at once. I went into the loop and rewrote the chunk of code that was recording the times. I re-cut and glued the side pieces which covered the wiring. I also helped install the hyperloop, which was not used on the final project due to design flaws. I built the framing for each magnet, and glued them into place. I completed a majority of the memo write-ups for our group. Lastly, I completed roughly 50% of the poster content.

RESOURCES

Our group was able to complete the project within the $100 budget. I personally spent approximately $50 which was what the wood sheets and the PCB components totaled too. I have learned that resource management is key and planning is important because it is easy to overlook purchases as the costs start to add up.

REFLECTIONS ON LEARNING

This project taught me a lot about circuitry and soldering. Prior to the project, I had no experience with either of these topics. The creation and implementation of the custom circuit board (PCB) was a large factor in bettering my understanding. I also gained experience using Arduino while assisting with the interface code/design. I taught myself a lot about electromagnets in order to understand the launch mechanism and help construct one. Using SolidWorks to design a 3D-printed component provided me with useful knowledge and experience that will apply to future projects. I am very proud of my improvement in the different software we have used, because I had little to know experience with any of them coming into the year.

REFLECTIONS ON WORKING IN A TEAM

Working with a team has been an excellent learning experience for me. It was my first engineering related team project that I have been a part of. I learned the value of communication. For everything to run smoothly, it was crucial that we kept in constant communication, voice our ideas, and be aware of our responsibilities. Another important aspect of a team is compromise. We each had to make compromises on certain aspects of the project, whether it was about an aesthetic component or a foundational component. We overcame these challenges by maintaining a professional environment and demeanor, which meant holding each other to certain standards and respect. I believe that I was an effective leader because I was assertive when assigning tasks and organizing meetings, but was understanding that each group member had different schedules and responsibilities. If I could go back to the beginning of this semester, I would try to be more efficient with our time and complete tasks further from the due date to avoid a last-minute panic. I feel like my biggest asset to the team was my willingness to work on anything that was assigned to me and help group members if they were struggling with their workload.

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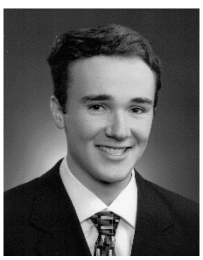
AUTHOR BIOGRAPHIES

Sidharth S Annapragada was born in Baltimore, Maryland, in 2001. Sidharth is pursuing a dual bachelor of science in electrical-computer engineering and behavioral neuroscience at Northeastern University in Boston, MA, USA. He plans to complete his degree in 2024. He has previously worked extensively on robotics projects, for both a team and for personal competitions. His experience includes PCB design, mechanical design, embedded firmware, and software development for robotics. His interest in robotics led to him pursuing electrical engineering, with a parallel path within neuroscience. Mr. Annapragada is a member of the Institute of Electrical and Electronics Engineers chapter of Northeastern, as well as Wireless Club.



Trevor Giardine was born in Syracuse, New York, in 2000. He received his high school diploma from Nottingham High School in Syracuse in 2019 is currently working on getting his BS/MS in mechanical engineering at Northeastern University's Boston campus. These degrees will be completed in 2024.

Since entering high school, he was active in various engineering classes and projects. After completing Rochester Institute of Technology courses for introductory engineering and design courses, he took his skills to the theatre by leading set design and construction for multiple shows during his time at Nottingham. In 2019, Trevor was awarded an internship with the lighting company Ephesus, who is responsible for sports lighting at various complexes (notably all the upcoming Super Bowls), in the summer of 2020. His passion for sports has made him want to be part of the sports engineering industry, and hopes to work with companies like Under Armour and Nike following his graduation from Northeastern

Mr. Giardine is a member of Northeastern's American Society of Mechanical Engineers, Engineers Without Borders, American Cancer Society, and Ski Club. Outside of Northeastern, Trevor volunteers at various walks, such as the MS Walk, Buddy Walk, and various Relay for Life events.

Giona A. Kleinberg was born in Livingston, New Jersey, in 2001. Giona is pursuing a bachelor of science in bioengineering at Northeastern University in Boston, MA, USA. He plans to complete his degree in 2023 along with two minors in computer science and materials science and engineering.

He has previously worked in education as a snowboard instructor and aspires to attain a PhD. to continue teaching at the collegiate level. He has many diverse interests, most prominently in bioinformatics, genetic engineering and tissue engineering. He also has a strong interest in biomimicry specifically related to the regeneration of Axolotls and hopes to pursue research relating to it.

Mr. Kleinberg is involved in many clubs at Northeastern University. Clubs include the Biomedical Engineering Society, E.N.D.

Initiative, Chess Club and many intramural sports. In his free time, he can be found snowboarding or coding various projects.

Demitri G. Kokoros was born on September 20th, 2000 in Boston, MA. Demitri graduated from Belmont High School in Belmont, MA, in 2019. He currently attends Northeastern University, located in Boston, MA. He is a mechanical engineering major, working toward his Bachelor of Science degree. He plans to earn his master's degree by 2024.

He does not have a lot of background experience with engineering. His interest in various STEM topics throughout high school led him to explore an engineering degree. He was interested in building and creating products that can help society and enjoyed working with a team.

Mr. Kokoros is a member of the American Society of Mechanical Engineers at Northeastern University.

APPENDICES

APPENDIX A – TEAM CONTRACT

This is a brief overview of our design team's policies, procedures, and goals. It will cover contact information, policies on respect, commitment, transparency, communication, justice, team goals, team roles, and a team calendar.

Contact Information

Name	Email	Phone Number
Sidharth Annapragada	annapragada.s@husky.neu.edu	302-513-4042
Trevor Giardine	giardine.t@husky.neu.edu	315-949-8663
Giona Kleinberg	kleinberg.g@husky.neu.edu	845-2177-131
Demitri Kokoros	kokoros.d@husky.neu.edu	617-480-4205

Table 1. Team Contact Information

Respect

Late Work Policy: If work is not completed by the agreed upon date in the calendar, it is considered "**late**."

Punctuality Policy: Attending a meeting more than 5 minutes after the scheduled time is considered unpunctual.

Procedure Upon Violation of Policies: Team members who violate the above policies will receive additional work as the project progresses to make up for the work they didn't complete on time or information missed at a meeting.

Commitment

Hour Availability: We expect team members to be available consistently from **4-6 everyday** with additional time before and after on Tuesdays and Wednesdays. Another possibility is meeting in the morning prior to our Tuesday cornerstone classes.

Expectations and Measurement of Quality: All work should be presented in a form that no other member could improve upon it. This is to ensure the group will present material to the height of its potential.

Procedure Upon Violation of Policies: If low quality of work is a result of laziness or time constraints it should be redone until it is done right. If the work cannot be completed at the expected level of quality due to the skillset of the team member working on it. The work will instead be given to the team member best equipped to handle it. Work from the team member best equipped will also be delegated to the team member who presented the low-quality work in order to ensure an equal workload.

TRANSPARENCY

Decision Making and Consensus: The group will meet *at least* once a week to determine the direction of the project. This includes, but not limited to; determining who does what on the project, what needs to be done, expenses, time spent at FYELIC, etc.

Information Sharing: All contact between members will be done within our four-person email chain or within our group chat to effectively "send a carbon-copy" to everyone in the group. This will keep everyone on the same page.

Procedure in the Case of Exclusion: If members feel excluded in some form, there will be communication with the milestone leader regarding the issue. This, consequently, will lead to an extended meeting the next time the whole group meets to address the issue and reevaluate the current predicament as to how roles are determined.

COMMUNICATION

Primary Method of Communication: Team Members will **need** to consistently check for texts and emails between group members. For meetings, group members will correspond primarily over text due to the high volume of emails.

Even Representation: We will attempt to operate in a democratic fashion, in order to ensure that everyone feels that they have a voice. Regular votes during meetings, and within communication channels should serve this purpose.

Group Reflection: We will attempt to allot some meeting time each week to discuss the group strengths and issues, and work towards solutions.

Conflict Resolution: We will immediately dedicate time to solving the issues at hand, and everyone will have a chance to voice their opinions. In extreme cases, we may bring the issue to Dr. O' Connell.

JUSTICE

Conflict Prevention: We will attempt to follow the above policies, in order to prevent conflict. In the event of conflict, a democratic resolution will be reached.

Equitable Contribution: Work will be divvied up evenly with attention to who's best fit to handle certain parts. Everyone will have to agree with the workload they are being assigned.

Procedure Upon Cessation of Contributions: Depending upon the reasons for the cessation, and extent of work missed, the late policy will be implemented, and in extreme cases, we will contact Dr. O' Connell.

TEAM GOALS

1. Our first goal is to minimize conflict and resolve conflicts quickly.
2. Our second goal is to do something unique with our project.
3. Our third goal is to make the project "professional" in form and function.
4. Our fourth goal is to stick to a schedule and get tasks done on time.

INDIVIDUAL GOALS

Giona:

- Giona is interested in giving himself a strong foundation of knowledge for future engineering endeavors.
- Giona would like to improve his skills in programming in order to pursue projects independently.

Sid:

- Sid would like to build his teamwork skills especially in a professional project.
- Sid would like to become more proficient in machining and manufacturing parts.

Demitri:

- Demitri would like to learn what it's like to be part of a cohesive engineering team.

- Demitri wants to become a much better coder using C++.

Trevor:

- Trevor wants to learn how to become proficient in coding.
- Trevor wants to achieve a high grade on all his labs.

Team Roles

Milestone 1: Sidharth Annapragada

Milestone 2: Giona Kleinberg

Milestone 3: Demitri Kokoros

Milestone 4: Trevor Giardine

Team Calendar

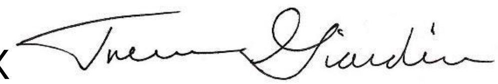
Based upon our schedules, we can meet on Tuesdays after 2:40pm, on Fridays after 11:30pm, weekends, and after 5:00pm on weekdays.

Agreement to Presented Terms

All group members, while evaluating this document individually, accept the presented terms and hereby agree to this contract for Cornerstones of Engineering:

X 

Sidharth Annapragada

X 

Trevor Giardine

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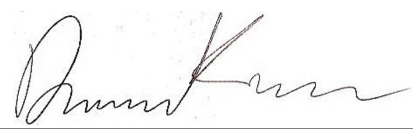
Giona Kleinberg

X 

Demitri Kokoros

APPENDIX B - DESCISION ANALYSES

There were two primary decision analyses that were undertaken during this project: deciding upon the topic and deciding upon the design concept. Specific quantitative details of both will be provided in this appendix.

TOPIC DECISION

Our process for deciding upon the topic of our project was as follows: brainstorm list of themes, rank-order engagement factors, brainstorm list of solutions, perform Kepner-Tregoe decision analysis on top three solutions

List of Themes

Electromagnetism; EDP (Engineering Design Process); Mechanism; Aerodynamics; Gravity; Solar Power/Sustainable Energy; Artificial Intelligence; Robotics; Virtual Reality/ Game Design; Stability/Architecture; Materials; Rockets; Conservation; Bioengineering; Space

Rank-order Analysis of Engagement Factors

	Tactile	Sensory	Competitive	Dynamic	Relevant	Gratification	Creative	Intellectual	Total
Tactile	-	1	1	1	1	1	1	1	**7**
Sensory	0	-	0	0	1	1	0	1	**3**
Competitive	0	1	-	1	1	1	.5	1	**5.5**
Dynamic	0	1	0	-	1	1	0	1	**4**
“Relevant”	0	0	0	0	-	0	0	0	**0**
Gratification	0	0	0	0	1	-	0	0	**1**
Creative	0	1	.5	1	1	1	-	1	**5.5**
Intellectual	0	0	0	0	1	1	0	-	**2**

Table 2. Rank-Order Analysis of Engagement Factors to determine what design aspects to prioritize.

List of Solutions

Electromagnetic trains/racing; Space elevator simulator; **Wind turbines**; Hovercrafts; **Earthquake simulator**; Battlebots; Levitating weights; Snapchat filters; Aerodynamics tube; Material strength; AI-Based engineer; Catapult; Drone; Build a robot; Water filter; **Ramp cars**; Build your own telescope; Balloon cars – Note that ramp cars and electromagnetic racer cars were combined into a singular idea.

Kepner-Tregoe Decision Analysis

	Musts	Racers	Turbine	Quaker
	Educational	GO	GO	GO
	Portable	-ISH	GO	GO
	Safe	GO	GO	GO
Wants	**Weight**			
Tactile	10	10(100)	10(100)	10(100)
Sensory	6	8(48)	6(36)	9(54)
Competitive	8.5	8(68)	8(68)	6(51)
Dynamic	7	10(70)	10(70)	10(70)
Relevant	3	5(15)	5(15)	4(12)
Gratification	4	7(28	8(32)	8(32)
Creative	8.5	5(42.5)	8(68)	8(68)
Intellectual	5	6(30)	7(35)	6(30)
SCORE		**401.5**	**424**	**417**

Table 3. Decision Analysis to choose our project topic, weighted based on the engagement factors.

Despite Turbines scoring the highest, the decision was made to go with Electromagnetic Racers, as it best fit with team goals, in addition to being relatively close to the other topics.

Design Concept Decision

Our process for deciding upon a design concept simply involved a Rank-Order analysis of design factors, and a Kepner-Tregoe Decision Analysis

Rank-Order Analysis of Design Factors

	Long Track	Sensors	LED Display	Cheap Materials	Custom -izable	Multiple Tracks	Safe	Practical	Time	Goals Met	**Total**
Track Length	-	0	0	1	0	0	0	0	1	1	**3**
Sensors	1	-	1	1	0	1	0	1	1	1	**7**
LED Display	1	1	-	0	0	1	0	0	0	1	**4**
Cheap Materials	0	0	0	-	0	1	0	0	0	1	**2**
Custom -izable	1	1	1	1	-	1	0	0	1	1	**7**
Multiple Tracks	1	0	0	1	0	-	0	1	0	1	**4**
Safe	1	1	1	1	1	1	-	1	1	1	**9**
Practical	1	0	1	1	1	0	0	-	1	1	**6**
Time	0	0	1	1	0	1	0	0	-	1	**4**
Goals Met	0	0	0	0	0	0	0	0	0	-	**0**

Table 4. Rank-order Analysis to determine which design concept features are the most important.

Kepner-Tregoe Decision Analysis

	Musts	Giona's	Demitri's	Sid's	Trevor's
	Track	GO	GO	GO	GO
	Electromagnets	GO	GO	GO	GO
	Cars	GO	GO	GO	GO
Wants	**Weight**				
Track Length	3	4(12)	6(18)	10(30)	8(24)
Sensors	7	0(0)	0(0)	10(80)	9(72)
LED Display	4	10(60)	4(24)	8(48)	7(42)
Cheap Materials	2	8(16)	8(16)	3(6)	5(10)
Customizable	7	10(100)	8(80)	10(100)	9(90)
Multiple Tracks	4	4(16)	0(0)	7(49)	10(70)
Safe	9	10(90)	9(81)	9(81)	9(81)
Practical	6	8(48)	6(36)	5(30)	4(24)
Time	4	10(40)	10(40)	8(32)	9(36)
Goals Met	1	10(10)	10(10)	10(10)	10(10)
SCORE		**392**	**305**	**466**	**459**

Table 5. Decision Analysis to choose which design concept to go with for the initial prototyping.

APPENDIX C - FINAL AUTOCAD/SOLIDWORKS DRAWINGS

This appendix will include drawings and renders for the final exhibit, as well as 3D printed parts. Only drawings of laser cut parts are included. All drawings and renders produced in Solidworks. AutoCAD drawings were not used in the CAD of the final design.

FINAL EXHIBIT: DRAWING

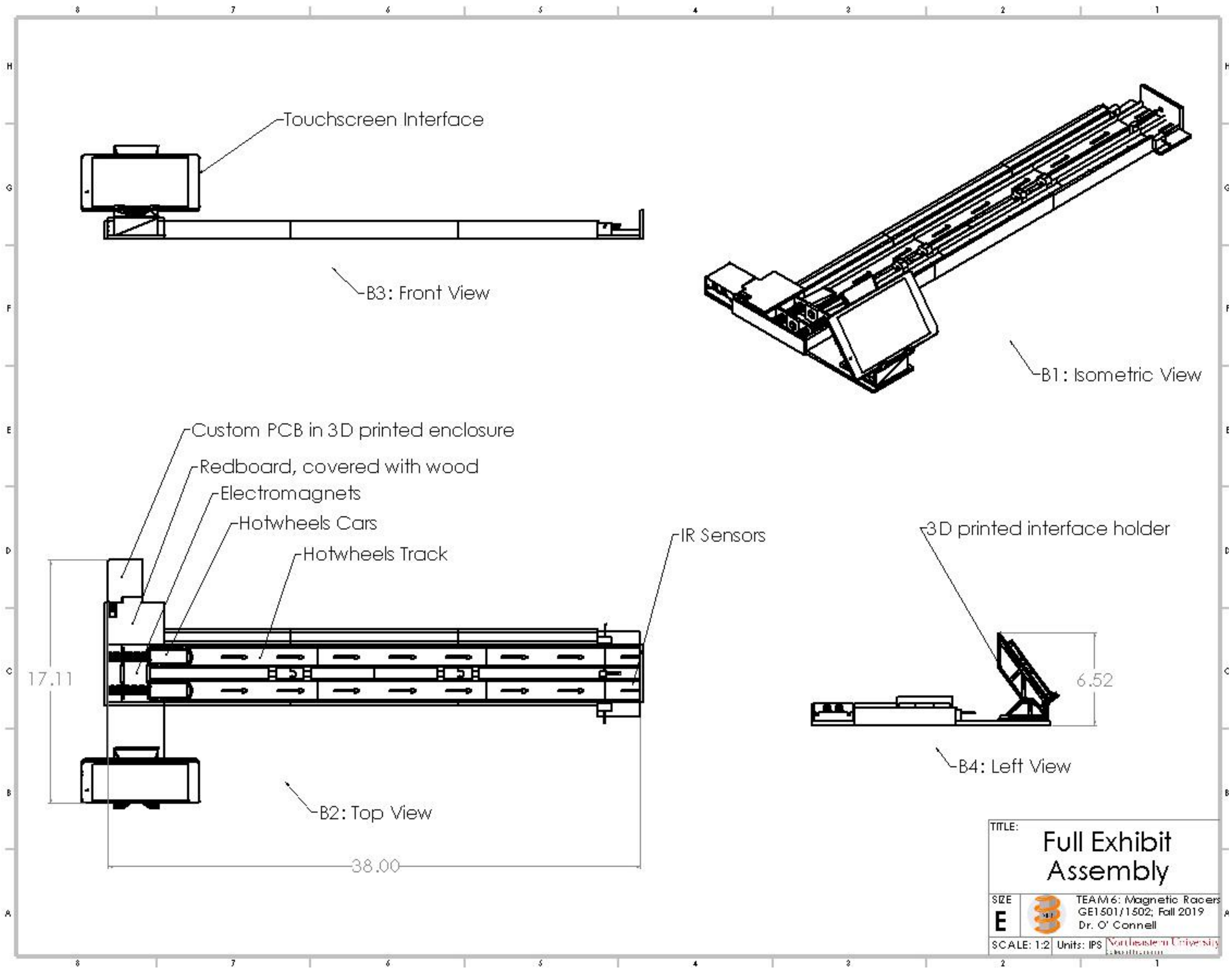


Figure 17. Solidworks drawing containing Isometric, Top, Front, and Left View of what the fully assembled exhibit looks like.

Final Exhibit: Renders

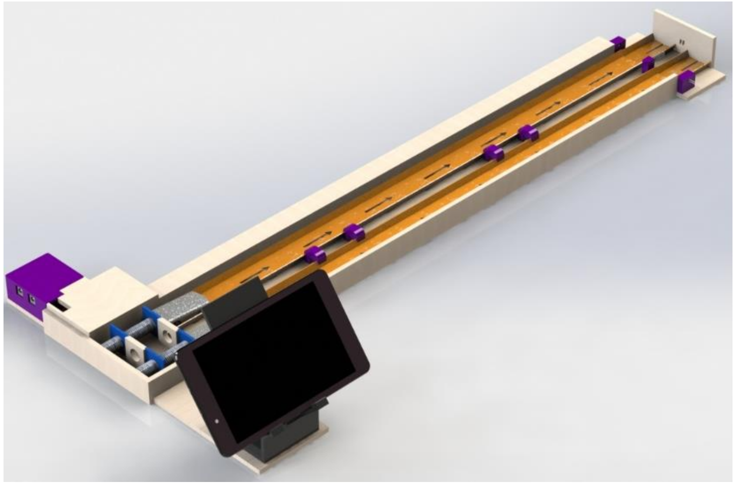


Figure 18. B1: Isometric View, Rendered.

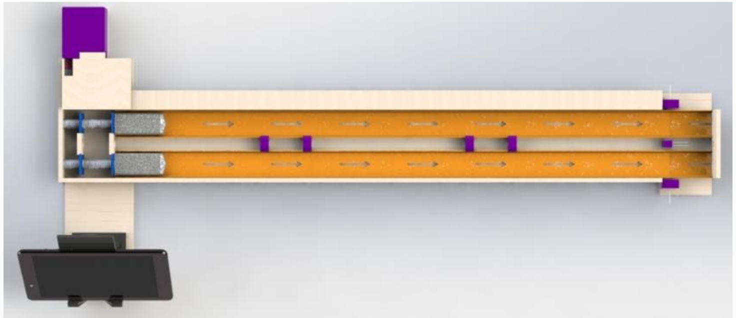


Figure 19. B2: Top View, Rendered.

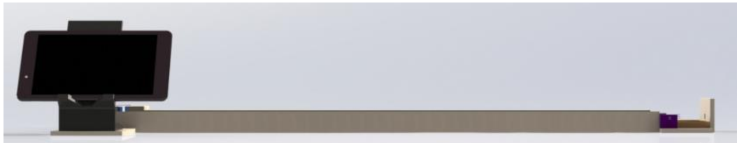


Figure 20. B3: Front View, Rendered.

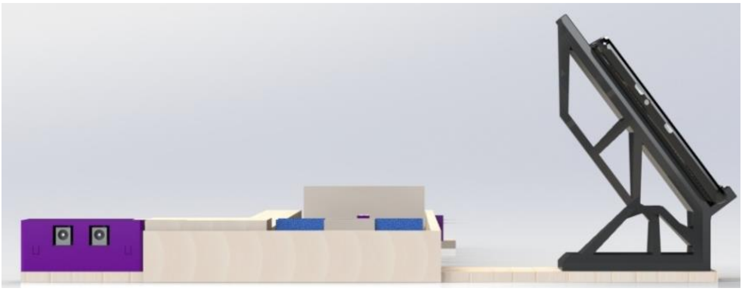


Figure 21. B4: Left View, Rendered.

3D PRINTED PARTS: DRAWINGS

Note: The interface holder was a 3D printed part, but we neither designed nor manufactured it. The part was found and used. Therefore no drawing or render is included of that particular part.

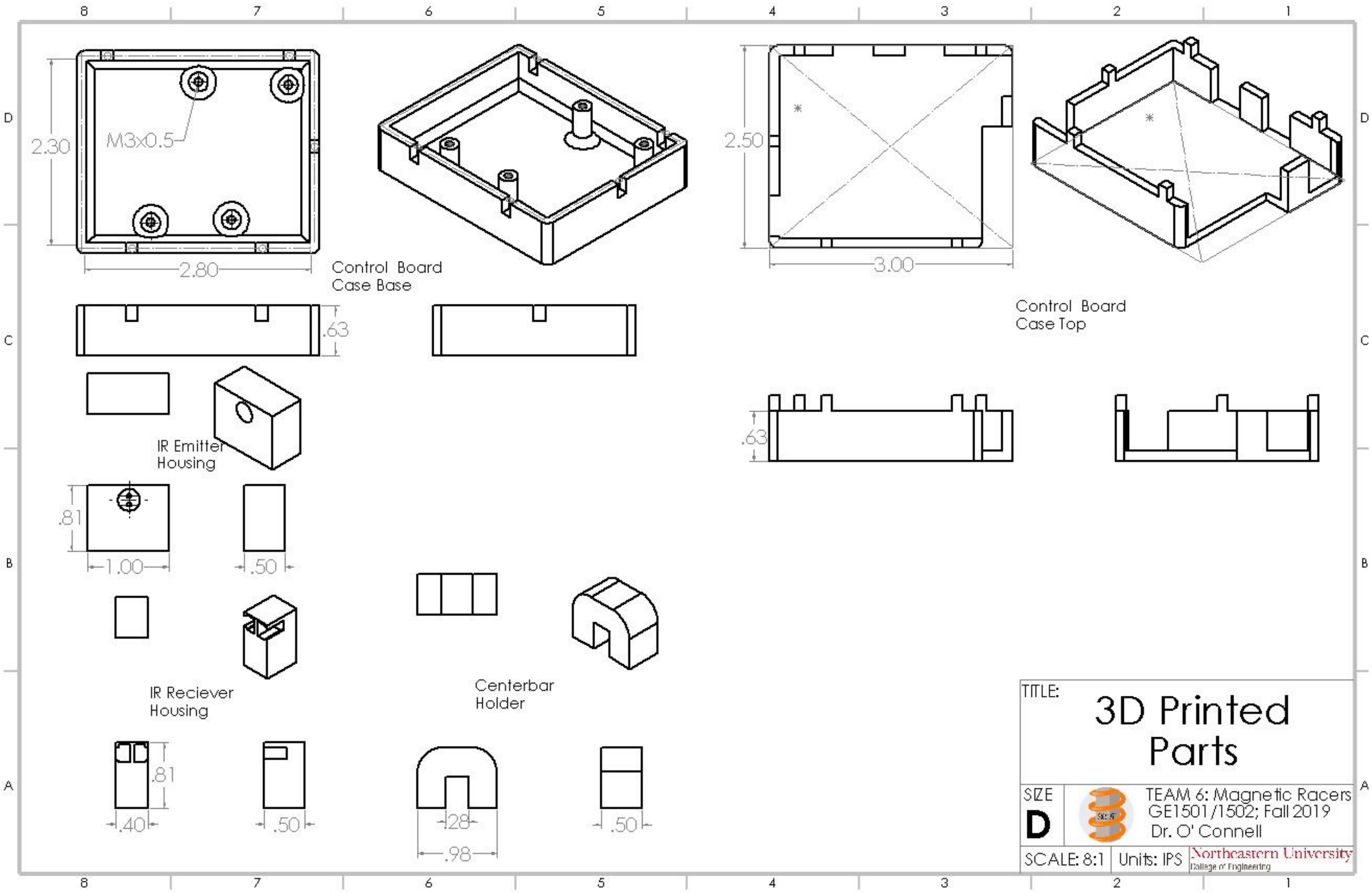


Figure 22. Solidworks drawing of all final 3D printed parts that we manufactured. These are purple in the renders.

3D Printed Parts: Renders

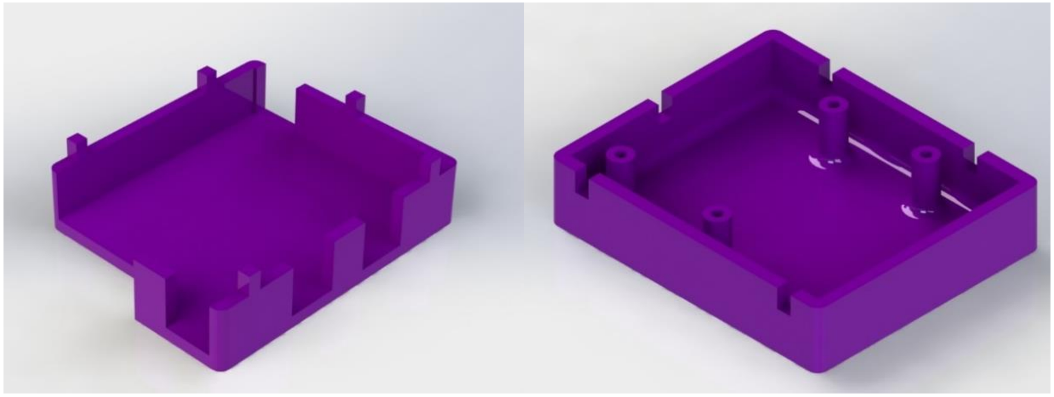


Figure 23. From Left to Right: Control Board Cap, Control Board Plate; Together these enclose the custom PCB.

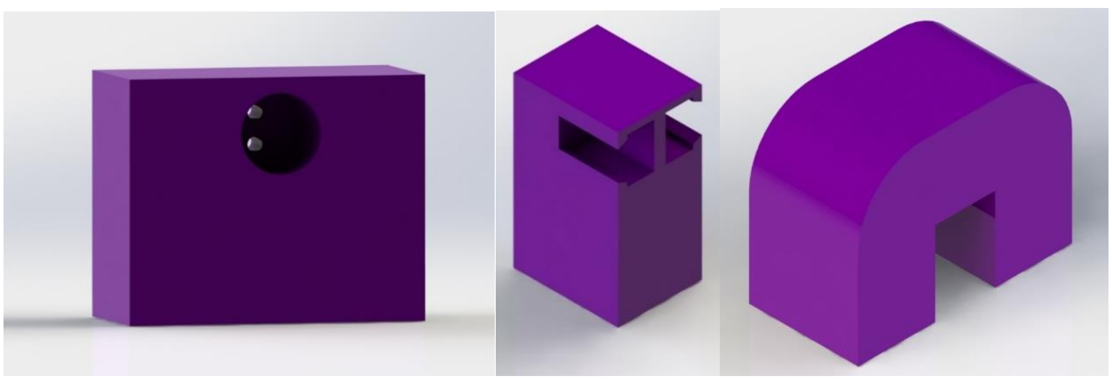


Figure 24. From Left to Right: IR Emitter LED mount, IR Reciever Mount, Centerbar holder.

LASER CUT PARTS: DRAWINGS

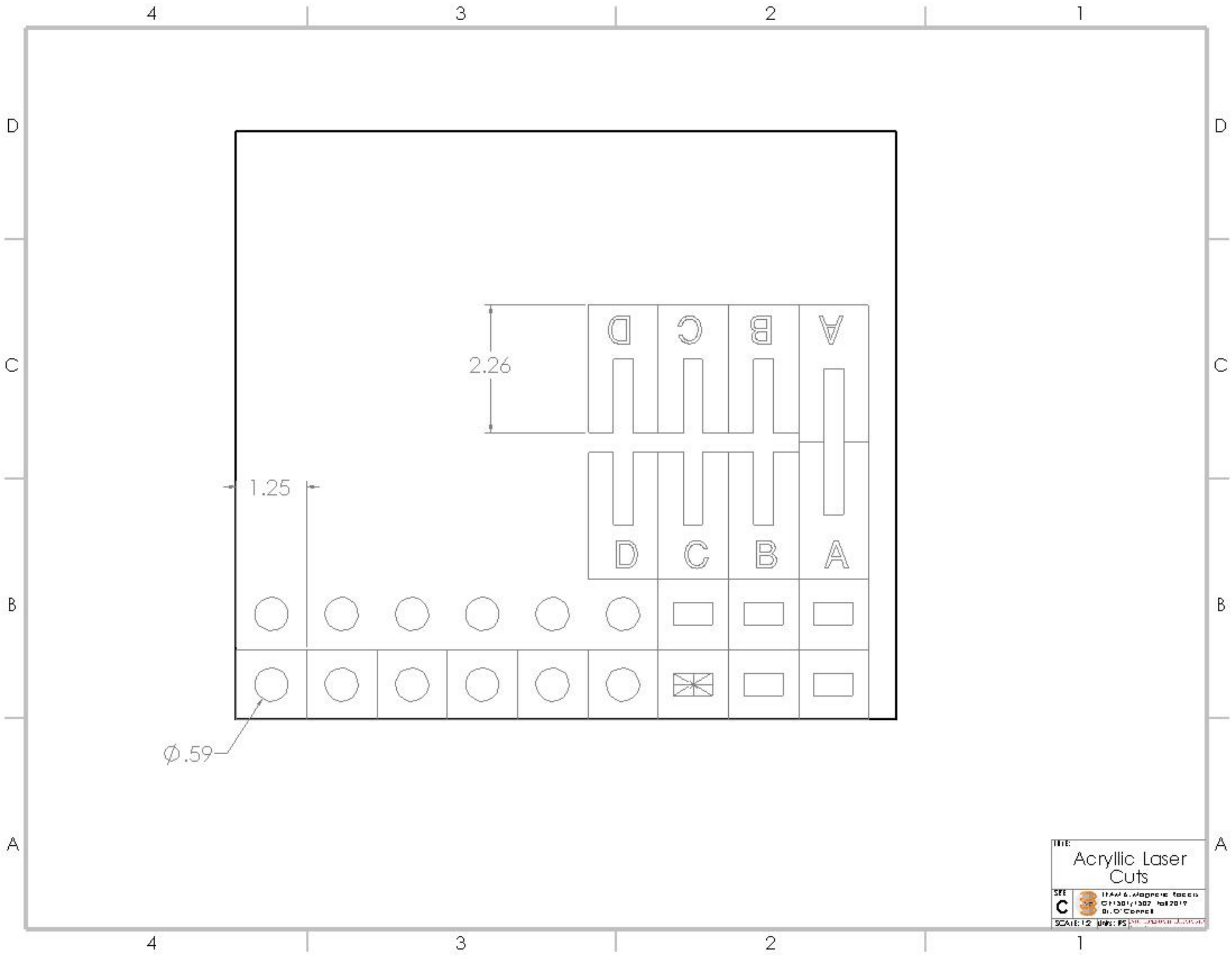


Figure 25. Solidworks drawing of laser cut acrylic pieces: Circular spacers and square caps with circles for the electromagnets. Square caps with rectangles for Coil C (rectangular core). Acrylic “cases”, with labels for the tops of the magnets.

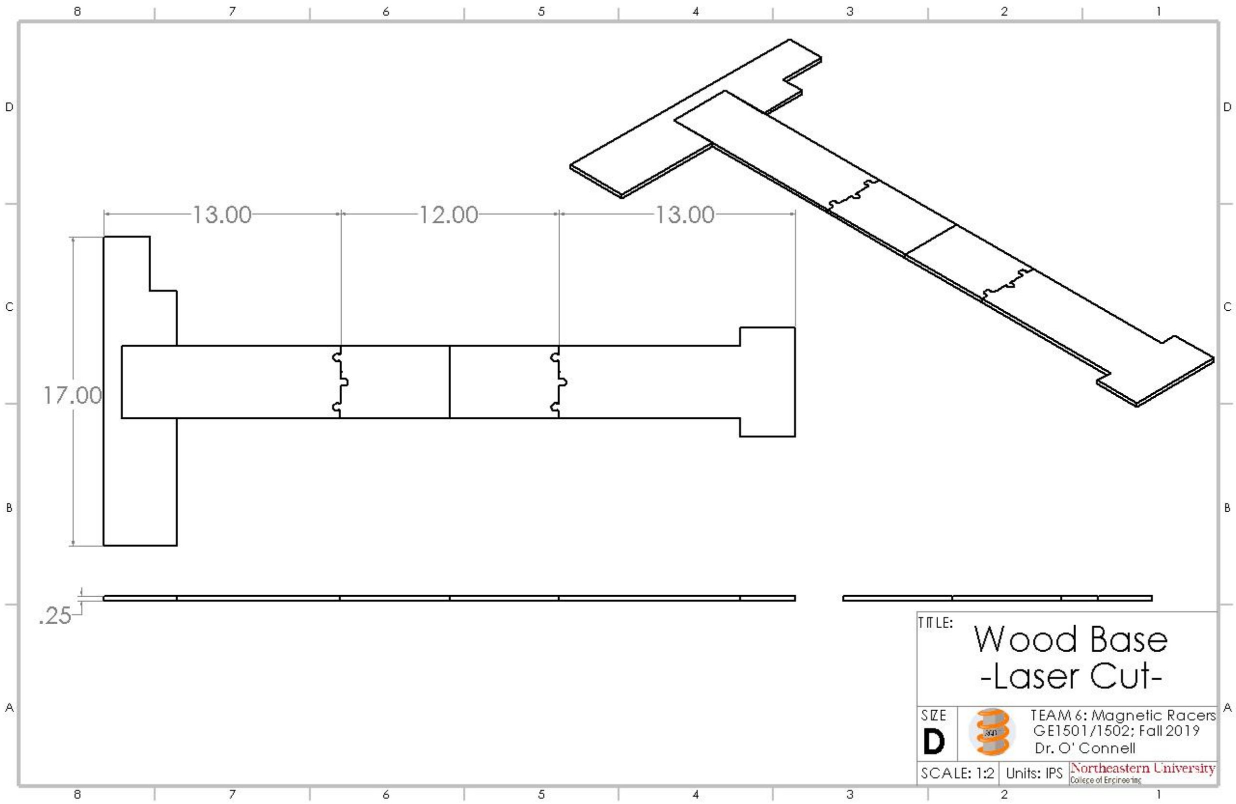


Figure 26. Solidworks drawing of wood laser cuts for base of exhibit. Only outside edge and puzzle piece shape are cut. Internal lines ignored by cutter. This is a three piece cut. Stock was ¼" thick birch wood.

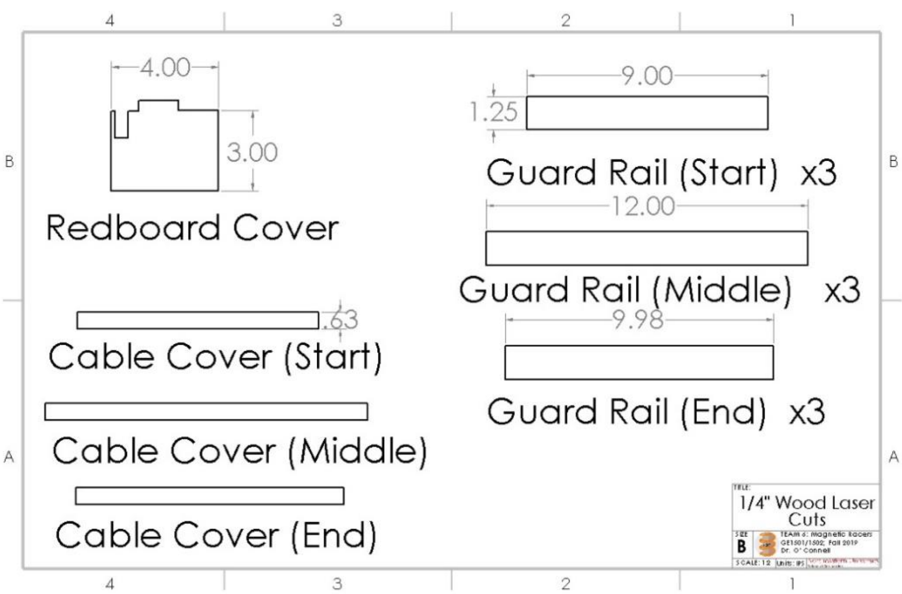


Figure 27. Solidworks drawing of other wooden laser cuts. ¼" birch wood. Includes cable and redboard covers, as well as multiple guardrails.

APPENDIX D – PRODUCT TESTING RESULTS

The prototype went through three primary rounds of testing prior to the final presentation. These included in depth interviews with three external users, an in-class gallery walk with our peers, an open-table test session in a public space, and quantitative consistency evaluations. Details of comments from all three are presented here. Results of these testing sessions can be found directly in the results section.

In-Depth Interviews

The first person that we approached to solicit tester feedback was Cheyenne Candlin. Cheyenne is 17 and a high school friend of Giona. She was interviewed on 11/7/19 at 7:30 pm on the Northeastern Campus in Stetson West. Cheyenne was chosen because we wanted the perspective of someone who is likely to interact with our exhibit at the Gallery Walk.

The second person that gave us feedback was Caroline Zhu. Caroline is 18 and a computer science major. She was interviewed on 11/8/19 at 6:30 pm on the Northeastern Campus in Stetson West. Caroline was selected because we wanted the perspective of a nonengineering major to interact with our exhibit without any prior technical knowledge.

The third person to provide us with feedback was Rex Giardine. Rex is Trevor's father and is a structural engineer and architect. He was interviewed on 11/9/19 at 7:30 pm on the Northeastern Campus in Stetson West. Rex was chosen in order to gain insight from someone established in the engineering field and who is familiar with the design process.

Each person interviewed was allowed to interact independently with our exhibit for as long as they chose (replicating how users will interact with our exhibit in a museum setting). After they interacted with the exhibit, each person was asked the following questions.

1. **What was your initial reaction to the exhibit before interacting with it?**

Cheyenne: It looked a little intimidating because there were wires everywhere. The electromagnets looked like they were going to shock me!

Caroline: I was surprised you guys made this in a class. It looks pretty cool.

Rex: It looks a lot like a freshman engineering project. The electromagnets look a little scrappy but having it function is much more important.

2. **What did you like most about the exhibit?**

Cheyenne: I really liked how the computer controlled the exhibit.

Caroline: Seeing the 3D printed parts was pretty cool.

Rex: I liked that the exhibit focused on clean energy and up-and-coming technology but I didn't really understand the circuitry.

3. **Did you find any part of the exhibit confusing or inaccessible?**

Cheyenne: Positioning the electromagnets was hard since I didn't know how to put them in place.

Caroline: No, it was fine.

Rex: The circuitry was confusing to follow for me.

4. **On a scale of 1 to 10, how would you rate the exhibit's ability to teach about electromagnetism?**

Cheyenne: I would give it a 10 since I didn't know what electromagnets were before this!

Caroline: The exhibit would be about a 5-6. I think you could add more of a description to what electromagnets exactly do.

Rex: 6. I think more information about the electromagnets would benefit the exhibit.

5. **On a scale of 1 to 10, how would you rate the exhibit's ability to hold your attention?**
   Cheyenne: I would give it a 9!

Caroline: 8.

Rex: The exhibit is very active and engaging so I would give it a strong 7.

6. **Was the exhibit fun to interact with?**

Cheyenne: Yes! It was really fun shooting the cars.

Caroline: Yeah, for sure. I think younger kids would enjoy it even more though.

Rex: I could see this exhibit being much more fun if I was younger.

7. What changes would you suggest to improve this exhibit?

Cheyenne: I would suggest hiding the wires, so the exhibit is not so intimidating.

Caroline: Color the cars so they look better. It's a good idea.

Rex: Add more information and focus more on making the exhibit a learning experience.

Gallery-Walk Feedback

The comments from our peers are summarized here:

- Improve Aesthetics
- GUI looks good
- Improve consistency/reliability
- Improve usability/confusing to use
- Improve learning elements

Open-Table Feedback

We set up the exhibit on a table in a public space – Stetson West Lobby – in order to solicit feedback from passerby. Here are the main points we gathered:

- Add pictures to make setup clearer
- Add more instructions to GUI
- Make the GUI a more prominent feature

QUANTITATIVE EVALUATIONS

Notes: 0 - misfire, 0.5 - fire no finish, 1: finish; the 't' designation indicates the duplicate coil; Not all coil permutations were tested, only a general idea of consistency was tested for, and it was assumed that this extrapolates.

11/24/19				
Project 2 Testing Data, Final Round	Coil A, At	Coil B, Bt	Coil A, B	Coil Bt, At
Trial 1	1	1	1	1
Trial 2	1	1	1	1
Trial 3	1	1	1	1
Trial 4	1	1	1	0.5
Trial 5	1	1	1	1
11/20/19				
Project 2 Testing Data, Middle Round	Coil A, At	Coil B, Bt	Coil A, B	Coil Bt, At
Trial 1	1	0	1	0.5
Trial 2	0	0	0	1
Trial 3	0.5	0.5	0	1
Trial 4	1	1	0.5	1
Trial 5	0.5	0.5	1	0
Trial 6	1	0	1	1
Trial 7	0	0.5	1	0
10/23/19				
Project 2 Testing Data	Coil A1, A2			
Trial 1	0			
Trial 2	0.5			
Trial 3	0.5			
Trial 4	1			
Trial 5	0			
Trial 6	0.5			
Trial 7	1			
Trial 8	0			
Trial 9	1			
Trial 10	0.5			

Table 6. Quantitative test data for evaluation of magnet consistency

APPENDIX E – CODE USED IN PROJECT

```
classdef InterfaceUpgrade < matlab.apps.AppBase


    % Properties that correspond to app components
    properties (Access = public)
        EmagUI                 matlab.ui.Figure
        IntroScreen            matlab.ui.container.Panel
        IntroArtboard          matlab.ui.control.Image
        ContinueButton1        matlab.ui.control.Image
        WelcomeScreen          matlab.ui.container.Panel
        WelcomeArtboard        matlab.ui.control.Image
        InstructionsScreen     matlab.ui.container.Panel
        InstructionsArtboard   matlab.ui.control.Image
        BackButton1            matlab.ui.control.Image
        ContinueButton2        matlab.ui.control.Image
        EndScreen              matlab.ui.container.Panel
        EndArtboard            matlab.ui.control.Image
        HomeButton             matlab.ui.control.Image
        CoilScreen             matlab.ui.container.Panel
        CoilArtboard           matlab.ui.control.Image
        BackButton2            matlab.ui.control.Image
        ContinueButton3        matlab.ui.control.Image
        SilverCarScreen        matlab.ui.container.Panel
        CoilS                  matlab.ui.control.Image
        CoilSP                 matlab.ui.control.Image
        NextCoilS              matlab.ui.control.Image
        PrevCoilS              matlab.ui.control.Image
        PurpleCarScreen        matlab.ui.container.Panel
        CoilP                  matlab.ui.control.Image
        CoilPP                 matlab.ui.control.Image5
        NextCoilP              matlab.ui.control.Image
        PrevCoilP              matlab.ui.control.Image
        ResultsScreen          matlab.ui.container.Panel
        ResultsArtboard        matlab.ui.control.Image
        PurpleTime             matlab.ui.control.Label
        SilverTime             matlab.ui.control.Label
        EndButton              matlab.ui.control.Image
        BackButton3            matlab.ui.control.Image
        FillerSpace            matlab.ui.control.Button
        StartButton            matlab.ui.control.Image
        ResetButton            matlab.ui.control.Button
    end


    %%%%% ELECTROMAGNETIC RACERS CODE %%%%%
    %Team 6: Magnetic Racers
```

```
    %GE1501/1502, Fall 2019
    %Dr. O' Connell
    %Northeastern University, College of Engineering

    %%%%% APPLICATION NOTES %%%%%
    %These notes are important to gain a basic understanding of this
    %applications functionality
    %
    %This app is essentially a collection of panels, that are slid into
and
    %out of the UIFigure element that displays on the screen.
    %
    %Each panel contains a background image, as well as images that act as
    %buttons. Occasionally, an actual button or text label is used.
    %
    %Image clicked callbacks are used to grant functionality to the
images.
    %Images were used as opposed to the default matlab components for
    %aesthetic purposes.
    %
    %Images, including the backgrounds for each panel were created in
    % Adobe XD, a free UI prototyping software.
    %
    %For more context to this code,please reference the GUI screenshots in
    %Appendix G. This includes all Adobe XD images.
    %
    %For any questions please contact the author, Sidharth Annapragada, at
    %annapragada.s@husky.neu.edu

    properties (Access = private)

        animTime = 7; % Time to Fully transition screens
        animRefreshRate = 0.03; % Rate at which screen is redrawn
        silverSelector = 1; % Number that designates which silver car coil
is selected on the selector screen
        purpleSelector = 2; % Number that designates which purple car coil
is selected on the selector screen
        maxCoilNumber = 4; % The total number of coils that there are, for
the selector screen logic
        RBrd % Stores the arduino object
        misfires; % stores a count of the misfires
        silverRuns; %counts number of times silver is shot and makes it to
the end
        purpleRuns; %counts number of times purple is shot and makes it to
the end
        silverTimes; % keeps running average of times for the silver car
        purpleTimes; % keeps running average of times for the purple car
    end
```

```
    methods (Access = private)

        %% Both functions here are for the animation of the screen

        function results = leftSlide(app, prevScreen, screen, nextScreen)
%Slides in screen from the right (aka slides the screen left)
            %'screen' is the screen we want in view, prevScreen is the
screen
            %that was in view, and nextScreen is the screen that comes
after
            %'screen' in the sequence
            screen.Position(1) = 2000; % Set screen to just outside of
view
            prevScreen.Position(1) = -2000; %Move current screen out of
view
            nextScreen.Position(1) = 2000; % Move the nextScreen to just
outside of view
            prevScreen.Visible = 'off'; %Turn off screens we don't want
visible
            nextScreen.Visible = 'off';
            screen.Visible = 'on'; %Turn on the screen we want
            tic; %Start timer
            time = 0;
            while (time < app.animTime) %While we are under the timeout
                time = toc;
                speed = abs(screen.Position(1)) / app.animTime; %Calculate
speed: it is a decreasing rate
                screen.Position(1) = screen.Position(1) - speed; % Shift
screen left
                refresh(app.EmagUI); %Redraw UIFigure
                pause(app.animRefreshRate); %Slows down the rendering to
not eat too much processor
            end
            results = 0;
        end

        %This function acts the same as the previous one, but moves the
        %screen in the opposite direction
        function results = rightSlide(app,prevScreen, screen, nextScreen)
            screen.Position(1) = -2000; %Moves screen to left position,
ready to slide right
            prevScreen.Position(1) = 2000; %moves screen that was in
window to the left
            nextScreen.Position(1) = -2000; %moves the next screen in the
left que to the left position
            prevScreen.Visible = 'off';
            nextScreen.Visible = 'off';
```

```
            screen.Visible = 'on';
            tic;
            time = 0;
            while (time < app.animTime)
                time = toc;
                speed = abs(screen.Position(1)) / app.animTime;
                screen.Position(1) = screen.Position(1) + speed; % Shift
screen right
                refresh(app.EmagUI);
                pause(0.03);
            end
            results = 0;
        end
    end



    % Callbacks that handle component events
    methods (Access = private)


        % Code that executes after component creation
        function startupFcn(app)
            %Initialize redboard and visibility here!

            %Turn off extraneous panels, except welcome panel.
            app.EndScreen.Visible = 'off';
            app.IntroScreen.Visible = 'off';
            app.InstructionsScreen.Visible = 'off';
            app.CoilScreen.Visible = 'off';
            app.WelcomeScreen.Visible = 'on';

            com = 'com3'; % defines port
            app.RBrd=arduino(com,'uno'); % defines arduino
            app.RBrd.writeDigitalPin('D3',0); %turns off electromagnet
pin3
            app.RBrd.writeDigitalPin('D4',0); %turns off electromagnet
pin4

        end


        % Image clicked function: WelcomeArtboard
        function WelcomeArtboardImageClicked(app, event)
            %Transition out of welcome screen to introduction screen
            leftSlide(app, app.WelcomeScreen, app.IntroScreen,
app.InstructionsScreen);
            %Initialize some variables for future screens
```

```
            app.silverSelector = 1; %Sets silver to coil A
            app.purpleSelector = 2; %Sets purple to coil B
            app.StartButton.ImageSource = "button_normal.png"; %Sets the
start button to "Start!" image
            time = 0; %Resets car times
            time = sprintf('%1.2fs', time); %Prints 0.0s as the car times
            app.SilverTime.Text=time;
            app.PurpleTime.Text=time;

        end


        % Image clicked function: ContinueButton1
        function ContinueButton1Clicked(app, event)
            %Move from intro to Instructions Screen
            leftSlide(app, app.IntroScreen, app.InstructionsScreen,
app.EndScreen);
        end


        % Image clicked function: ContinueButton2
        function ContinueButton2Clicked(app, event)
            %Move from Instructions to Coil Selector Screen
            leftSlide(app, app.InstructionsScreen, app.CoilScreen,
app.ResultsScreen);
        end


        % Image clicked function: BackButton1
        function BackButton1Clicked(app, event)
            %Move back from Instructions to Intro Screen
            rightSlide(app, app.InstructionsScreen, app.IntroScreen,
app.WelcomeScreen);
        end


        % Image clicked function: ContinueButton3
        function ContinueButton3Clicked(app, event)
            %Move from Coil Selector Screen to Racing/Results Screen'

            %Reinitialize Race Screen Variables to defaults
            app.StartButton.ImageSource = "button_normal.png"; %Set start
button image to "Start!"
            %Reset car times, and print time as 0.0s
            time = 0;
            time = sprintf('%1.2fs', time);
            app.SilverTime.Text=time;
            app.PurpleTime.Text=time;
```

```
            app.StartButton.Enable = 'on'; %Enable start button
            app.RBrd.writeDigitalPin('D3',0); %turns off electromagnet
pin3
            app.RBrd.writeDigitalPin('D4',0); %turns off electromagnet
pin4
            app.ResetButton.Visible = 'off'; %Disable reset button
            app.ResetButton.Enable = 'off';
            leftSlide(app, app.CoilScreen, app.ResultsScreen,
app.EndScreen);
        end


        % Image clicked function: BackButton2
        function BackButton2Clicked(app, event)
            %Move Back from Coil Selector Screen to Instructions Screen
            rightSlide(app, app.CoilScreen, app.InstructionsScreen,
app.IntroScreen);
        end


        % Image clicked function: NextCoilS
        function NextCoilSClicked(app, event)
            %Coil Selector Screen, next silver coil button

            %Logic to update the display for the next coil.
            app.silverSelector = app.silverSelector + 1;

            %Turns off previous coil button if screen is on coil A
            if app.silverSelector > 1
                app.PrevCoilS.Visible = 'on';
            else
                app.PrevCoilS.Visible = 'off';
            end
            %Turns off next coil button if screen is on coil B
            if app.silverSelector == app.maxCoilNumber
                app.NextCoilS.Visible = 'off';
            else
                app.NextCoilS.Visible = 'on';
            end

            %Updates the background for the coil selector and coil based
on
            %the selector value. Background images are named accordingly
            %for this to work
            backgroundPath = sprintf("Carosel%1i.png",
app.silverSelector);
            plaquePath = sprintf("Plaque%1i.jpg", app.silverSelector);
```

```
            app.CoilS.ImageSource = backgroundPath;
            app.CoilSP.ImageSource = plaquePath;
        end


        % Image clicked function: NextCoilP
        function NextCoilPClicked(app, event)
            %Does the same as NextCoilSClicked but for the purple coil.
See
            %Function above (line 210) for comments.
            app.purpleSelector = app.purpleSelector + 1;
            if app.purpleSelector > 1
                app.PrevCoilP.Visible = 'on';
            else
                app.PrevCoilP.Visible = 'off';
            end

            if app.purpleSelector == app.maxCoilNumber
                app.NextCoilP.Visible = 'off';
            else
                app.NextCoilP.Visible = 'on';
            end

            backgroundPath = sprintf("Carosel%1i.png",
app.purpleSelector);
            plaquePath = sprintf("Plaque%1i.jpg", app.purpleSelector);

            app.CoilP.ImageSource = backgroundPath;
            app.CoilPP.ImageSource = plaquePath;
        end


        % Image clicked function: PrevCoilS
        function PrevCoilSClicked(app, event)
            %Does Does the same as NextCoilSClicked but decrements the
selector instead of incrementing it. See
            %Function NextCoilSClicked (line 210) for comments.
            app.silverSelector = app.silverSelector - 1;

            if app.silverSelector > 1
                app.PrevCoilS.Visible = 'on';
            else
                app.PrevCoilS.Visible = 'off';
            end

            if app.silverSelector == app.maxCoilNumber
                app.NextCoilS.Visible = 'off';
            else
```

```
                app.NextCoilS.Visible = 'on';
            end

            backgroundPath = sprintf("Carosel%1i.png",
app.silverSelector);
            plaquePath = sprintf("Plaque%1i.jpg", app.silverSelector);

            app.CoilS.ImageSource = backgroundPath;
            app.CoilSP.ImageSource = plaquePath;
        end


        % Image clicked function: PrevCoilP
        function PrevCoilPClicked(app, event)
            %Does the same as NextCoilSClicked but for the purple coil and
selector is decremented instead of incremented. See
            %Function NextCoilSClicked (line 210) for comments.
            app.purpleSelector = app.purpleSelector - 1;
            if app.purpleSelector > 1
                app.PrevCoilP.Visible = 'on';
            else
                app.PrevCoilP.Visible = 'off';
            end

            if app.purpleSelector == app.maxCoilNumber
                app.NextCoilP.Visible = 'off';
            else
                app.NextCoilP.Visible = 'on';
            end

            backgroundPath = sprintf("Carosel%1i.png",
app.purpleSelector);
            plaquePath = sprintf("Plaque%1i.jpg", app.purpleSelector);

            app.CoilP.ImageSource = backgroundPath;
            app.CoilPP.ImageSource = plaquePath;
        end


        % Image clicked function: BackButton3
        function BackButton3Clicked(app, event)
           %Moves from Race/Results screen to Coil SelectorScreen
            app.RBrd.writeDigitalPin('D3',0); %turns off electromagnet
pin3
            app.RBrd.writeDigitalPin('D4',0); %turns off electromagnet
pin4
            rightSlide(app, app.ResultsScreen, app.CoilScreen,
app.InstructionsScreen);
```

```
        end


        % Image clicked function: EndButton
        function EndButtonClicked(app, event)
        %Moves from Race/Results screen to Conclusions Screen
        leftSlide(app, app.ResultsScreen, app.EndScreen, 
app.WelcomeScreen);
        end


        % Image clicked function: StartButton
        function StartButtonClicked(app, event)
            %This runs the race when the start button is pressed. Arguably
            %the most important function
            app.StartButton.ImageSource = "button_pressed.png"; % Update 
start button image to "Running..."\

            %Turns on first magnet for 30 miliseconds, then turns on the
            %next one. This is because there are cases where turning on
            %both will trip the overcurrent protection in the power supply
            %and require it to be unplugged and then replugged. The issue
            %is discussed in my recommendations section, but suffice it to
            %say that choosing a different power supply would likely fix
            %this issue. A circuit analysis of the new supply would be 
nececary
            %however to be sure.
            app.RBrd.writeDigitalPin('D3',1); %turns on electromagnet pin3
            pause(0.03);
            app.RBrd.writeDigitalPin('D3',0); %turns off electromagnet 
pin3
            app.RBrd.writeDigitalPin('D4',1); %turns on electromagnet pin4
            pause(0.03);
            app.RBrd.writeDigitalPin('D4',0); %turns off electromagnet 
pin4
            %Booleans that store whether the cars have arrived at the end.
            silverIn = false;
            purpleIn = false;
            %Store the times for each car
            silverTime = 0.0;
            purpleTime = 0.0;
            tic; %Start timer
            time = 0;
            while (time < 2.5 && ~(silverIn && purpleIn)) %While the time 
is less than 2.5seconds and cars aren't in; If either goes true, loop 
exits

                time = toc; %Get current time
```

```
                 if readDigitalPin(app.RBrd,'D2') == 1  && ~silverIn %
checks for first breakbeam sensor
                    times= sprintf('%1.2fs', time);
                    silverTime = time; %Records time
                    app.SilverTime.Text=times; % prints time of first car
                    silverIn = true; %Toggles boolean
                end
                if readDigitalPin(app.RBrd,'D5' ) == 1 && ~purpleIn%
checks for second breakbeam sensor
                    times = sprintf('%1.2fs', time);
                    purpleTime = time;
                    app.PurpleTime.Text=times; % prints time of second car
                    purpleIn = true;
                end
            end

            %%%% Datalogging elements for extra credit %%%%
            if ~(silverIn && purpleIn) %Counts misfires. If one of the
cars doesn't reach, it is considered a misfire.
                app.misfires = app.misfires + 1;
            end

            if (silverIn) %Computes running average of silver times
                app.silverRuns = app.silverRuns + 1;
                app.silverTimes = (app.silverTimes +
silverTime)/app.silverRuns;
            end

            if (purpleIn) %Computes running average of purple times
                app.purpleRuns = app.purpleRuns + 1;
                app.purpleTimes = (app.purpleTimes +
purpleTime)/app.purpleRuns;
            end

            app.RBrd.writeDigitalPin('D3',0); %turns off electromagnet
pin3
            app.RBrd.writeDigitalPin('D4',0); %turns off electromagnet
pin4

            app.StartButton.Enable = 'off'; %Disable start button
            app.StartButton.ImageSource = "finished_button.png"; %Set
start button image to "Finished!"

            %turn on reset button
            app.ResetButton.Visible = 'on';
            app.ResetButton.Enable = 'on';
```

```
        end

        % Image clicked function: HomeButton
        function HomeButtonClicked(app, event)
        %Moves from Conclusions/End Screen to Welcome Screen
        leftSlide(app, app.EndScreen, app.WelcomeScreen, app.IntroScreen);
        end

        % Close request function: EmagUI
        function EmagUICloseRequest(app, event)
            delete(app) % Close app if x button is pressed
        end

        % Button pushed function: ResetButton
        function ResetButtonPushed(app, event)
       % Resets race screen for another race.
            app.StartButton.ImageSource = "button_normal.png"; %Set start
button image to "Start!"
            app.StartButton.Enable = 'on'; %Reenable start button
            %Print times as 0.0s
            time = 0;
            time = sprintf('%1.2fs', time);
            app.SilverTime.Text=time;
            app.PurpleTime.Text=time; % prints time of second car
            app.RBrd.writeDigitalPin('D3',0); %turns off electromagnet
pin3
            app.RBrd.writeDigitalPin('D4',0); %turns off electromagnet
pin4
            app.ResetButton.Visible = 'off'; %Turns off reset button
            app.ResetButton.Enable = 'off';
        end
    end

    % Component initialization
    methods (Access = private)

        % Create UIFigure and components
        function createComponents(app)

            % Create EmagUI and hide until all components are created
            app.EmagUI = uifigure('Visible', 'off');
```

```
            app.EmagUI.AutoResizeChildren = 'off';
            app.EmagUI.Position = [0 0 1920 1080];
            app.EmagUI.Name = 'Bullet Cars!';
            app.EmagUI.Resize = 'off';
            app.EmagUI.CloseRequestFcn = createCallbackFcn(app,
@EmagUICloseRequest, true);


            % Create IntroScreen
            app.IntroScreen = uipanel(app.EmagUI);
            app.IntroScreen.Position = [2000 0 1920 1080];


            % Create IntroArtboard
            app.IntroArtboard = uiimage(app.IntroScreen);
            app.IntroArtboard.Position = [1 1 1919 1080];
            app.IntroArtboard.ImageSource = 'Intro Screen.png';


            % Create ContinueButton1
            app.ContinueButton1 = uiimage(app.IntroScreen);
            app.ContinueButton1.ImageClickedFcn = createCallbackFcn(app,
@ContinueButton1Clicked, true);
            app.ContinueButton1.Position = [1823 -2 97 99];
            app.ContinueButton1.ImageSource = 'button_next.png';


            % Create WelcomeScreen
            app.WelcomeScreen = uipanel(app.EmagUI);
            app.WelcomeScreen.AutoResizeChildren = 'off';
            app.WelcomeScreen.Position = [0 0 1920 1080];


            % Create WelcomeArtboard
            app.WelcomeArtboard = uiimage(app.WelcomeScreen);
            app.WelcomeArtboard.ImageClickedFcn = createCallbackFcn(app,
@WelcomeArtboardImageClicked, true);
            app.WelcomeArtboard.Position = [3 1 1916 1080];
            app.WelcomeArtboard.ImageSource = 'Welcome Screen.png';


            % Create InstructionsScreen
            app.InstructionsScreen = uipanel(app.EmagUI);
            app.InstructionsScreen.AutoResizeChildren = 'off';
            app.InstructionsScreen.Position = [4000 0 1920 1080];


            % Create InstructionsArtboard
            app.InstructionsArtboard = uiimage(app.InstructionsScreen);
```

```
            app.InstructionsArtboard.Position = [1 2 1917 1077];
            app.InstructionsArtboard.ImageSource = 'Instructions.png';

            % Create BackButton1
            app.BackButton1 = uiimage(app.InstructionsScreen);
            app.BackButton1.ImageClickedFcn = createCallbackFcn(app,
@BackButton1Clicked, true);
            app.BackButton1.Position = [2 1 97 99];
            app.BackButton1.ImageSource = 'button_previous.png';

            % Create ContinueButton2
            app.ContinueButton2 = uiimage(app.InstructionsScreen);
            app.ContinueButton2.ImageClickedFcn = createCallbackFcn(app,
@ContinueButton2Clicked, true);
            app.ContinueButton2.Position = [1820 1 97 99];
            app.ContinueButton2.ImageSource = 'button_next.png';

            % Create EndScreen
            app.EndScreen = uipanel(app.EmagUI);
            app.EndScreen.AutoResizeChildren = 'off';
            app.EndScreen.Position = [10000 0 1920 1080];

            % Create EndArtboard
            app.EndArtboard = uiimage(app.EndScreen);
            app.EndArtboard.Position = [1 -2 1919 1081];
            app.EndArtboard.ImageSource = 'Conclusions.png';

            % Create HomeButton
            app.HomeButton = uiimage(app.EndScreen);
            app.HomeButton.ImageClickedFcn = createCallbackFcn(app,
@HomeButtonClicked, true);
            app.HomeButton.Position = [747 41 411 300];
            app.HomeButton.ImageSource = 'HomeButton.png';

            % Create CoilScreen
            app.CoilScreen = uipanel(app.EmagUI);
            app.CoilScreen.AutoResizeChildren = 'off';
            app.CoilScreen.Position = [6000 0 1920 1080];

            % Create CoilArtboard
            app.CoilArtboard = uiimage(app.CoilScreen);
            app.CoilArtboard.Position = [1 2 1919 1077];
```

```
            app.CoilArtboard.ImageSource = 'Coil Picker.png';

            % Create BackButton2
            app.BackButton2 = uiimage(app.CoilScreen);
            app.BackButton2.ImageClickedFcn = createCallbackFcn(app,
@BackButton2Clicked, true);
            app.BackButton2.Position = [1 1 100 100];
            app.BackButton2.ImageSource = 'button_previous.png';

            % Create ContinueButton3
            app.ContinueButton3 = uiimage(app.CoilScreen);
            app.ContinueButton3.ImageClickedFcn = createCallbackFcn(app,
@ContinueButton3Clicked, true);
            app.ContinueButton3.Position = [1819 1 100 100];
            app.ContinueButton3.ImageSource = 'button_next.png';

            % Create SilverCarScreen
            app.SilverCarScreen = uipanel(app.CoilScreen);
            app.SilverCarScreen.AutoResizeChildren = 'off';
            app.SilverCarScreen.Position = [251 155 528 715];

            % Create CoilS
            app.CoilS = uiimage(app.SilverCarScreen);
            app.CoilS.ScaleMethod = 'stretch';
            app.CoilS.Position = [1 0 529 715];
            app.CoilS.ImageSource = 'Carosel1.png';

            % Create CoilSP
            app.CoilSP = uiimage(app.SilverCarScreen);
            app.CoilSP.Position = [1 157 529 455];
            app.CoilSP.ImageSource = 'Plaque1.jpg';

            % Create NextCoilS
            app.NextCoilS = uiimage(app.SilverCarScreen);
            app.NextCoilS.ImageClickedFcn = createCallbackFcn(app,
@NextCoilSClicked, true);
            app.NextCoilS.Position = [447 22 83 82];
            app.NextCoilS.ImageSource = 'Path 294.png';

            % Create PrevCoilS
            app.PrevCoilS = uiimage(app.SilverCarScreen);
```

```
            app.PrevCoilS.ImageClickedFcn = createCallbackFcn(app,
@PrevCoilSClicked, true);
            app.PrevCoilS.Visible = 'off';
            app.PrevCoilS.Position = [15 15 82 83];
            app.PrevCoilS.ImageSource = 'Path 296.png';


            % Create PurpleCarScreen
            app.PurpleCarScreen = uipanel(app.CoilScreen);
            app.PurpleCarScreen.AutoResizeChildren = 'off';
            app.PurpleCarScreen.Position = [1175 155 528 715];


            % Create CoilP
            app.CoilP = uiimage(app.PurpleCarScreen);
            app.CoilP.Position = [1 0 529 720];
            app.CoilP.ImageSource = 'Carosel1.png';


            % Create CoilPP
            app.CoilPP = uiimage(app.PurpleCarScreen);
            app.CoilPP.Position = [1 175 529 385];
            app.CoilPP.ImageSource = 'Plaque1.jpg';


            % Create NextCoilP
            app.NextCoilP = uiimage(app.PurpleCarScreen);
            app.NextCoilP.ImageClickedFcn = createCallbackFcn(app,
@NextCoilPClicked, true);
            app.NextCoilP.Position = [437 16 83 82];
            app.NextCoilP.ImageSource = 'Path 294.png';


            % Create PrevCoilP
            app.PrevCoilP = uiimage(app.PurpleCarScreen);
            app.PrevCoilP.ImageClickedFcn = createCallbackFcn(app,
@PrevCoilPClicked, true);
            app.PrevCoilP.Visible = 'off';
            app.PrevCoilP.Position = [13 16 83 82];
            app.PrevCoilP.ImageSource = 'Path 296.png';


            % Create ResultsScreen
            app.ResultsScreen = uipanel(app.EmagUI);
            app.ResultsScreen.AutoResizeChildren = 'off';
            app.ResultsScreen.Position = [8000 0 1920 1080];


            % Create ResultsArtboard
```

```
            app.ResultsArtboard = uiimage(app.ResultsScreen);
            app.ResultsArtboard.Position = [1 -6 1913 1081];
            app.ResultsArtboard.ImageSource = 'Race.png';


            % Create PurpleTime
            app.PurpleTime = uilabel(app.ResultsScreen);
            app.PurpleTime.HorizontalAlignment = 'center';
            app.PurpleTime.FontName = 'SansSerif';
            app.PurpleTime.FontSize = 50;
            app.PurpleTime.FontColor = [0.302 0.2863 0.6196];
            app.PurpleTime.Position = [1102 131 347 200];
            app.PurpleTime.Text = {'0.00s'; ''};


            % Create SilverTime
            app.SilverTime = uilabel(app.ResultsScreen);
            app.SilverTime.HorizontalAlignment = 'center';
            app.SilverTime.FontName = 'SansSerif';
            app.SilverTime.FontSize = 50;
            app.SilverTime.FontColor = [0.302 0.2863 0.6196];
            app.SilverTime.Position = [483 131 347 200];
            app.SilverTime.Text = {'0.00s'; ''};


            % Create EndButton
            app.EndButton = uiimage(app.ResultsScreen);
            app.EndButton.ImageClickedFcn = createCallbackFcn(app,
@EndButtonClicked, true);
            app.EndButton.Position = [1742 -24 178 141];
            app.EndButton.ImageSource = 'EndButton.png';


            % Create BackButton3
            app.BackButton3 = uiimage(app.ResultsScreen);
            app.BackButton3.ImageClickedFcn = createCallbackFcn(app,
@BackButton3Clicked, true);
            app.BackButton3.Position = [1 -3 100 100];
            app.BackButton3.ImageSource = 'button_previous.png';


            % Create FillerSpace
            app.FillerSpace = uibutton(app.ResultsScreen, 'push');
            app.FillerSpace.BackgroundColor = [1 1 1];
            app.FillerSpace.FontColor = [1 1 1];
            app.FillerSpace.Position = [801 341 317 174];
            app.FillerSpace.Text = '';
```

```
            % Create StartButton
            app.StartButton = uiimage(app.ResultsScreen);
            app.StartButton.ImageClickedFcn = createCallbackFcn(app,
@StartButtonClicked, true);
            app.StartButton.BusyAction = 'cancel';
            app.StartButton.Interruptible = 'off';
            app.StartButton.BackgroundColor = [0.0863 0.098 0.2392];
            app.StartButton.Position = [800 341 319 175];
            app.StartButton.ImageSource = 'button_normal.png';


            % Create ResetButton
            app.ResetButton = uibutton(app.ResultsScreen, 'push');
            app.ResetButton.ButtonPushedFcn = createCallbackFcn(app,
@ResetButtonPushed, true);
            app.ResetButton.IconAlignment = 'center';
            app.ResetButton.BackgroundColor = [0.2392 0.2941 0.451];
            app.ResetButton.FontName = 'SansSerif';
            app.ResetButton.FontSize = 30;
            app.ResetButton.FontColor = [1 1 1];
            app.ResetButton.Enable = 'off';
            app.ResetButton.Visible = 'off';
            app.ResetButton.Position = [907 116 100 46];
            app.ResetButton.Text = {'Reset'; ''};


            % Show the figure after all components are created
            app.EmagUI.Visible = 'on';
        end
    end


    % App creation and deletion
    methods (Access = public)


        % Construct app
        function app = InterfaceUpgrade


            % Create UIFigure and components
            createComponents(app)


            % Register the app with App Designer
            registerApp(app, app.EmagUI)


            % Execute the startup function
```

```
            runStartupFcn(app, @startupFcn)

            if nargout == 0
                clear app
            end
        end

        % Code that executes before app deletion
        function delete(app)

            % Delete UIFigure when app is deleted
            delete(app.EmagUI)
        end
    end
end
```

APPENDIX F – WIRE DIAGRAMS

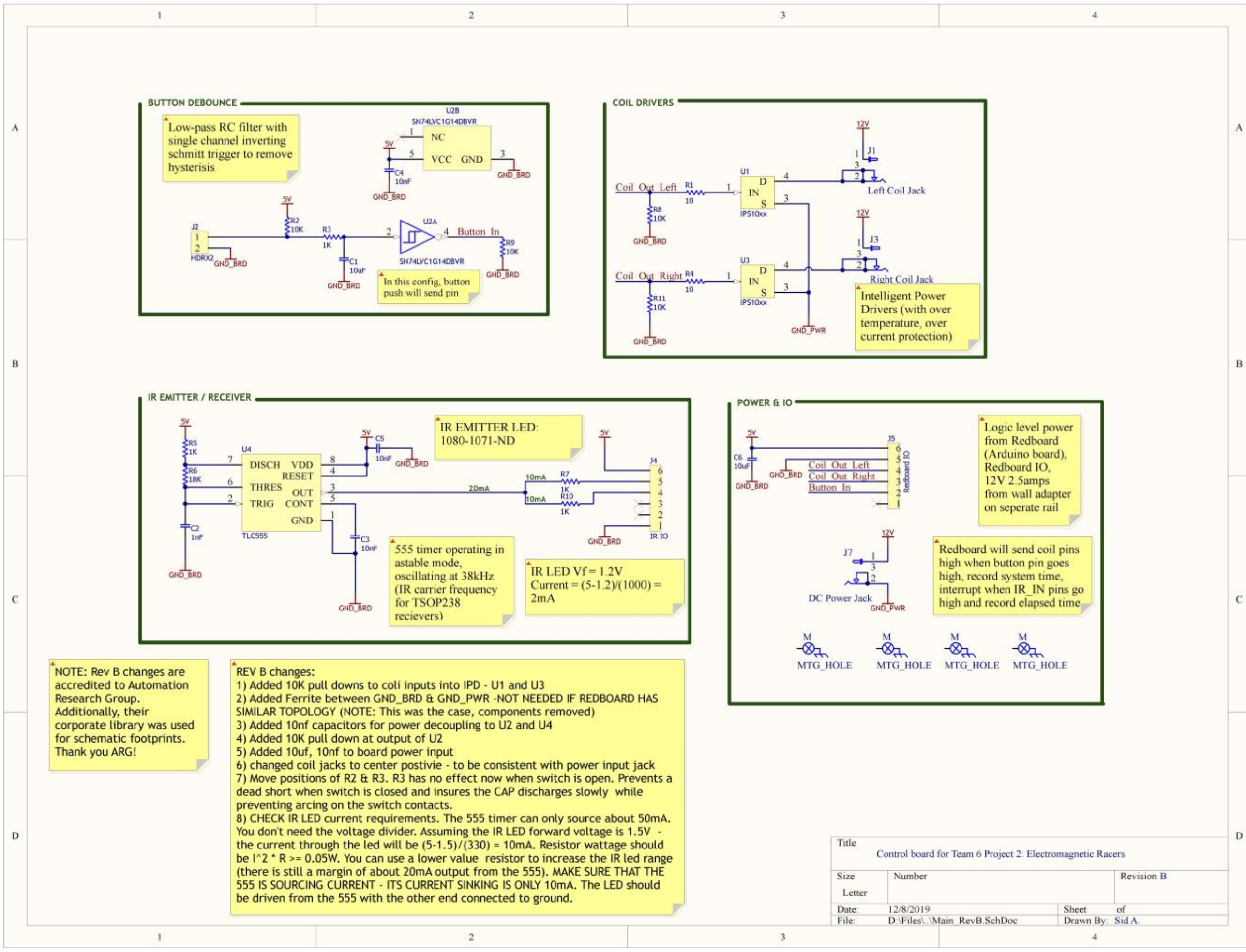


Figure 28. Schematic for Control Board. Design created in Altium Designer, under a student license.

Please note that some part numbers and other details are non-obvious from this depiction. If you would like the schematic files, or have any questions, please contact Sidharth Annapragada, at annapragada.s@husky.neu.edu. Contact information also listed in Appendix A.

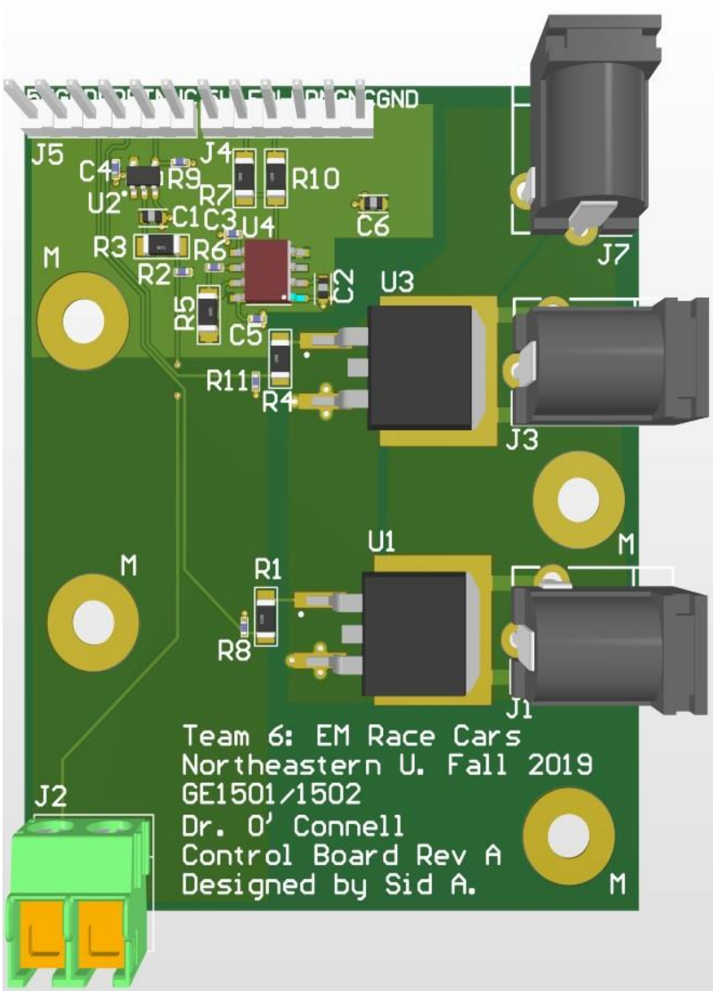


Figure 29. 3D view of Control Board Layout in Altium.

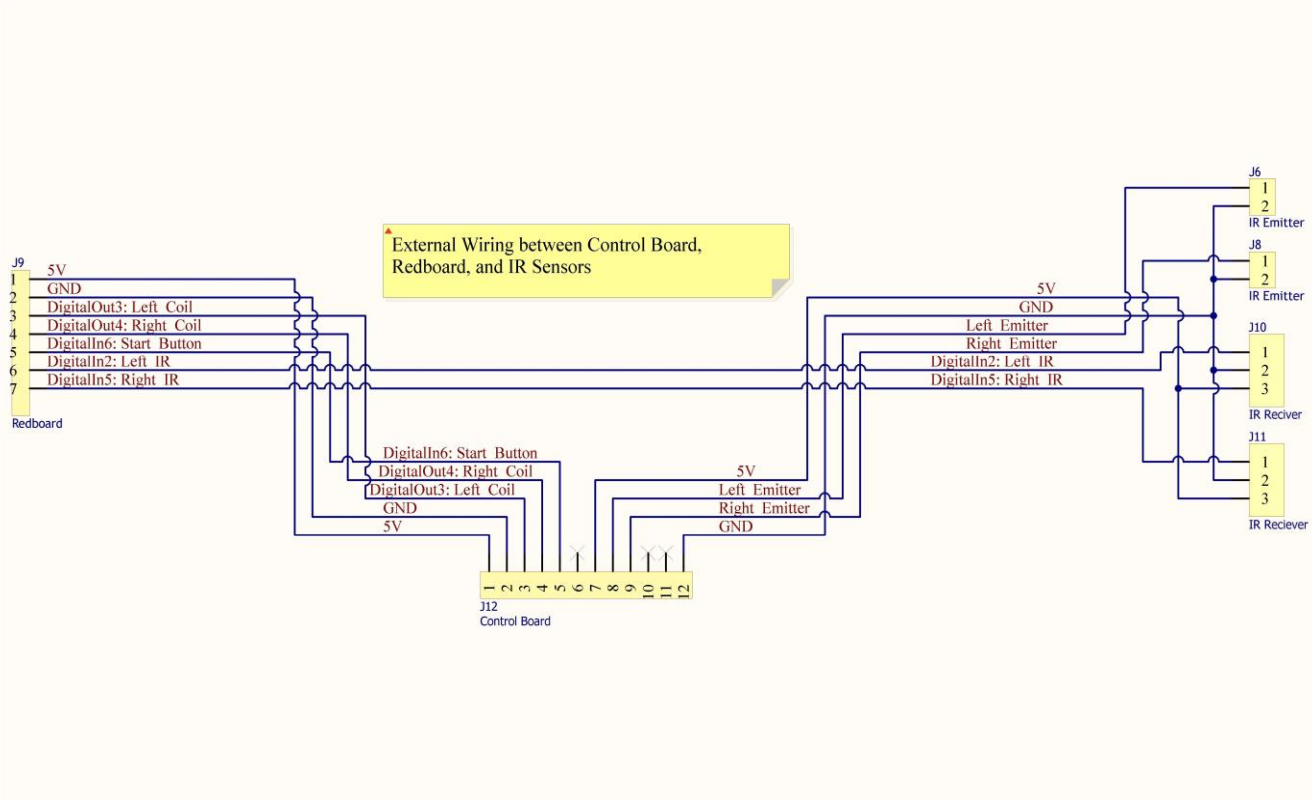


Figure 30. Off board Wiring diagram. Shows connections between Custom PCB, Redboard, and IR Sensors.

APPENDIX G – PHOTO LOG

This appendix will include pictures from each milestone of the project, photographs of the final version of the prototype, and screenshots from the initial and final graphical user interface.

PROTOTYPE PICTURES

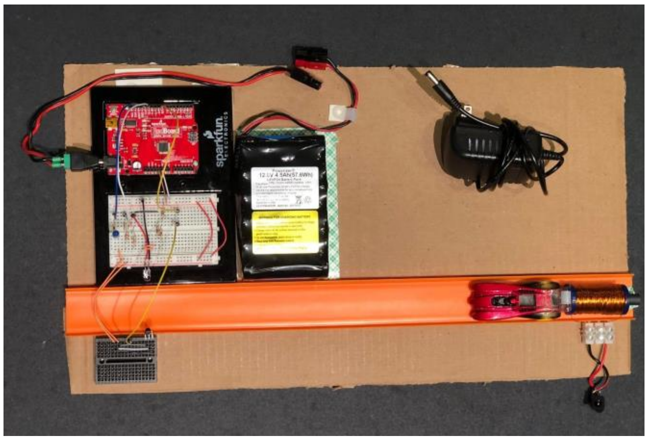


Figure 31. Picture of carboard prototype from Milestone 3.

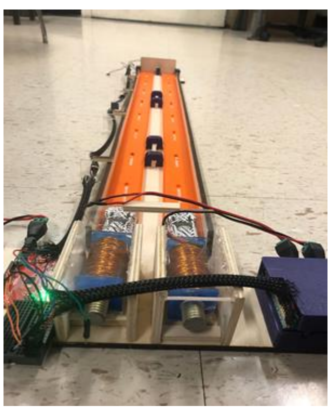


Figure 33. Picture of 50% complete prototype from Milestone 4.

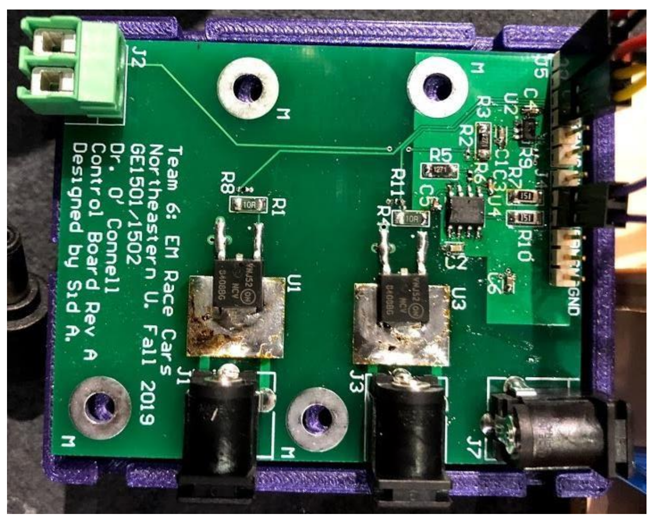


Figure 32. Picture of Custom PCB added in Milestone 4.

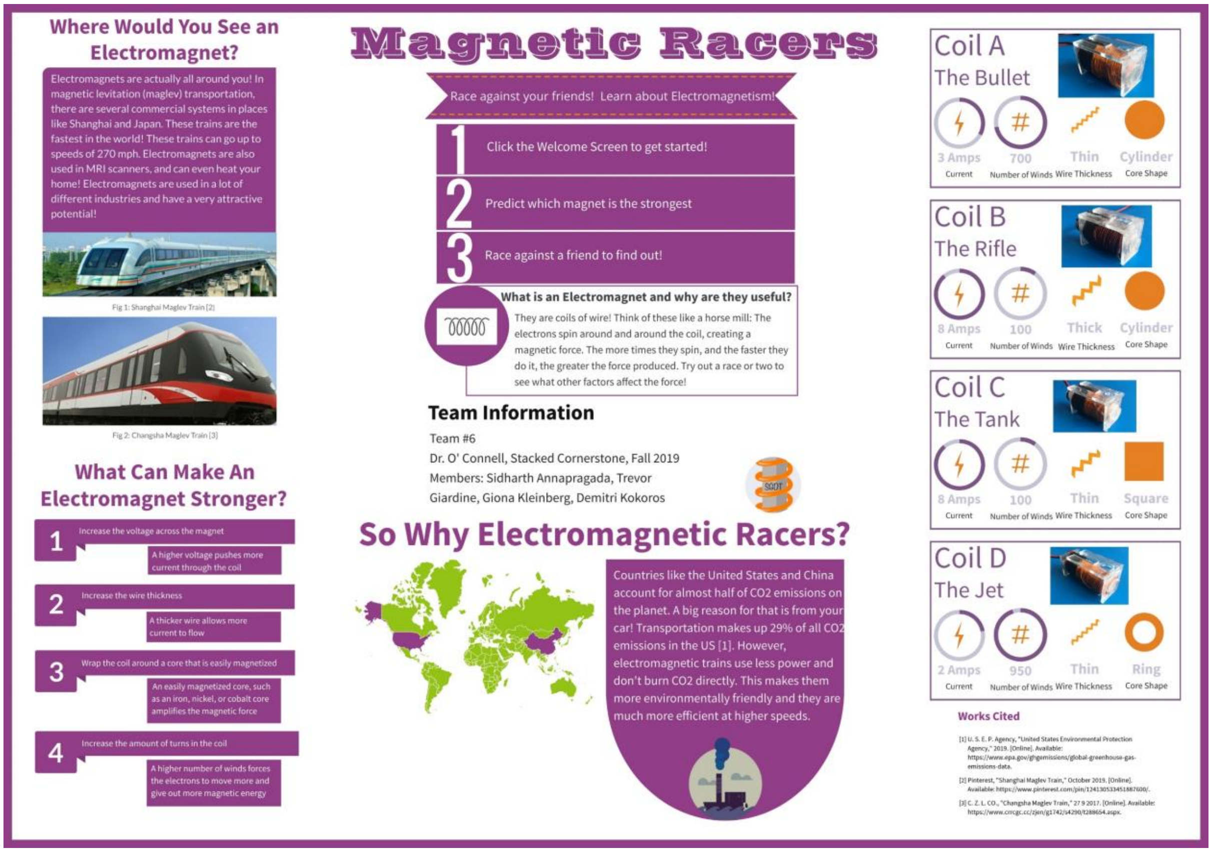


Figure 35. Poster for Exhibit from Milestone 7

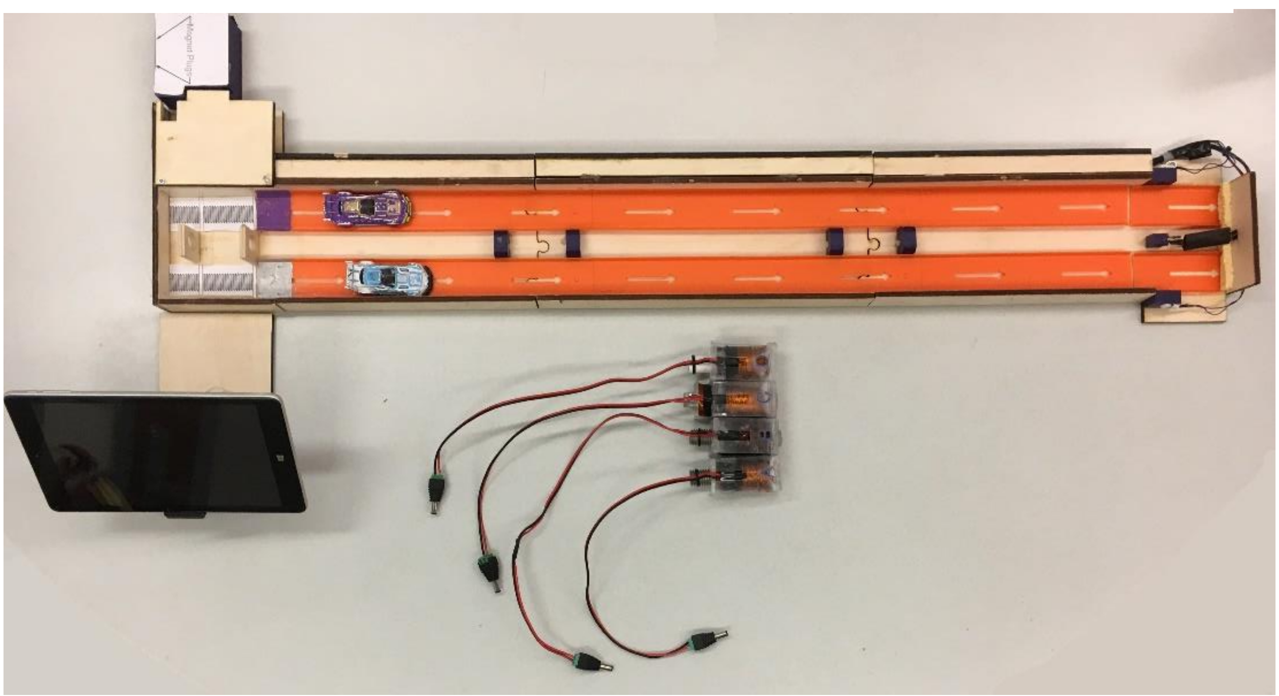


Figure 34. Picture of our final prototype from Milestone 7.

GUI SCREENSHOTS: PROOF OF CONCEPT

Figure 36. Screenshots of part of our Initial GUI prototype. Top Left: Coil Selection Screen; Top Right: Instructions Screen; Bottom: Race Screen

GUI Screenshots: Final Version

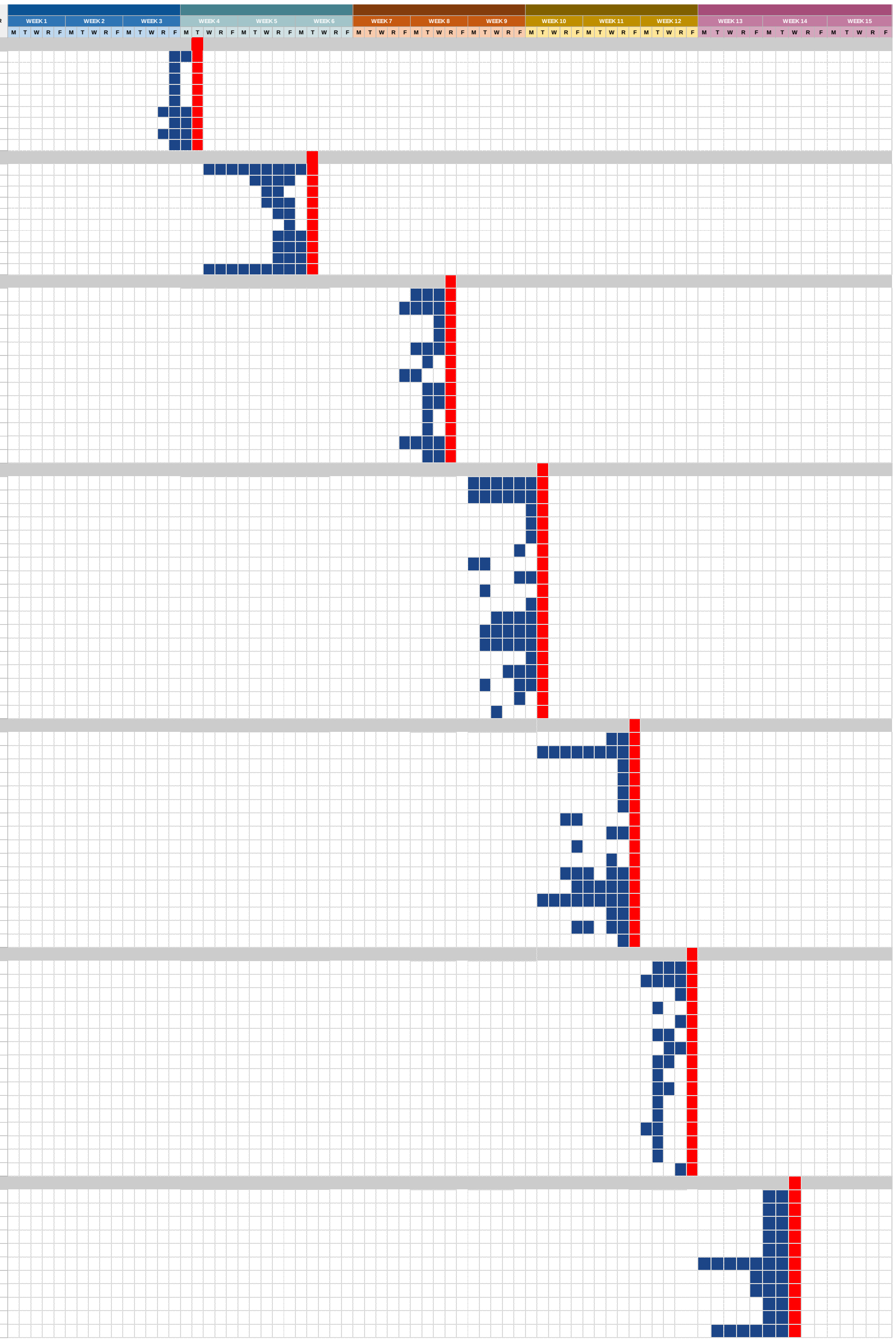
Figure 37. Final version of the GUI from Milestone 5. Graphics wre upgraded and animations added. From Left to Right, Top to Bottom: Welcome Screen, Information Screen, Instructions Screen, Coil Selection Screen, Race Screen Start, Race Screen Finished, Conclusions Screen. User interaction flows in same order.

APPENDIX H – FINAL GANNT CHART

Major Design Project: Gantt Chart

PROJECT TITLE	Major Design **Class**	GE 1501/1502: Cornerstone of Engineering	Due Date = RED
PROJECT MANAGER	Denoted next to each Milest **DATE**	12/11/19	

WBS NUMBER	TASK TITLE	TASK OWNER
1	**Milestone 1**	
1.1	Design Notebook	All
1.2	Brainstorm	All
1.3	Answer Questions to Narrow Down	All
1.4	Decide on Project	All
1.5	Revise Problem Statement	All
1.6	Create and Update Gantt Chart	Giona K.
1.7	User Research	Trevor G.
1.8	Project Manager	Sid A.
1.9	Client Research	Demitri K.
2	**Milestone 2**	
2.1	Design Notebook	All
2.2	Individual Research	All
2.3	Concept Image	All
2.4	Concept Drawing	All
2.5	Project Paragraph	All
2.6	Meet with Mentor	All
2.7	Update Gantt Chart	Trevor G.
2.8	Create AutoCAD Drawing	Sid A.
2.9	Update Problem Statement	Demitri K.
2.10	Project Manager	Giona K.
3	**Milestone 3**	
3.1	Project Manager	Demitri K.
3.2	Design Notebook	Demitri K.
3.3	Update Gantt Chart	Giona K.
3.4	Hours Sheet	Giona K.
3.5	Image Log	Giona K.
3.6	Flowchart	Giona K.
3.7	Universal Design Paragraph	Sid A.
3.8	Budget/Bill of Materials	Trevor G.
3.9	AutoCAD Sketch	Trevor G.
3.10	Electronics	Sid A.
3.11	Testing	Sid A.
3.12	Construction	Sid A.
3.13	Solidworks Sketch	Trevor G.
4	**Milestone 4**	
4.1	Project Manager	Trevor G.
4.2	Design Notebook	Trevor G.
4.3	Update Gantt Chart	Giona K.
4.4	Hours Sheet	Trevor G.
4.5	Image Log	Giona K.
4.6	Feedback Plan	Giona K.
4.7	Wire Diagram	Sid A.
4.8	Budget/Bill of Materials	Demitri K.
4.9	AutoCAD Sketch	Demitri K.
4.1	Summary of Changes	Giona K.
4.11	Creation of GUI	Giona K.
4.12	Construction of Electromagnets	Sid A.
4.13	General Construction	Sid A., Trevor G., Demitri K.
4.14	Demo UI and Sparkfun Code	Giona K.
4.15	Put together circuitry	Sid A.
4.16	Create circuitboard for electromagnets	Sid A.
4.17	Solidworks Sketch of part connectors	Giona K.
4.18	Solidworks Sketch of magnet holders	Demitri K.
5	**Milestone 5**	
5.1	Write-Up	Demitri K.
5.2	Design Notebook	All
5.3	Update Gantt Chart	Giona K.
5.4	Hours Sheet	Trevor G.
5.5	Image Log	Giona K.
5.6	Mentor Email	Giona K.
5.7	Wire Diagram	Sid A.
5.8	Budget/Bill of Materials	Trevor G.
5.9	AutoCAD Sketch	Demitri K.
5.10	Abstract	Demitri K.
5.11	GUI Improvement	Sid A.
5.12	Construction of Electromagnets	Sid A.
5.13	General Construction	All
5.14	Demo UI and Sparkfun Code	Sid A.
5.15	Put together circuitry	Sid A.
5.16	Rapid Prototype Object Description	Sid A.
6	**Milestone 6**	
6.1	Write-Up	All
6.2	Design Notebook	All
6.3	Update Gantt Chart	Giona K.
6.4	Winding New Electomagnets	Giona K.
6.5	Bill of Materials	Trevor G.
6.6	Troubleshooting Wiring	Sid A.
6.7	Working on Poster	All
6.8	Adding Hyperloop	Trevor G.
6.9	Wire Barrier	Demitri K.
6.1	Wiring New Electromagnets	Sid A.
6.11	Painted Cars	Demitri K.
6.12	Added Break System	Trevor G.
6.13	Cleaned up GUI	Sid A.
6.14	Moved sensors back	Sid A.
6.15	Moved PCB to back of exhibit	Giona K.
6.16	Hours Sheet	Giona K.
7	**Milestone 7**	
7.1	Exhibit Description Paragraph	Demitri K.
7.2	Primary Functional elements parg.	Giona K.
7.3	Educational elements parg.	Giona K.
7.4	Transportability parg.	Demitri K.
7.5	Photolog	Trevor G.
7.6	Finish electromagnet building	Sid A.
7.7	Finish poster	Trevor G.
7.8	Finish GUI	Sid A.
7.9	Get Interface working	Sid A.
7.1	Mount interface	Trevor G.
7.11	Finish Testing	Sid A., Trevor G.



APPENDIX I – FINAL BUDGET

Type of Item	Item	Qty.	Value (each)	Cost	Description	Source	Added in
Base	Birch 12”x16”, 1/4”	2	$3.98	$7.96	Wood used to make the base of the prototype and to mount all tracks and components.	Purchased from the bookstore.	Milestone 4
	Acrylic 12”x16”, 1/8”	1	$4.98	$4.98	Used to make some of the magnet casings and potentially to make the actual car protectors (electromagnets can be dangerous).	Purchased from the bookstore	Milestone 5
Sparkfun	Redboard	1	$19.95	$0*	Used to process and allow us to operate and begin the electromagnets with multiple inputs/outputs.	Owned	Milestone 3
	USB Cable	1	$3.95	$0*	To connect the Redboard to the sensors and power sources.	Owned	Milestone 3
	Wires and Connectors	12	$13.00	$0*	For cable connecting boards to sensors, and barrel jacks connectors for magnets	Wireless Club	Milestone 4
Mechanical Parts	Straight Hot Wheels tracks	4	$1.00	$0*	To make the tracks for the electromagnets to shoot down.	Owned	Milestone 3
	Hot Wheels Cars	3	$0.99	$2.97	Used to launch the electromagnets.	Purchased from Target	Milestone 4
	Hot Wheels track connectors	2	$.10	$0*	To connect the track pieces for the electromagnet track.	Owned	Milestone 4
	Sponge	1	$1.98	$1.98	To absorb impact of cars	Blick Art Store	Milestone 5

3D Printing	Sensor Mounts	3	$0.30	$0*	To hold and protect the IR Sensors	FYELIC	Milestone 4
	PCB Case	1	$0.50	$0*	To hold and protect the PCB from being handled and to ensure that the wires are organized.	FYELIC	Milestone 4
	Centerbar Connectors	4	$0.3	$0*	To allow for bars to hold track down	FYELIC	Milestone 5
	Interface Holder	1	$1.2	$0*	To hold the touchscreen	Owned	Milestone 7
Sensors	IR Emitter	2	$2.39	$0*	To help track times of the racers	Owned	Milestone 3
	IR Receiver	2	$2.39	$0*	To determine when the racers cross the finish line	Owned	Milestone 3
	555 Timer	1	$0.15	$0*	Drive IR emitters	Wireless Club	Milestone 4
	PCB + Components (resistors, capacitors, etc.)	1	$30.00	$30.00	Drives magnets, and sensors	PCB ordered from JLCPCB. Parts sourced from Digikey and Wireless Club	Milestone 4
Magnetics and Power	Power Supply	1	$59.99	$0*	Used to power the electromagnets.	Owned	Milestone 3
	Thick magnetic wire	1	$89.18	$0*	For winding Coil B	Dr. O' Connell	Milestone 5
	Thin magnetic wire	2	$46.15	$0*	For winding other Coils	Wireless Club	Milestone 3
	Steel Rod	1	$12.99	$12.99	Used to wrap the coil around to make the electromagnet.	TrueValue Hardware	Milestone 4

	Magnets	2	$2.99	$5.98	Permanent magnets to go on cars	Digikey	Milestone 3
UI	NuVision 8" Touchscreen Windows Tablet	`1	$54.64	$0*	To run interface code	Owned	Milestone 6
Mounting	Cable Mounts	5	$0.07	$0*	Attach cables to base.	Owned	Milestone 3
	Cable Sleeves	1	$3.00	$0*	Cover cables	Wireless Club	Milestone 4
	Screws	6	$0.4	$0*	Attach wood cover to guardrails, PCB to case, and interface holder to wood	Wireless Club	Milestone 6
			Total Cost	$66.86			

Table 7. Final Budget. Includes items used, unit value, qty, amount paid, description, source, and timeline.

Note: This is not as detailed as a full Bill of Materials. Only for showing budget rather than parts. For more detailed parts lists, contact one of the authors. Contact information in Appendix A, Table 1. Team Contact Information.

1.31 APPENDIX J – PROJECT HOURS LOG

Members:	Sid	Demitri	Giona	Trevor	Milestone Totals
Milestone 0					8
Totals	2	2	2	2	
Milestone 1	PM				52
User Research				6	
Client Research		4			
Create Gantt Chart			1		
Town Hall Presentation Preparation	2				
Organizing Milestone 1 Report	2				
Updating Design Notebook	2				
Decision Analysis	1	5	5	5	
Brainstorming Meeting	4	5	5	5	
Totals	**11**	**14**	**11**	**16**	
Milestone 2			PM		30
Research	1	1	2	1	
Concept Drawing	1	1	1	1	
Design Brainstorming	1	1	1	1	
Update Problem Statement		1			
Mentor Meeting	1	1	1	1	
Update Gantt Chart				1	
AutoCAD Top Design	2				
Decision Analysis		1			
Town Hall Presentation Preparation			3		

Organizing Milestone 2 Report			2		
Updating Design Notebook			3		
Totals	**6**	**6**	**13**	**5**	
Milestone 3		PM			31
Project Manager		5			
Design Notebook	1	2		1	
Update Gantt Chart			1		
Hours Sheet			1		
Image Log			2		
Flowchart			2		
Design Paragraph	1				
Bill of Materials				2	
AutoCAD Sketch				2	
Testing	2				
Construction	3	2		1	
Solidworks				3	
Totals	**7**	**9**	**6**	**9**	
Milestone 4				PM	81
Project Manager				7	
Design Notebook			1	2	
Update Gantt Chart				1	
Hours Sheet				1	
Image Log				1	
Feedback Plan			1	1	
Wire Diagram	1				
Budget/Bill of Materials				2	
AutoCAD Sketch		2			

Summary of Changes			2		
Creation of GUI			7		
Construction of Electromagnets	5	1			
General Construction	9	9		9	
Demo UI and Sparkfun Code			2		
Put together circuitry	5				
Create circuitboard for electromagnets	5				
Solidworks of Exhbit	4	1			
Solidworks Sketch of magnet holders		2			
Totals	**29**	**15**	**13**	**24**	
Milestone 5					72
Write-Up		1			
Design Notebook	0.5	1	1	1	
Update Gantt Chart			1		
Hours Sheet		1			
Image Log				1	
Mentor Email			1		
Wire Diagram	0.5				
Budget/Bill of Materials				2	
AutoCAD Sketch				1	
Abstract		1			
GUI Improvement	5				
General Construction	15	13	10	15	

Rapid Prototype Object Description	1				
Totals	**22**	**17**	**13**	**20**	
Milestone 6					69
Write-Up		2	2	4	
Design Notebook		1	1	1	
Update Gantt Chart			0.5		
Winding New Electomagnets		1	2		
Bill of Materials				1	
Troubleshooting Magnets	5				
Working on Poster		1	1	1	
Adding Hyperloop					
Wire Barrier		1			
Wiring New Electromagnets	2				
Painted Cars		1			
Added Break System				2	
Hours Sheet			0.5		
General Construction	10	10	8	11	
Totals	**17**	**17**	**15**	**20**	
Milestone 7					16
Exhibit Description Paragraph		1			
Primary Functional elements parg.			1		
Educational elements parg.			1		

Transportability parg.		1			
Photolog				1	
Finish electromagnet building	2				
Finish poster				2	
Finish GUI	1				
Get Interface working	2				
Mount interface				2	
Finish Testing	1			1	
Totals	**6**	**2**	**2**	**6**	
Total hours:	100	82	75	102	359

Table 8. Project Hours Log