HoverRail

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***Abstract*—HoverRail is a system designed to levitate and propel a model magnetic levitation train (Maglev), catering to train hobbyists and beginner electromagnetics students. Existing Maglev models typically come at a high cost or necessitate materials that are difficult for the average person to obtain. Moreover, many of these models lack interactivity, thereby limiting the learning potential. With HoverRail, the goal is to develop an affordable, accessible, and remote-controlled Maglev model that is suitable for everyone.**

***Index Terms*—Maglev, Electromagnetics, CAD Design, Signal Processing, Train Models, Pulse Width Modulation**

I. INTRODUCTION

Magnetic Levitation Trains (MagLev Trains) have revolutionized travel by utilizing electromagnetic fundamentals. Traditional trains used widely across the world are based on a mechanical design utilizing steel wheels, manipulated by gears, along steel tracks. While this design has effectively transported individuals and cargo for nearly 200 years, this design comes with several drawbacks. The interaction of the metal wheels, gears, and track creates friction, resulting in the deterioration of these parts over time. This results in manufacturers budgeting millions of dollars to replace corroding material to keep trains continuously running safely. Additionally, many traditional trains rely on fossil fuels as an energy source [14]. This results in environments surrounding train tracks being subject to pollution, negatively affecting the safety and wellness of these communities.

Maglev Trains are an alternative to the traditional train design. Through utilizing electromagnetic principles such as magnetism and polarity, MagLev Trains have created a form of transportation in which the carrier and track do not make contact. This lack of contact removes the possibility of friction. This eliminates the possibility of loss of parts from corrosion, saving MagLev operators time and money. The lack of friction also allows the carrier to utilize more energy toward propelling the carrier, moving the carrier at speeds as high as 310 mph [14]. This could make traveling from New York City to Washington DC a 45-minute trip. This can change how individuals commute, travel, where they choose to live, and other major life factors. The growing popularity and potential change this technology can bring shows a growing demand for educational tools that can teach the fundamentals of MagLev Trains.

One way to introduce people to magnetic levitation is through MagLev model train sets. Like traditional model train sets, MagLev model train sets are miniature versions of the original train model whose goal is to emulate the core behaviors of the train. However, existing MagLev train sets do not have nearly as many features as traditional train sets. Affordable Maglev Train Set options do not have enough features to be educational Maglev train sets. These train sets either propel with wheels, have little to no magnetic levitation, or lack a user interface to teach about the fundamentals of electromagnetics. MagLev train sets with enough features to be educational are significantly more expensive than other train sets. Prices rise to $1000 for model train sets that have systems that levitate the carrier, propel the carrier, and have a user interface [15]. These prices have made learning about this technology inaccessible to many individuals who fall into their consumer base. There is a hole in the market for accessible and affordable MagLev train sets that can serve as education tools for the fundamentals of magnetic levitation and electromagnetics.

For our capstone project, we are making a magnetic levitation train set. This train set was created to educate everyday people about the fundamentals of electromagnetism and how that has allowed the creation of technology like magnetic levitation trains. Our goal was to create a MagLev train that would levitate, propel, and be able to sense features of its environment. We implemented this by designing coils for propulsion, designing a track and carrier, and testing several designs for stable levitation and propulsion.

II. USE-CASE REQUIREMENTS

We wanted to create an affordable and interactive MagLev train that could levitate stably, propel stably, and have the ability to sense aspects of its environment. We planned to achieve this by setting goals for our carrier's levitation, our carrier's ability to propel, our carrier’s stability, our carrier's ability to communicate with the track, and the success rate of our sensing technology.

A key aspect of MagLev train sets is the carrier’s ability to levitate over the track. MagLev trains currently in use levitate between 0.5-3.394 inches along a track. The height of the carrier is subject to the weight of the carrier, the method of propulsion, and the strength of the magnets. After researching existing MagLev model train sets, we created a goal of 0.8 inches of levitation. This goal was made by looking at models that had a similar level of complexity to what we wanted to achieve.

MagLev train sets require a mechanism to propel the carrier. This is typically done by winding up a metal wire to create a solenoid. When this solenoid is connected to a power source and placed under a carrier, it can excite the electrons of the magnets on the carrier, propelling the carrier forward. For our system to be successful, we needed to create a wound metal solenoid–or speed-up coil– strong enough to propel our carrier over our track continuously.

For levitation and propulsion to be continuously successful, the design of the carrier and track must stabilize the magnetic levitation. Magnetic levitation is inherently unstable. Therefore, design choices must be made to provide stability to the carrier as it levitates and travels along the track. For our system to be successful, we needed to create a design that would stabilize the repulsion of the magnets on the carrier and the track.

We wanted our carrier to be able to observe aspects of its environment as it propelled along the track. The main way we wanted to do this was by adding stops along the track, having the carrier detect the stop, and having the carrier appropriately adjust its speed as it approached the stop. We planned to execute this by creating stops with magnets of different polarity along the track and adding linear hall effect sensors on both sides of the carrier. For the system to be successful, we aimed for the carrier to be able to detect a stop with the linear hall effect sensor and appropriately stop following this discovery.

For our carrier to be able to implement the information obtained from sensing the environment, the carrier circuit must have some way to communicate with the track circuit. This communication will allow the carrier to change the behavior of the speed-up coils if it senses a stop near the carrier. For the carrier to treat our stops similarly to existing stops for MagLev Trains, the communication needed to be fast enough to not dramatically affect the momentum of the carrier. This created limitations for the communication tools we could use and the information we could send with them.

III. Architecture and/or Principle of Operation

Our system consisted of the carrier subsystem and the tracking subsystem. Each system has a mechanical design and circuit design that help in achieving the desired features of our project.

Our carrier design consisted of a 3D-printed carrier and magnets along the bottom of the carrier. The carrier is 7 cm wide, 10 cm long, and 8 cm tall along the sides. The bottom of the carrier has circle magnets to help it levitate. These magnets have no space in between them, allowing for a stronger magnetic field while levitating and propelling the carrier. This is different from the design we used in the design review which had 1cm of spacing between each magnet. Additionally, the carrier is designed to be placed snugly along a 6.5 cm wide track. This carrier is supposed to be close enough to the track to help with stability but far enough for the carrier to have little friction as it propels along the track.

The carrier circuit includes a breadboard, an Arduino nano, an HC-05 chip, a 9V battery, and linear hall effect sensors. The 9V battery is used to provide power to the Arduino nano. The Arduino nano and two linear Hall effect sensors detect a change in the magnetic field that denotes the carrier is approaching a stop. The Arduino nano and the HC-05 work together to send this information from the carrier to the track circuit with its own HC0-5 to change the magnetic field produced by the speed-up coils, changing the speed of the carrier.

The track design consists of 3D-printed track, magnets for levitation, 3D-printed stops, and magnets for stops. The track is designed to have two rows of N42 rectangular magnets. The rows have a space of 1 cm between the rows. This spacing was decided by considering the magnets we have on the carrier and how we could best stabilize these magnets with our track design. Our carrier uses circle magnets that have a 2 cm diameter. The rectangle magnets along the track are 0.5 cm wide. This spacing means the circle magnets on the carrier are aligned between both rows of magnets. The track magnets repel the carrier magnets from the left and the right, helping stabilize the carrier. This is a different design from our design review. Our design review track used 2cm circle magnets in one row. However, this issue was not stable along its sides and would occasionally stick to the track. Through testing different iterations of tracks, we figured that for the best stability, it was best to use rectangular magnets and implement two rows instead of one.

The track circuit includes an Arduino Uno, h-bridges, wound copper wires, a power supply, and an HC-05. These components all work together to propel the carrier and respond to information received from the carrier. h-bridges are electrical components that act as a switch to change the direction current travels. In our circuit, h-bridges are connected to the wound copper wires and a power source that passes current through the H-Bridge to the copper wires. The switches on the h-bridge allow us to manipulate the magnetic field produced by the speed-up coils, allowing us to turn on and off particular speed-up coils to propel the track. The input received from the HC-05 can also affect the behavior of the speed-up coils. If a carrier detects a stop, this information can be sent from the HC-05 of the carrier to the HC-05 of the track. This information can then be used to determine whether or not to turn on or off particular coils to bring the carrier to a stop.

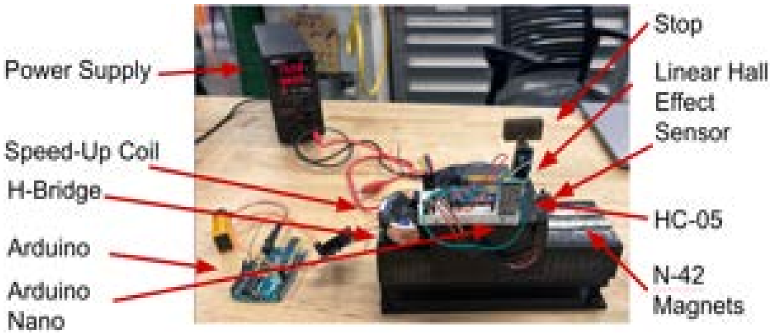


Fig. 1. Overall system with shortened track

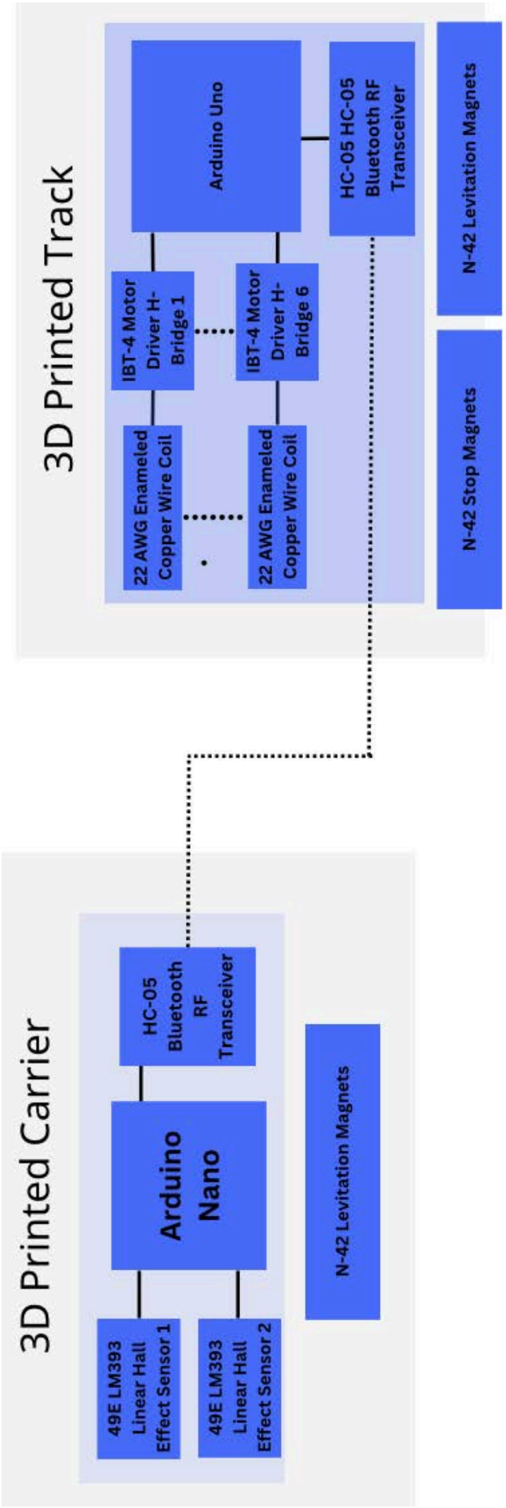


Fig 2. System Block Diagram

IV. DESIGN REQUIREMENTS

For our design requirements are divided into different subsections. The sections include the speed-up coil, the levitation system, and the sensing system.

The carrier's goal is to levitate 0.8 inches. To achieve this height, design choices needed to be made that would allow the carrier magnets and track magnets to repel each other in a manner that allows levitation. This meant considering the configuration of the magnets, the design of the carrier, and the weight of the carrier. To meet this goal, we created a design requirement in which the carrier and track had to be designed to allow consistent, stable levitation.

To propel the carrier, the h-bridge, coils, power source, and Arduino must work together. Propulsion is achieved by manipulating the current that passes through the h-bridges, changing the magnetic field created by the speed-up coils. The magnetic field produced is dependent on the grade of the copper coils used, the amount of copper wire used, the inner diameter of the speed-up coils, and the number of turns in the speed-up coil. To effectively propel the carrier, we need to achieve approximately 200 turns while allowing for around 6 Amps to run through the coil while power is being supplied to the coil. We have come up with these specific numbers for turns and the amount of current running through the coil from current models of MagLev Train sets that implement such coils. Such a coil would then allow for the carrier to consistently and stably propel along the track. For the h-bridge, since we are allowed to change the polarity of the current going through the coil, we want the change in polarity to operate in under 3 seconds, meaning the appropriate switches built in the chip will turn on/off depending on the polarity within those 3 seconds; allowing for a smooth transition for the carrier to stop moving in one direction, and to start heading into the opposite direction.

For our carrier to be able to effectively sense a stop along the track, specifications must be made for what change in magnetic field denotes a stop and what distance the sensors must be from the stop to detect a change in magnetic field. The linear Hall effect sensor measures the strength of the magnetic field in Ohm-cm/Gauss. This unit measures the relationship between the strength of the magnetic field and the proximity. To detect a stop, we denoted that any jump in the magnetic field within 75 Ohm-cm/Gauss in the positive or negative direction meant a stop was detected. To detect this change, we made a goal for our sensors to be able to detect stop magnets within 5 cm of the carrier.

For the carrier to effectively make a stop, the carrier and track must be able to communicate seamlessly. To do this, the carrier must be able to send a message to the track at a speed that would allow the track to appropriately respond without dramatically changing the behavior of the carrier. To achieve this, we create a goal that our communication between our carrier and track must happen fast enough to not affect the carrier's ability to levitate and propel.

V. DESIGN TRADE STUDIES

To meet our use case requirements, we needed to create a magnetic levitation train that can levitate stably, propel a carrier, and detect objects within 2 centimeters of the track. To meet these requirements, we looked over various components and design styles to ensure that they meet our goals. This involved analyzing magnets of different strengths, going over multiple designs for our speed-up coils and their ability to create a suitable magnet field, and researching different ways to implement a start and stop system that would interact with our track and carrier.

Design trade-offs for our projects were split into categories based on the portion of the train they applied to. These categories included:

- Magnets
- Speed Up Coils
- Start/Stop System

A. Magnets

Several factors were considered when determining the magnets that would be used. One major factor was whether to use super-cooled magnets. Many maglevs, including the current systems used in countries in Eastern Asia, use supercooled magnets because of their ability to withstand overheating in magnets, creating a stronger magnetic field due to energy not dissipating from the heat. While this would highly increase the strength and effectiveness of the magnets, they require access to liquid nitrogen. Not only is this inaccessible, but direct physical contact with liquid nitrogen is dangerous for the assembler of the track and participants who may want to use the model maglev. Given these risks, we decided to not attempt to create supercooled magnets

Determining the proper magnets was something that took extensive research. To determine the strength of the magnet, maximum energy product (BHmax), residual induction (Br), cost, and maximum operating temperature needed to be considered. Maximum energy product (measured in Gauss-Oersteds) measures the " volume of magnetic martial required to project a given level of magnetic flux" [4] . Put simply, the higher the maximum energy product, the higher the surface magnetism of the material [5]. Residual induction (measured in Gauss), also known as magnetic flux density, tells users the intensity of magnetic fields.

While looking over existing magnetic levitation model trains, we found that most models used ceramic magnets or neodymium magnets. Ceramic Grade 5 magnets–the strongest grade in ceramics–are widely used in industry in products ranging from motors, automotive sensors, and speakers [6]. A significant reason for their wide use is their high maximum operating temperature as shown in table 1. However, their low BHmax and Br values would make it difficult to levitate a carrier as desired. The neodymium magnets have higher BHmax and Br values, making them extremely strong in comparison to most magnets in use. While they have a low operating temperature, this can be managed by regulating the current that makes contact with the magnets.

Samarium Cobalt magnets were another form of magnets that were used in projects relating to magnetic levitation. This magnet has high Br, high BHmax values, and a high operating temperature. However, the cost of the magnets was out of scope for our current project.

Following an analysis of the three magnets, neodymium N42 magnets were determined to be the best fit due to their applicability to our project. Though they had a low maximum operating temperature, their strength, shown through their high BHmax and Br values, combined with their low cost made them the best magnet for a model remote control magnetic levitation train.

Table I - Strength of Magnets Relative to Cost
[7] [8] [9] [10]

Magnet Type	**Qualities of Magnet**			
	BHmax -> Maximum Energy Product (MGOe)	***Residual Induction (Gauss)***	***Max Operating Temp (Celsius)***	***Cost per magnet (Dollar USD)***
Neodymium 42	42	13,050	150	0.70
Ceramic (ferrite)	3.6	3,950	300	1.42
Samarium Cobalt 26	26	10,500	350	5.34

B. Speed Up Coils (Wire and Transistor)

Multiple considerations were taken when determining the setup of our speed coils. The considerations included determining how to manipulate the current flow into the speed-up coil and the materials for the coils. For the current flow to meet our needs, the direction and intensity of the

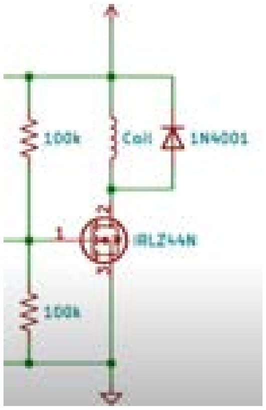
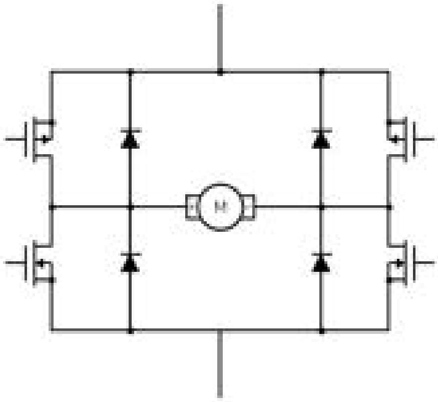


Fig.3. Initial Speed-Up Coil Circuit

current needed to be able to be manipulated. This manipulation would allow us to control when the carrier moves and the speed at which it moves. At first, we considered using a digital potentiometer. We planned to change the resistance of the potentiometer depending on the magnetic field we wanted. The problem with this design is the lack of protection of the circuit from damage if resistance ever drops below a particular point. From this, we pivoted to our initial design as shown in Figure 3. The N-channel MOSFET transistor in the circuit (IRLZ44N) acts as a switch for the current flowing into the "speed up" coils. The diode (1N4001) to the right of the coils protects the components of the circuit from any damage if a high current suddenly enters the circuit. While this allows us to manipulate the current going into the coils, it limits the intensity of the current in the fields given the options are just "on" or "off". An alternative to this system is the H-Bridge. This pre-built circuit component has built-in flyback diodes and switches that control the movement of current flow in two different directions. Depending on the switches that are turned on, current flows in different directions, allowing the user to manipulate the current and further the magnetic field in the speed-up coils. This allows us to gradually increase, decrease, start, and stop the magnetic field in our circuit, meeting our use case requirements.

When determining which wire was the best fit for the project, we exclusively saw copper wires being used in similar designs. Copper wires are highly conductive and affordable, making them a good option for our project. As a result, we did not consider any other conductive material for the design of the coils in the speed-up coils.

Fig.4. H-Bridge. Note: M represents the placement of the coils



II. *Start and Stop System*

Multiple considerations were taken when determining how to implement the start and stop system for the carrier. To meet use case requirements, the stop-and-start system needs to be able to sense a stop and then send a signal to the track to slow down the speed-up coils. The key to this system working properly is sensing when the carrier is approaching a stop. We considered using an ultrasonic sensor or a linear hall effect with a magnetometer.

In the ultrasonic system, when a particular stop was selected, a step motor would drop a divider in the middle of the track. As the carrier with the ultrasonic sensor approaches the stop, the divider would be detected. This would result in the ultrasonic sensor sending a signal to the speed-up coils to slow down the carrier. While this system works effectively, the addition of a step motor and a divider would involve building various mechanical components. Also, there is a possibility that the step motor would malfunction due to being near the track magnets or track magnets would be attracted to materials in the step motor, resulting in us having to build extra safety measures than what is in our original design. Additionally, such a system deviates from the model maglev systems we have seen in the past.

In the linear hall effect with a magnetometer system, each stop has a unique amount of magnets elevated along the track. As the carrier with the linear hall effect with a magnetometer approaches the stop, the sensor detects the unique magnetic field produced by the stop. If this field matches the expected field of the desired stop, a signal will be sent to the speed-up coils to slow down the system. This system depends on the Arduino being able to differentiate between the magnetic field of the track and carrier and the magnetic field of the track, carrier, and stop along the track. Additionally, a strong material must be used to elevate the magnets on the stop to ensure that they do not attach to the track magnets despite their attraction. However, this system depends on electromagnetic principles. Given that a major goal of our project is to further educate on principles of electromagnetic principles, this implementation meets a major goal.

After analyzing both systems, the linear hall effect with a magnetometer system was the best option. Given that we will use the ultrasonic sensor to stop the train if there are obstructions, this will be available as a backup system.

VI. System Implementation

The magnetic levitation is implemented through a magnetic track, a carrier that looks over details in the track, and an Arduino managing the relationship between the track and the carrier.

The magnetic track is responsible for helping the system levitate and propel. The magnets along the track work with the magnets on the carrier to levitate the carrier. Additionally, speed-up coils throughout the track control the speed at which the track moves. We intended for the carrier, along with assisting in levitation, to use ultrasonic sensors to detect an obstruction and a linear hall effect with a magnetometer to detect designated stops along the track. An Arduino attached to the carrier (Arduino Nano) communicates with an Arduino connected to the track (Arduino Uno) to allow the track and the sensors on the carrier to communicate to implement the stop, start, and speed system along with dealing with obstructions. We decided to forgo the ultrasonic sensing because of our time constraints along with the added weight to the carrier causing lessened levitation. The lessened levitation made our carrier unable to clear the height of our speed-up coils.

A. Magnetic Track

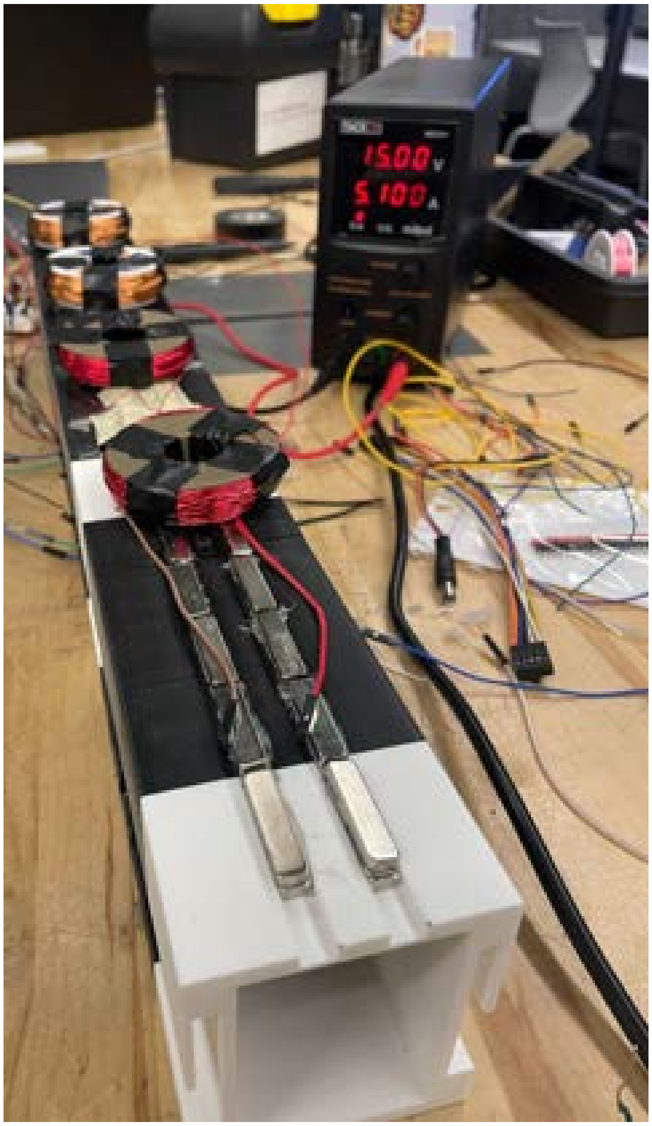


Figure 5: Track with speed-up coils

The magnetic track consists of a 3D printed track, N42 magnets, and speed up coils. The track is designed to have cutouts along the top in the shape of N42 magnets. These magnets are key to creating a magnetic field that will produce levitation and propulsion. The strength and spacing of the magnets along the track determine the strength and consistency of the magnetic field. While a strong magnetic field will ensure that our carrier will levitate, too strong of a magnetic field can create an unstable carrier. N42s are a magnet we consistently saw in designs similar to our goal, which is what led us to choose these magnets. In terms of spacing, the multiple prototypes we created helped us determine the best placement for magnets along the track to optimize levitation while maintaining stability.

We wanted N42 magnets to be used as stops along the track. These magnets were supposed to be placed on elevated surfaces along the track. Sensors in the carrier would detect a difference in magnetic field compared to the usual airspace resulting in a series of software commands that would slow the current in the “speed up” coils, stopping the carrier. Each stop would have a different amount of magnets with different polarities, creating a unique magnetic field that the system can distinguish. These magnets will be elevated by strong, not magnetic material that can keep the stop magnets from attaching to the track magnets despite their attraction.

Lastly, the track contains “speed up” coils that will be used to control propulsion. This system includes copper wires that are tightly wound and attached to a H-Bridge which is attached to an Arduino Uno and a power source. A H-Bridge, as shown in figure 4, is an electronic component that has transistors along the sides (they create a “H”-shape”) that act as switches for current. These switches often work in pairs of diagonals, creating a current flow that looks like an S (or an S reflected along the y-axis) depending on which switches are activated. If these switches are not activated in pairs, they will not effectively pass current through the system, something we plan to use as the “speed up” coils off state. Though many H-Bridges exist, our team decided to use an H-Bridge with fly-back diodes to prevent any damage to the components in case we have a spike in current unexpectedly. At the center of the H-Bridge (in the middle of the “H”), a wound coil will be attached. By Lenz Law, the current passing through these coils will create a perpendicular magnetic field which will result in the propulsion of the system.

The H-Bridge and power source–the direction and strength of the current–are controlled by an Arduino Uno. Depending on our commands, the Arduino will appropriately respond by regulating the current that goes into the system through the power source and regulating the direction of propulsion by manipulating the switches on the H-Bridge program that interfaces with both the track and the carrier.

B. *Magnetic Carrier*

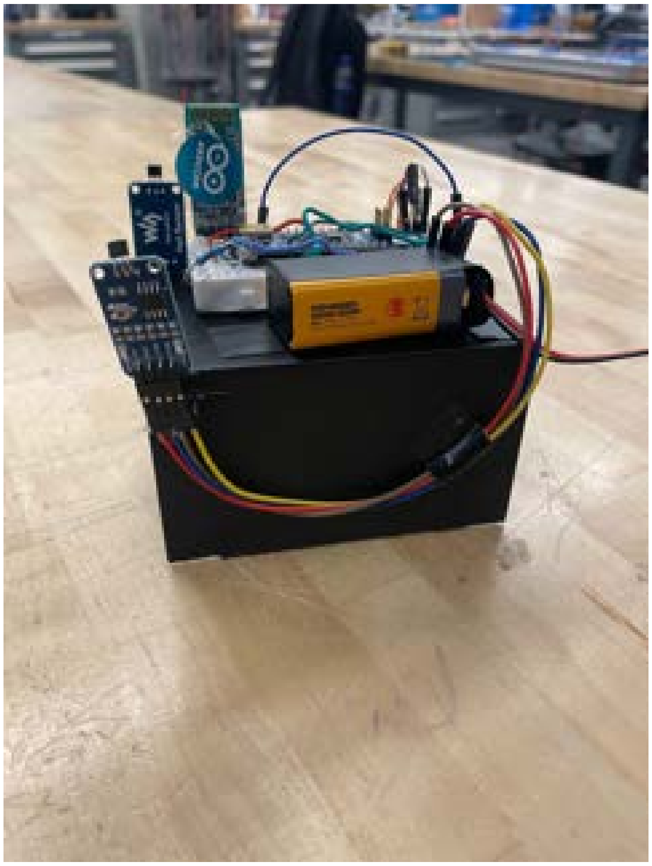


Figure 6: Carrier with hardware components

The carrier consists of a 3D printed track, N42 magnets, an ultrasonic sensor, a linear hall effect with a magnetometer, and an Arduino Nano. The track is designed to be long and to have lengthened sides. In our research, we have seen that longer carriers are more stable. Additionally, the lengthed sides ensure the train will not flip over, another way of maintaining stability. N42 magnets will be placed at the bottom of the outside of the carrier to ensure the track will levitate.

The linear hall effect and the Arduino Nano along with the user interface would implement the train stops. The propulsion of the carrier is a result of the magnetic field created by the track magnets, carrier magnets, and "speed up" coils. Due to stops having magnets on an elevated surface, a different magnetic field is created once the carrier approaches these magnets. The linear hall effect with a magnetometer would have produced a serial output when connected to an Arduino that shows the intensity of the magnetic field. If plotted, this will appear as a sinusoidal. The stops would cause spikes or changes in amplitude in comparison to the sinusoidal of the carrier, track, and speed-up coils. The Arduino Nano will determine if the current magnetic field is consistent with the original sinusoidal. If not, this is an indication that we are approaching a stop. The Arduino Nano will communicate via Bluetooth to the Arduino Uno, notifying the speed-up coils to reduce their magnetic field, further reducing the speed of the carrier. The peak-to-peak distance along the sinusoidal will also be used to determine the speed at which the carrier is going. As mentioned before we did not implement stops in our system this way because of time constraints.

C. *Software and User Interface*

The Arduino Nano's main job is to take in data from the environment of the carrier. For the linear hall effect with the magnetometer, the sensor is also designed to provide a serial output of the current intensity of the magnetic field. Given that that track does not have a constant stream of magnets, when plotted, this will appear as a sinusoidal. Through signal processing, we will establish a baseline sinusoid for the magnetic field created from the track magnets, carrier magnets, and "speed-up coils". This baseline sinusoid will be used for a few different applications. This sinusoid will be measured from peak-to-peak to determine the speed at which the track is moving. The sinusoid can also be analyzed to determine if there is a stop. If there are any sudden peaks in the sinusoidal, the Arduino Nano will communicate via Bluetooth to the Arduino Uno to reduce the current in the "speed up" coils. We did not use the signals from the linear hall sensors in our final design.

The Arduino Uno's main job is to manipulate the "speed up" coils depending on its inputs to change the speed of the carrier. This was done through working with the H-Bridge. The H-Bridge switches can be turned on and off by using them as PINs in the Arduino program. Turning on the 1st and 3rd Switch will result in current flowing in the left direction in the coil, creating a magnetic field in the copper coils that will move the carrier forward. Turning on the 2nd and 4th switches will result in current flowing in the copper coils in the right direction, creating a magnetic field in the copper coils that will move the carrier backward. If these switches are not turned on in these pairs, the current will not effectively move through the copper coils at the center of the H-Bridge. Therefore, the "speed up" coils would be considered "off" if the H-Bridge switches are turned on in this manner. Taking advantage of this "off" state will be an alternative to reducing the current in the "speed up" coils if we are unable to manipulate the current coming in and out of the power source.

We did not use signal processing and Bluetooth communication between the carrier and track to achieve propulsion. In our software, we scripted the Arduino to turn on alternating coils intermittently so that the adjacent magnetic fields would not counteract each other. We had to do research into the optimal time delay between switching the coils from the on state to an off state to ensure that our carrier was not losing a lot of momentum. We found that a 400-ms delay between alternating the coils allowed for the best balance of speed and somewhat smooth propulsion.

VII. TEST, VERIFICATION AND VALIDATION

The following sections discuss our testing plans for each of our subsystems.

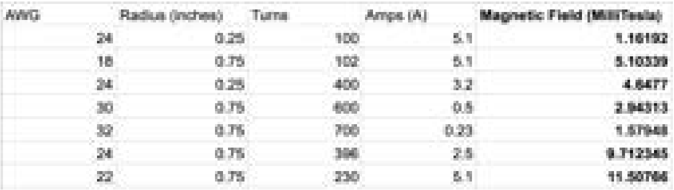
A. *Results for Speed-Up Coil System*

We conducted multiple tests to make sure we created a speed-up coil strong enough to continuously propel the carrier along the track. Our first test was done by calculating the magnetic field produced by our coils. By utilizing the magnetic formula produced by solenoids, shown below, we saw that the field relies on multiple components other than the number of turns and amps, such as the radius of the coil, and the distance from our coil to the carrier.

$$B_z \approx \frac{\mu_0 I N R^2}{2\sqrt{R^2 + z^2}^3}$$

Figure 4: Solenoid Magnetic Field Formula

By relying on this formula, we calculated each iteration of coils produced, to get a better understanding of which coil produces the most field, which in hand resulted in the carrier being pushed a greater distance along the track. As specified in the design requirements, we wanted to achieve a coil with 200 turns and 6 Amperes. We based these numbers on other MagLev designs that made similar coils. We initially wanted to wrap the coil around an ¼ inch bolt, meaning that the radius of the coil would be significantly small, which is shown in the results. Based on the results, you can see a clear change in our process of creating coils, going from the bolt to using a plastic spool with a radius of ¾ inches to improve the magnetic field. After final measurements, we were able to determine that the coil which used 22 AWG Copper Wire, was able to achieve 230 turns but only 5.1 Amps, which was limited by the power supply that we had. The coil we produced also achieved 0.75 inches in radius, leading to a coil producing 11.5 milliTeslas.



AWG	Radius (inches)	Turns	Amps (A)	**Magnetic Field (MilliTesla)**
24	0.25	100	5.1	**1.16192**
18	0.75	102	5.1	**5.10339**
24	0.25	400	3.2	**4.6477**
30	0.75	600	0.5	**2.94313**
32	0.75	700	0.23	**1.57948**
24	0.75	396	2.5	**9.712345**
22	0.75	230	5.1	**11.50766**

Figure 7: Magnetic Field Calculations for Coils

We then conducted readings via the Linear Hall Effect Sensors and looked at the peak readings via a serial plotter monitor that graphs the digital output of the sensors depending on the polarity of the magnetic fields produced, to confirm whether or not the calculations are correct, and to distinguish the coils based on their field strengths. Those readings did confirm that through every iteration of the coils we produced, the peaks of these coils increased on the monitor, meaning that the 22 AWG copper wire was the strongest coil we produced. Visual testing such as seeing whether or not the coil could propel the carrier with added weights resulted in the carrier traveling the entirety of the carrier, thus confirming that we have met our use-case requirement of creating a solenoid strong enough to continuously propel our carrier over the track.

B. Results for Levitation System

We manually verified the height of our carrier above the track with physical measurements. We would have met our design and use case requirements if we achieved a levitation of 0.8 inches. The levitation distance was measured from the top of the track to the bottom of the carrier. After final measurements, we were only able to achieve 0.5 inches of levitation which was caused by the weight being added onto the carrier, such as the 9V battery and the breadboard. Though we didn't achieve the desired 0.8 inches, we were still able to have enough levitation to pass over the speed-up coil and allow the carrier to propel along the track. After visually testing how the carrier responded to the track and the propulsion, it was best that we didn't achieve the 0.8 inches of levitation because of how the carrier reacted with the coil and how it propelled. Pointing back to the magnetic field formula stated above, the denominator variable z is the distance from the solenoid itself to the carrier, meaning the larger the z or in this case, the larger the levitation, the smaller the magnetic field would have been produced. Thus, even though we didn't get the 0.8 inches, we were able to optimize the magnetic field production.

C. Results for Start/Stop/Speed Up System

We verified the speed at which the HC-05 Bluetooth devices were able to send and receive a signal by using a timer that was built in the Arduino functions we used for testing. The way that worked was by creating a simple function that would run before the function that tested the HC-05s ran, then creating another simple function after the HC-05 function ran, then taking the time difference between those two times, which would then represent how long the HC-05s took to communicate with each other. After timing multiple iterations of sending the string "SENT" from the transmitting HC-05 to the receiving HC-05, we then took the averages of those times and came up with about 52 ms.

What is being sent?	Time (ms)
String "SENT"	47.62
String "SENT"	57.03
String "SENT"	53.76
String "SENT"	49.91
String "SENT"	50.13
Average Time:	**51.69**

Figure 8: HC-05 Communication Timing Results

Due to timing constraints, we weren't able to continue with the HC-05 to represent the start/stop/speed-up system and had to alternate to a different design, pivoting to an even/odd coil system where the "even" coils were activated while the "odd" ones for off and vice versa where the "odd" coils were activated while the "even" coils were off. To test this system, we needed to first test the optimal position of where the back of the carrier should be positioned concerning the coil, to maximize the distance traveled for the carrier. The next component that needed to be tested was the distances the carrier traveled for each coil, to properly place the next coil on the track in a position where the back of the carrier travels and stops at the previously mentioned "optimal position". The last component that needed to be tested was the timing of each coil, so then the coil the carrier was over would have enough time to propel the carrier to the next coil, and not have the next coil turn on too quickly to push back the carrier, or too late to where the carrier isn't continuously moving along the track. Again due to timing constraints, we didn't get the chance to properly measure and write down the results of each iteration. The final results that we came up with were that each coil needed to be activated and have a waiting period from that current coil to the next coil of about 400 ms, with each coil having around 3.5 inches of spacing, to achieve a carrier that is continuously moving along the track.

VIII. PROJECT MANAGEMENT

A. *Schedule*

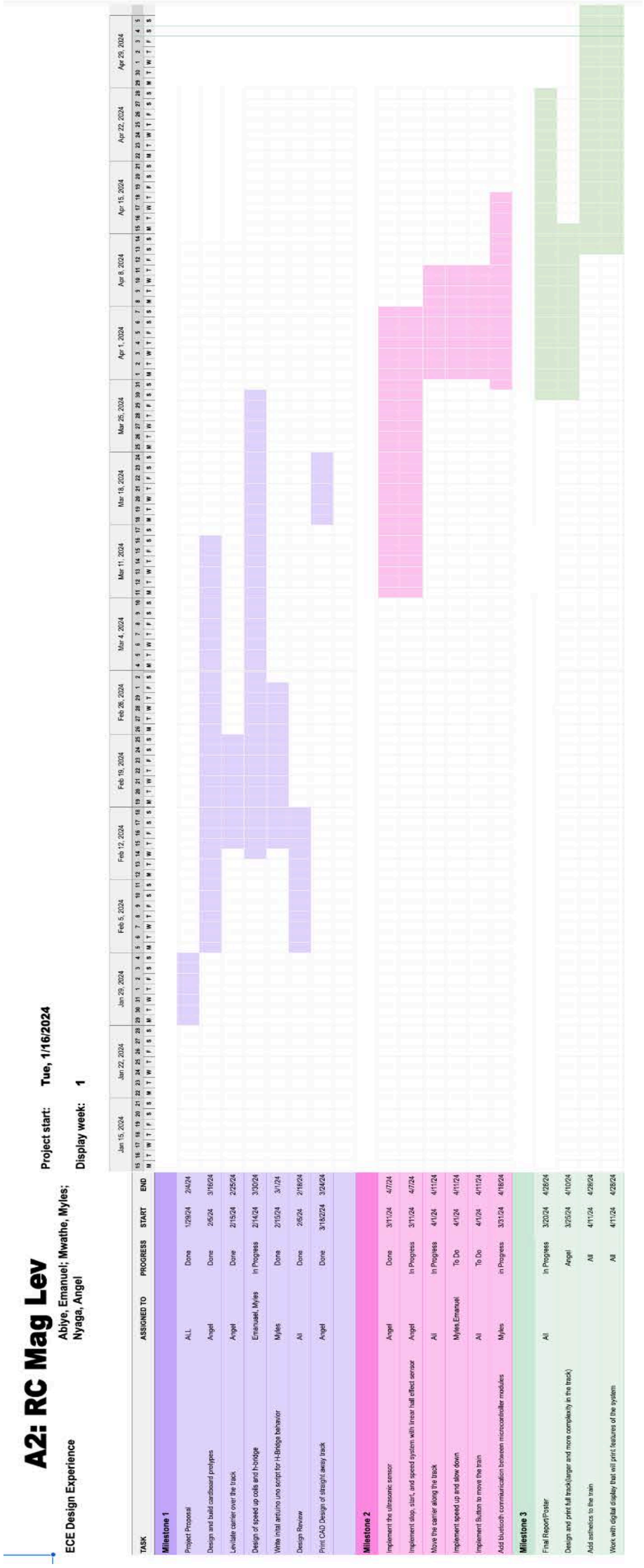
Our schedule is split into 3 main milestones. The first two have to do with creating and improving multiple prototypes of different components of the systems and the last focused on integration and testing.

Our first milestone is where we focus on making our initial prototypes of the track, the carrier, and the speed coils. In this time, we made several versions of each component and tested them based on our requirements to determine if they would make an effective MagLev model train.

Our second milestone was where we focused on improving our initial prototypes. Prototypes in the previous milestone still needed to be fine-tuned to become effective MagLev model train sets. During this time, we worked on testing and improving new designs for our track and carrier with different magnet configurations. We also tried testing speed-up coils of different grades and turns. We also worked on developing how the linear hall effect sensor would detect a stop.

Our final milestone was where we focused on testing our prototypes and integrating our different components. We tested the carrier's ability to levitate, the strength of the magnetic field from the speed-up coils, the linear Hall effect sensor's ability to detect stops, and communication response time. We spent time integrating the carrier and track with the speed-up coils to effectively propel the carrier. During this process, we tested several speed-up coils' ability to propel the track and adjusted the times at which the h-bridges were turned on and off to allow the carrier to propel.

This schedule has changed significantly from what we presented in our design review. We decided to focus on creating a straight track as opposed to a track with curves because we wanted to spend more time creating a stable carrier and track design. We also chose not to implement the ultrasonic sensor and decided to not make the carrier operate through remote control. If we had more time to work on this project, we would work on implementing these components.



A2: RC Mag Lev

ECE Design Experience

Abiye, Emanuel; Mwathe, Myles; Nyaga, Angel

Project start: Tue, 1/16/2024

Display week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Milestone 1				
Project Proposal	ALL	Done	1/29/24	2/4/24
Design and build cardboard protypes	Angel	Done	2/5/24	3/16/24
Levitate carrier over the track	Angel	Done	2/15/24	2/25/24
Design of speed up coils and h-bridge	Emanuel, Myles	In Progress	2/14/24	3/30/24
Write intal arduino uno script for H-Bridge behavior	Myles	Done	2/15/24	3/1/24
Design Review	All	Done	2/5/24	2/18/24
Print CAD Design of straight away track	Angel	Done	3/18/2/24	3/24/24
Milestone 2				
Implement the ultrasonic sensor	Angel	Done	3/11/24	4/7/24
Implement stop, start, and speed system with linear hall effect sensor	Angel	In Progress	3/11/24	4/7/24
Move the carrier along the track	All	In Progress	4/1/24	4/11/24
Implement speed up and slow down	Myles,Emanuel	To Do	4/1/24	4/11/24
Implement Button to move the train	All	To Do	4/1/24	4/11/24
Add bluetooth communication between microcontroller modules	Myles	In Progress	3/31/24	4/18/24
Milestone 3				
Final Report/Poster	All	In Progress	3/20/24	4/28/24
Design and print full track(larger and more complexity in the track)		Angel	3/25/24	4/10/24
Add asthetics to the train		All	4/11/24	4/28/24
Work with digital display that will print features of the system		All	4/11/24	4/28/24

Figure 9: Gantt Chart

B. Team Member Responsibilities

Angel spent time creating the different track and carrier prototypes. The initial prototypes were made of cardboard and circle N42 magnets. The following and final prototypes were generated with CAD in Fusion 360, based on the takeaways from the cardboard prototypes. Different prototypes were developed to help improve stability and increase the amount of levitation. Angel also worked with setting up the linear hall effect sensors and the Arduino to detect stops.

Myles spent time working on the software that would change when the h-bridges allowed current to pass through the speed-up coils. He worked on improving the design of the speed-up coils to create a stronger magnetic field. Myles also worked on the communication software with the HC-05, the carrier circuit, and the track circuit.

Emanuel spent time creating the speed-up coil prototypes. He made multiple prototypes with different copper wire grades and different amounts of turns to create a coil with a magnetic field strong enough to propel the carrier but physically small enough to be placed on the track. Emanuel also worked on creating the software to manipulate the h-bridges and how they propelled the carrier.

As a team, we integrated the different components to get the carrier to propel along the track. New design choices that were made to improve the carrier's ability to propel were also made as a team.

C. Bill of Materials and Budget

See Table II. NOTE - while the hall effect sensors were not used they were still attached to the carrier for weight distribution purposes. This was also the case for our HC05 Bluetooth module as well.

D. Risk Management

Due to time constraints, we had to find a simpler, less constraining way to programmatically move our carrier. As a result, we focused on general integration at the end of development rather than fine-tuning precise algorithms for data collection and working with Bluetooth components. Towards the end of the project, the majority of our time was occupied by CAD designing and physically wiring the components onto our track, ensuring everything was properly powered by the power supply. We encountered obstacles with 3D printing due to the dimensions of our track and the capabilities of the immediately available 3D printers. To address this, we had to print our carrier in pieces and physically attach them afterward. Additionally, we added rows of magnets to each section of the track and included intermediate smaller pieces between tracks to allow for some tolerance with imprecise magnet spacing. However, when we attempted to attach everything, we found that the magnets in separate pieces would repel each other, so we used zip ties to keep the tracks together. We decided to reduce the overall size of our track to about half of what we originally discussed in the design review (1 meter). We lacked sufficient filament to print our meter track and did not have enough speed-up coils and h-bridges to line our track appropriately. Although we had five compatible h-bridges and coils, we only had six pins on our Arduino board that were pulse-width compatible. These PWM pins allow us to control the current output in the coil, determining the strength of the push it provides. To achieve alternating coils turning on simultaneously, we utilized multiple h-bridges receiving PWM input from the same pins on the Arduino. For coil ordering on the track, odd-spaced coils were connected to one set of PWM pins, and even coils were connected to another set, enabling us to command multiple coils simultaneously without manually writing a PWM signal to each one. Regarding the decision not to utilize the functionality of the components on our carrier, we opted to keep the components physically attached for weight distribution purposes. It should be noted that we had an ultrasonic sensor on our carrier as well but we found that this particular component weighed down our carrier too much and found that the added levitation height was worth sacrificing for the added functionality. Our system can function without the ultrasonic sensor, and we had not figured out a mechanism to physically stop our carrier on command so we abandoned this component entirely. Our levitation and magnetic strength estimations were based on the carrier being weighed down by the components, which also aided carrier propulsion, as the closer our carrier was to the speed-up coils, the more propulsion we could achieve.

IX. ETHICAL ISSUES

If HoverRail becomes widely adopted, a potential worst-case scenario emerges where users may tamper with its components, affecting critical factors such as magnetic fields, current flow, magnet strength, and heat generation. This modification poses a risk to the health of individuals who wear conductive accessories or have conductive medical devices. This outcome contrasts sharply with our intended purpose, which is to provide a safe environment for learning about magnetism, electromagnetics, and magnetic propulsion. Disruption of the magnets not only jeopardizes the project but also endangers users, ranging from novice students of electromagnetism to enthusiasts of train technology. Particularly vulnerable are individuals with conductive medical devices or those wearing conductive materials. For example, a child using HoverRail who inadvertently comes into contact with a significantly heated propelling coil could sustain burns. Such incidents could erode confidence in the product's safety and undermine the user's responsibility, as tampering with it could result in unforeseen consequences.

X. RELATED WORK

Several maglev model trains exist on the market. Many affordable versions of this technology do not have enough features to be an educational maglev train. However, the maglev train with enough features to be educational is expensive.

One example is Takara-Tomy's Linear Liner toy, a maglev set that is sold in Japan. This carrier levitates 2 mm above the track and runs at speeds as high as 310 mph. It is currently being sold for $500 [16]. Outside these listed features, this maglev set has no more features. The main way a user interacts with the system is through turning the system on and off.

While this product is similar to our design in terms of price point and the ability to propel, this train could use more features to be used as an educational tool. The carrier magnets and track magnets are hidden in these designs, providing little insight as to how the levitation is taking place. Also, little to no information is provided as to how the carrier levitates as opposed to our system where speed-up coils are exposed and turned on by a power source. If we had more time to work on the project, we would have implemented a stop system, another feature this existing model does not have.

Through research, it is clear that there is a need for more educational maglev model train sets. While we were not able to complete all the features promised for our train set, we believe that the trains' open design, ability to levitate, and ability to propel would benefit individuals interested in learning about maglev and electromagnetics.

XI. Summary

At the end of this entire building process, we were able to create a levitating carrier that was able to propel the entire length of the track. Breaking it down into each subsystem, for the speed-up coils, we were able to create multiple coils that were strong enough in terms of magnetic field production, to be able to propel the carrier from one coil to another, eventually clearing the entire length of the track. We were able to achieve the design specification of 200 turns or more for our coils, but couldn’t achieve the 6 Amperes as we were limited to just 5.1 Amperes. With the kind of copper wire that we were using for our coils, 22 AWG, we could have reached up to 7 Amperes which would produce an even stronger magnetic field, thus decreasing the amount of coils needed, and potentially decreasing the bills of materials since each coil used 4 ounces of 22 AWG Enameled Copper Wire. For this section, if we had more time to work on this project and to improve it, we definitely would have looked into getting a new power supply that had a higher limit for its Amperes, so then the coils would be able to have 7 Amps running through them, thus creating a stronger magnetic field. The difference between the magnetic fields with the 5.1 Amps we currently use compared to the magnetic field if we had 7 Amps, would have been around 5 milliTeslas, which could have easily been utilized to propel the carrier even further.

For the levitation system, we were able to only get the levitation of the carrier and the track to reach around .5 inches, which is .3 inches less than what we hoped for under our design specifications. As previously stated, that much change in the levitation did some good for our entire system because of how it caused our magnetic fields that are being produced by the coils to create an even stronger field. If we were granted extra time to improve this section, a huge part would be towards redistributing the weight on the carrier, since the way the levitation and stability changed while the carrier was being propelled along the track caused the carrier to nosedive in both directions when moving from one coil to the next, and a lot of time was dedicated to figuring out where to optimally place both the battery and the breadboard on the carrier, to allow for stable levitation. Another part of this subsystem that could use some improvement is the magnet placement along the track. We realized that if we double up each row of rectangle magnets on the track with another arrow of similar magnets, then the amount of levitation space would increase. We utilized that double row system to achieve the 0.5 inches of levitation that was large enough to clear the coils. If we had more time to work on the project, we would have looked into possibly adding another layer of rectangular magnets, to further increase the levitation space, and potentially reaching our design specification of 0.8 inches.

For our last subsystem, this is where timing constraints caused us to alter our system as a whole. We were able to create an alternative start and speed-up system where the carrier would start moving and continuously travel from one coil to the other, completing the entirety of the track. If we were granted more time for this subsystem, we would have gone back to our original design of implementing stops along the track. The reason why we have Linear Hall Effect Sensors on our carrier is so that it can detect a change in magnetic field when passing by these stops, which would have used N42 magnets, thus making it easy for the carrier to detect the change. That change would have then been able to be sent via the HC-05s in the calculated 52 ms. As shown above, we realized that it takes about 400 ms for the carrier to travel from one carrier to the next, and so if we used the original design, that 52 ms would have meant nothing and not caused an issue for the system as a whole.

Talking about the project as a whole, there are a lot of other things we would have done differently, such as finding a better adhesive to stick the magnets down together, as magnets flying off the track was a huge issue and caused a lot of issues in making progress since we had to continuously go back and reapply the magnets on the track. Another thing we would have done differently is implementing the UltraSonic Sensor that we discussed in our Design Report but was ultimately scratched due to timing constraints, as well as the weight of the device causing the carrier to nosedive when it propelled along the track. Another thing we would have done differently is changing our approach towards 3D printing components since we went back and forth between using the 3D printers from TechSpark which would take several days to print, and using someone else's 3D printer that was even faster. We spent a large portion of our time waiting for things to be printed which hindered our progress. One last thing we would have improved on if time was granted was to implement a user-interactive component, either a controller or buttons that make the carrier start. In the end, though timing and budget constraints played a huge role, we are very pleased with the end product that we created, and we believe that our project could still serve as a learning experience for users while being accessible in terms of our projected price tag for our product.

A. Lessons Learned

Reflecting on our journey developing HoverRail, several key lessons have emerged. Adding slopes and curves proved challenging, we decided to forgo making our track more complex for the sake of time because of this. Understanding the shape and magnetic properties of magnets significantly influenced our design choices, highlighting the importance of careful magnet selection for stability and performance. Moreover, navigating the intricacies of magnet levitation revealed inherent instability, prompting us to refine our approach to achieve consistent levitation heights. Managing multiple stops along the track demanded innovative solutions to maintain efficiency and reliability. Lastly, doing CAD design without prior experience presented its own set of hurdles, underscoring the value of hands-on learning and collaboration in overcoming challenges. These lessons have not only enriched our understanding of electromagnetics and train dynamics but also reinforced the importance of adaptability and perseverance in engineering innovation.

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Description	Model	Manfactuerer	Quantity	Cost	Total
Large Current 50A H Bridge High Power Single Channel Motor Driver Module		Hilitand	5	$11.49	$57.45
Ultrasonic Distance Sensor	HC-SR04	SparkFun	1	$4.50	$4.50
Arduino Uno		Arduino	1	$20.00	$20.00
Arduino Nano		Arduino	2	$24.90	$49.80
1 x 1/4 x 1/8 Inch Neodymium Rare Earth Bar Magnets N42 with 3M Self-Adhesive (20 Pack)		totalElement	4	$18.99	$75.96
24 AWG Magnet Wire - Enameled Copper Wire - Enameled Magnet Winding Wire - 4 oz - 0.0197" Diameter 1 Sp		BNTECHGO	2	$11.45	$22.90
22 AWG Magnet Wire - Enameled Copper Wire - Enameled Magnet Winding Wire - 4 oz - 0.0197" Diameter 1 Sp		BNTECHGO	3	$11.45	$34.35
HC-05 Wireless Bluetooth RF Transceiver Master Slave Integrated Bluetooth Module 6 Pin Wireless Serial Port C		HiLetgo	4	$10.39	$41.56
30Pcs Super Strong Rare Earth Magnets Disc, 20 x 3mm Decorative Round Fridge Neodymium Magnets		MIN CI	3	$19.78	$59.34
3D Printing - Carrier, Track					$0.00
Resistors					$0.00
Copper Wire					$0.00
Breadboard					$0.00
5pack 9v Battery Clip with 2.1mm X 5.5mm Male DC Plug		Corporate Computer	1	$5.99	$5.99
9 volt batteries - Amazon Basics 8-Pack 9 Volt Alkaline Performance All-Purpose Batteries		Amazon Basics	1	$12.57	$12.57
OVERTURE PLA Plus (PLA+) Filament 1.75mm PLA Professional Toughness Enhanced PLA Roll, Cardboard Sp		OVERTURE	2	$24.99	$49.98
49E Hall Sensor LM393 Linear Hall Effect Sensitivity Detection Module		Raspberry Pi	4	$9.99	$39.96
					$474.36
Green - new item after design report					
Red - not used					

Table II. Bill of Materials