MEAM Machine Final Report

History

Magnetic levitation (Maglev) trains are a form of high-speed transportation that use magnetic forces to lift and propel trains above the track, eliminating friction between wheels and rails. The concept of magnetic levitation was first explored in the early 20th century, but major development began in the 1960s and 1970s as engineers searched for faster and more efficient transportation systems. Germany and Japan became leaders in maglev technology, with Germany developing the Transrapid system and Japan creating superconducting maglev trains capable of exceeding 300 mph. Today, maglev trains are recognized for their smooth operation, high speeds, and reduced maintenance compared to traditional rail systems, making them an important advancement in modern transportation technology.

Project Overview

The enterprise chose to make a Maglev train for this project, utilizing rapid prototyping for the train and track and a mix of permanent magnets and electromagnets for the propulsion (see below). The enterprise was split into three teams: track, train, and propulsion. The track team was responsible for designing a smooth track upon which a cart could levitate and move along without friction. The cart team was likewise responsible for designing a frictionless system that allowed the train to glide effortlessly, moved by the propulsion system. Finally, the propulsion system was responsible for producing a system to move the cart along the track through a series of magnets.

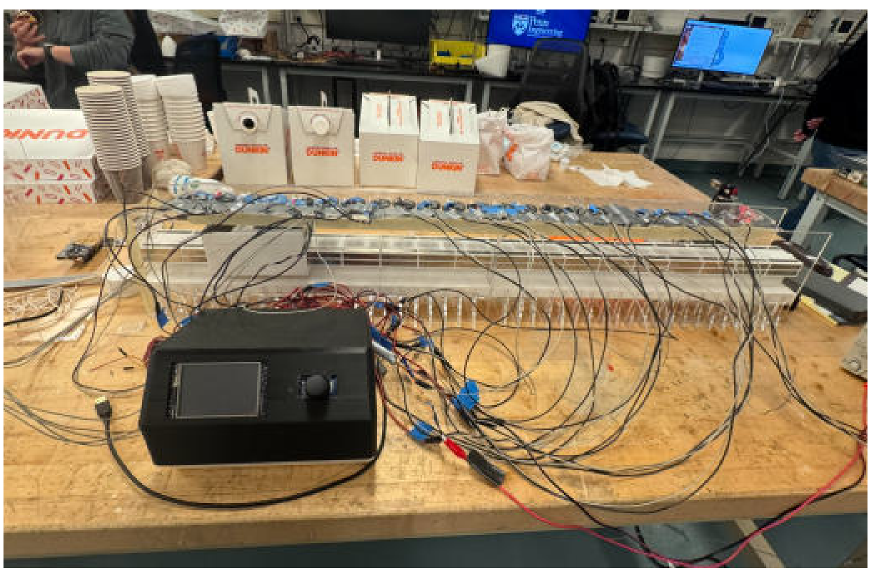


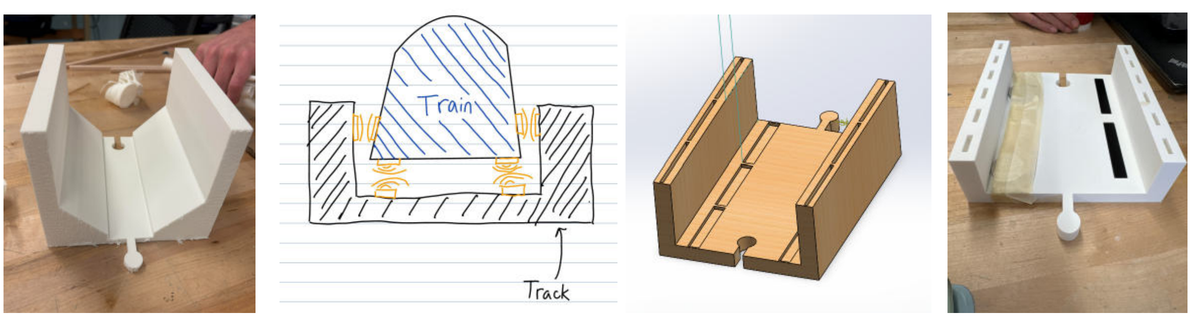
Figure 1: Final track, cart, and propulsion system fully integrated

The track and cart were designed to interface in a way that eliminated all friction, with the cart levitating steadily above the track at a specified height. By eliminating friction, we would be able to reduce the propulsive power required to move the train. The propulsion system functions through a series of alternating electromagnets that can be sequenced to move the cart along the track.

Track

Preliminary Design & Concept Development

We seek a track design that fulfills the following functions: 1. Generates sufficient magnetic levitation force to balance the weight of the train 2. Stabilizes unavoidable, small displacements of the train from perfect center position during real-world operation. 3. Constrain the train to move in a straight-line without causing excessive friction. We began with brainstorming and sketching the alternative track geometries then down selected our ideas to the following three designs for prototyping and testing: (1) a flat track surface containing permanent magnets for levitation with magnetized vertical side walls to provide lateral stability; (2) an inclined, magnetized V-shaped track with bar magnets on the track surface that provide both levitation and lateral stabilization without additional side-walls, and (3) an I-beam shaped track with a top surface for levitation and side surface for lateral stabilization. We CADed and 3D-printed each of the three configurations above and tested their performance. In our first test, we used refrigerator magnets for levitation, which turned out to be too weak to support the weight of the train. In our second trial, we switched to neodymium magnets and successfully lifted the model train by more than 1 cm. However, we still could not stabilize the train as any small displacement from equilibrium position is observed to attract the train immediately to either the top or the side walls. We also compared the three designs. In experiments, the V-shaped track provided the weakest lateral stability and levitation force was also compromised. Designs 2 and 3 performed similarly in levitation, but the I-shaped track (design 3) provided stronger lateral stability and straight-line guidance. We continued to iterate our design in follow-up experiments, tuning parameters such as the clearance between the train and the side-walls, the number and location of the magnets on each wall, the height of the side walls etc. to improve track performance.



(a) (b) (c) (d)

Figure 2: (a) V-shaped track design; (b), (c) , (d) Sketch, CAD, and 3D print of alternative track design with flat levitation surface and magnetized vertical walls for lateral stability

Analysis & Simulations

We analyzed the reason for the lack of stability in the train. Our design includes one strip bar magnets for both levitation and lateral stabilization. In this configuration, the direct pole to pole interaction area is narrow and small displacements would cause the two magnets to misalign. Then, field lines emanating from the north pole of one magnet partially reconnect to the south-return pole of the other magnet, and the fringe fields would also interact, producing non-vertical forces that cause lateral movement and rotation. These unstable forces push the magnets away from, rather than back towards the pole-to-pole aligned position, causing the train to settle into an alternative equilibrium where the levitation magnets on the train and track are exactly offset and they attract along the lateral edge rather than repelling on the face. Similarly on vertical walls where spatial displacement can cause the desired face-to-face repulsion force to turn into attractive force along the edge, which is a lower-energy state. In fact, Earnshaw's theorem shows that stable levitation could not be achieved with any combination of permanent ferro-magnets as the levitation equilibrium position is always unstable, which can be easily proved: The static force as a function of position ***F(x)*** acting on any body in a vacuum due to gravitation, electrostatic, and magnetostatic fields will always be divergence free: div $\boldsymbol{F} = 0$. At a point of equilibrium, the force is zero. If the equilibrium is stable, the force must point in towards the point of equilibrium on some small sphere around the point, meaning the net flux across some epsilon sphere around the equilibrium position is non zero. However by Gauss's theorem, $\oint_S \mathbf{F}(\mathbf{x}) \cdot d\mathbf{S} = \int_V (\nabla \cdot \mathbf{F}) \, dV$ that flux must be zero for a divergence free field, thus we have a contradiction.

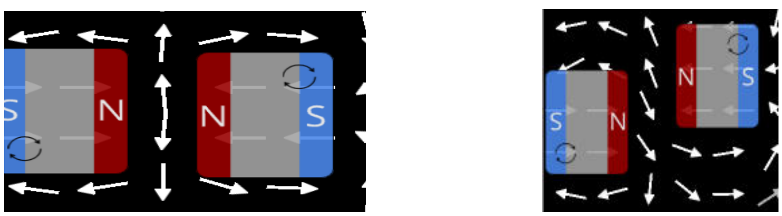


Fig 3. Aligned vs misaligned magnetic field. Qualitatively simulated in physicsClassroom.com.

Real maglev trains evade Earnshaw's theorem by using electro-magnets that are actively or passively adaptive and/or super-conducting magnets instead of permanent ferro-magnets. Given the above analysis, we must incorporate side-walls to stabilize the train and achieve straight-line motion. Acrylic laser-cut side walls are thus added. We designed a variable slider to adjust the location of these walls and the best clearance with the track and the car was determined through iterative experiments. We also tested different bar magnets of different strengths for levitation, and coordinated with the train-team to adjust the train's weight so we achieve a moderate amount of levitation and the bottom of the train does not contact the bottom of the track. We also worked with the propulsion team to make sure any friction from the side-walls wasn't preventing the car from moving freely.

Final Track Design

The final track design, the I-shaped track with one strip of neodymium magnets for levitation and two strips of regular ferro-magnets for lateral stabilization, was built to solve the alignment and stability issues we ran into during our earlier testing. The whole track was mounted inside acrylic side-walls.An additional acrylic ceiling is made where the electromagnets of the propulsion team would be mounted.

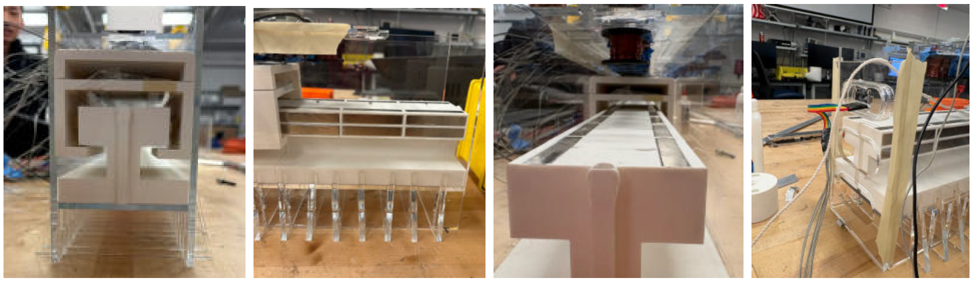


Figure 4: Final track I-design and testing. Left to right: cross section of I shaped track and cart, side magnets, levitation magnets, end cap for addressing failure mode.

Failure Mode and Mitigation

The mode that we chose was failure of the propulsion system to decelerate the cart before reaching the end of the track. To address the failure, we added a solid acrylic wall to act as an end stop at the end of the track, so in case of failed brakes, the train would not fly off and cause damage. To test our failure mode, we cut the propulsion at the end of the track to see how the car would behave without it. The car stayed guided along the track, and the end cap was able to stop the car when the propulsion was unable to stop it. If the car ever made it to the end at full speed, we could be sure the bumper would bring it to a stop.

Integration with the Full System from the Track

When we were doing the full integration with all of the systems, it took lots of continuous testing and consistent communication within the groups and in our full group chat. We used the group chat to discuss design updates, testing observations, system adjustments, and full updates from each lab section. We had to have a lot of communication with the car team, since the train car dimensions and geometry needed to properly fit and operate with the final track design. We also paid close attention to making sure the magnet placement between the track and car was properly aligned, as even small positioning errors would affect levitation, propulsion, and overall stability.

Future Improvements

Going forward, the team hopes to improve the functionality of the design rather than focusing on cost-reduction. We also would like to design a better mechanical fixture to hold the magnets in place. Tape is not strong enough to hold magnets against strong interaction from train and other magnets, while glued magnets cannot be taken off if needed to.

Team Roles & Responsibilities

The team members contributed equally on design idea formulation, testing, and design revisions. Tom focused on CAD design iterations, laser-cutting of side-walls, and engaged in 3D printing. Kylie engaged in track assembly, project management, and led the failure mode analysis. Mickey engaged in theoretical and design analysis, track manufacture, force testing, analysis of test failures and design revisions.

Train

Preliminary Design and Concept Development

The initial goal of the train design process was to create a lightweight and stable carriage that could reliably levitate while interfacing with both the track and propulsion subsystems. We initially came up with a bullet train-inspired 3D printed design with permanent magnets inset along the bottom surface. We expected these magnets to interact with the track to provide levitation, but early testing quickly revealed several issues; lateral instability caused drifting side-to-side or snapping toward one edge due to slight inconsistencies in magnet strength and alignment. Additionally, maintaining a consistent levitation height proved difficult, as small variations in spacing led to large changes in magnetic force.

The initial bullet-train style designs also featured a single aerodynamic nose on the front of the train. Although this choice was more visually appealing, the asymmetrical geometry introduced uneven weight distribution during levitation tests. Since the levitation system is highly sensitive to mass placement and magnetic alignment, the singular nose shifted the center of mass forward and created small pitching moments that negatively affected stability. To address this, the design was later modified to include noses on both ends of the train. This change improved overall symmetry, resulting in a more balanced distribution of mass and magnetic forces across the carriage. The dual-ended design also reduced directional bias during motion, allowing the train to behave more consistently regardless of travel direction while improving stability during levitation and transitions along the track.

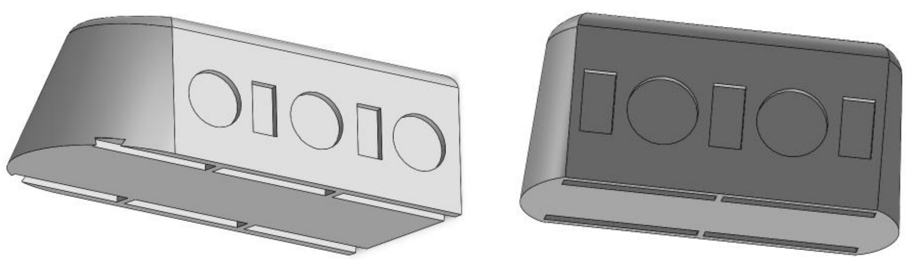


Figure 6: Initial bullet-train style designs

Knowing that the magnet forces would vary across magnets due to material properties and alignment tolerances, the next design focused on mitigating instabilities using a T-shaped track design, which significantly changed how the train interfaced with the system. Instead of relying only on bottom-mounted magnets, we redesigned the train to include magnets along its sides for lateral stability and magnets positioned to interact vertically for levitation. Then coordinating with the propulsion team led to a concept that incorporated magnets on multiple components that made up the train, allowing it to simultaneously interact with the track for levitation and stability and with the propulsion system for motion.

Analysis

Most analysis was spent on the magnets and how to optimally place them to prevent misalignment issues. We observed that the levitation height and lateral static position was extremely sensitive to both magnet strength and spacing. When the train sat too low, it made contact with the track and introduced mechanical friction, which prevented smooth motion. On the other hand, when the train levitated too high, the side-mounted magnets were no longer within an effective range to provide lateral stability, causing the train to become unstable. In addition, we analyzed how the train would interact with the propulsion system. The spacing and alignment of the top-mounted magnets needed to match the electromagnet array so that the propulsion forces would be applied smoothly and consistently. Misalignment in this interface often resulted in uneven forces, causing jerky motion or stalling.

Another key realization from our testing was how sensitive the system was to the mass of the train. Because magnetic force drops off rapidly with distance, even small changes in weight affect the levitation height. This made it clear that a fixed-mass design would not be sufficient, as the optimal configuration depended on the exact magnetic interactions within the system.

Figure 7: Instance of magnetic strength difference during iteration

Final Train Design

The final train design was a two-part modular system consisting of a bottom component and a removable top component, each with a specific function. The bottom portion of the train was designed to interface directly with the track and contained two magnets per side and four on top. This configuration ensured that the train remained centered and could levitate without contacting the track under the right conditions. The top portion of the train was designed to interface with the propulsion system and contained additional permanent magnets aligned with the overhead electromagnets. These magnets allowed the train to be pulled and pushed along the track through controlled magnetic fields. We worked closely with the propulsion team to match the spacing and placement of these magnets to the electromagnet array, ensuring that the forces applied to the train were consistent and effective.

A key feature of the final design was the inclusion of an adjustable gap between the top and bottom components. This space allowed the team to insert flat, rectangular acrylic or MDF pieces to vary the mass of the train. By adjusting the weight, we were able to fine-tune the levitation height and achieve a better balance between stability and propulsion performance. This modular approach also made it easier to iterate on the design and test different configurations for either the train-track interface or the train-propulsion interface without needing complete redesigns or reprints of the entire carriage assembly.

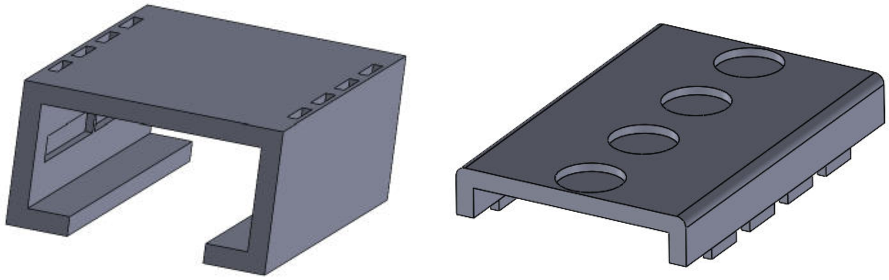


Figure 8: CAD for train bottom (left) and top (right)

Failure Mode and Mitigation

The primary failure mode we identified in our train design was improper levitation height, which could lead to either excessive friction or instability. To address this issue, we implemented the adjustable mass system in our design. By adding or removing acrylic weights within the train, we were able to control the levitation height and maintain the correct balance of magnetic forces. This solution allowed us to quickly adapt the system during testing and ensured that the train could operate within an optimal range without requiring changes to the magnet configuration.

Future Improvements

While our final train design was able to successfully demonstrate levitation and propulsion, there are several areas where we believe improvements could be made. One major area is magnet placement and consistency, as small variations had a significant impact on system performance. Using higher precision manufacturing methods or adjustable magnet mounts could help reduce these issues. Additionally, stronger or more uniform magnets could improve both levitation stability and propulsion efficiency.

We also believe that incorporating more advanced methods for controlling the train's mass distribution could further improve performance. While our adjustable weight system was effective, a more precise or dynamic method of tuning the mass could allow for finer control of levitation height. Finally, future designs could explore incorporating active stabilization or feedback mechanisms to reduce reliance on purely passive magnetic forces. Overall, while our design met the project goals, these improvements could make the system more robust, consistent, and easier to tune.

Team Roles and Responsibilities

- **Ethan:** Carriage structure: Design and 3D print of carriage
- **Helen:** Magnet integration: Work with track group to determine optimal magnet type and placement
- **Harrisen:** Carriage stability/track integration: Work with track group to find best configuration for magnet stability
- **Jason:** Propulsion magnets integration: Work with propulsion team to find which configuration/type of magnets work best to prevent stalling

Propulsion

Preliminary Design and Concept Development

The goal of the propulsion subsystem was to move a passive magnetic cart along a straight track using a sequence of electromagnets controlled in real time. From the beginning, the system was intended to operate as a closed-loop controller: the cart position would be measured using a time-of-flight sensor, processed by an onboard microcontroller, and used to dynamically energize track electromagnets to generate motion in either direction.

Our earliest concept used only two permanent magnets on the cart interacting with a series of fixed electromagnets on the track. However, during early design reviews we realized this configuration would likely cause the cart to rock or pivot as forces shifted between the front and rear magnets. To improve stability, the cart design was changed to use four evenly spaced permanent magnets. This allowed the propulsion system to apply force across a larger section of the cart and significantly reduced pitching motion during operation.

The original electrical design also relied on commercially available iron-core electromagnets and DRV8871 motor driver ICs. During procurement and testing, two major issues emerged. First, the DRV8871 drivers became unavailable, forcing the system to pivot to the SN754410 H-bridge driver. Second, the commercial electromagnets retained residual magnetization after being de-energized, continuously attracting the cart magnets even when polarity was reversed. This behavior prevented reliable repulsion-based propulsion. To solve this issue, we designed and wound custom coils around 3D-printed plastic cores, eliminating remnant magnetic effects and allowing full control of magnetic polarity.

Several engineering calculations and trade studies informed the final design. Coil resistance and wire geometry were selected using basic circuit analysis to keep the electromagnets within the SN754410 driver's 1 A current limit. Using 26 AWG magnet wire, each coil was wound to approximately 500 turns and targeted a resistance of roughly 4.2 Ω based on the operating voltage and desired current draw. We also considered the inductive current rise behavior of the coils during switching to ensure the electromagnets could respond quickly enough for real-time propulsion control. In addition, sensor filtering tradeoffs were evaluated experimentally. A three-sample averaging buffer significantly reduced noise and instability in the control loop, though it introduced approximately 150 ms of response latency, which was determined to be acceptable for the relatively low cart speeds used in the system.

Final System Design

The propulsion system is centered around an Arduino Mega R3 microcontroller, which coordinates the electromagnet array, time-of-flight sensor, display, and joystick input. A dual-output bench power supply provided separate voltage rails: 4.2 V for the electromagnet coils and 5 V for the control electronics and display.

The electromagnet array consists of twenty custom-wound coils spaced 1.6 inches (40.6 mm) apart along the track. Each coil was wound to approximately 4.2 Ω to maintain safe operating current through the SN754410 driver ICs. Ten SN754410 quadruple half-H driver ICs were used to create twenty full H-bridge channels, allowing each electromagnet to operate in attraction, repulsion, or off states. The driver enable pins were permanently tied high, and all driver grounds were connected to provide both electrical grounding and thermal dissipation. The figure below shows the wiring and board setup for all electromagnets and sensors

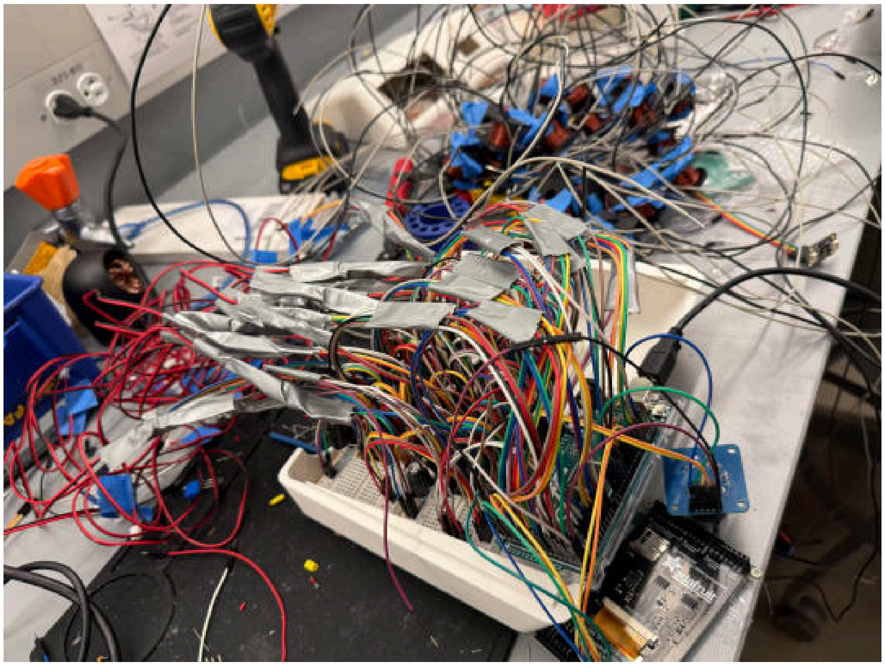


Figure 9: Wiring of board, sensors, and electromagnets

A VL53L1X time-of-flight sensor at the end of the track provided continuous cart position measurements through the I2C interface. An HX8357D TFT display connected over SPI provided a live interface showing operating mode, cart position, and electromagnet status. An analog thumb joystick was used to command cart direction and switch between operating modes.

The firmware was built around a four-mode state machine consisting of Setup, Calibration, Operation, and All Off modes. Setup mode allowed individual testing of all electromagnets and generated a polarity inversion table to compensate for coils that were wound or wired in reverse. Calibration mode locked the cart at the start of the track using alternating magnetic polarity and established the positional offset used during operation.

During normal operation, the firmware continuously tracked the cart position and energized the surrounding electromagnets to create a traveling magnetic wave. The four magnets directly beneath the cart, along with one neighboring magnet on either side, were activated while all others remained off. As the cart crossed from one magnetic zone to the next, the polarity pattern inverted to maintain force in the commanded direction.

Sensor measurements were filtered using a three-sample averaging buffer to reduce noise and prevent instability in the control loop. The display used selective redraw logic so only changing elements were updated, reducing flicker and improving responsiveness.

Integration with the Full System

The propulsion subsystem required close coordination with both the cart and track teams. The cart team matched the spacing of the onboard permanent magnets to the 40.6 mm spacing of the track electromagnets to ensure proper interaction with the magnetic wave. The track team worked with us to maintain a consistent 1/8-inch air gap between the cart magnets and the track electromagnets, balancing magnetic coupling strength with mechanical clearance.

We also coordinated with the track team on the mounting geometry for the VL53L1X sensor to ensure a clear line of sight along the track while maintaining a rigid mounting structure. Because the firmware and electronics were developed modularly, much of the propulsion system could be tested independently before full integration onto the final assembled track.

Unfortunately, since we didn't have a testable track until closely before the presentation day of the project, we were somewhat limited in how much integration testing we could do, so the system performance was slightly inconsistent. The track and cart also had an impactful amount of friction, so the train did not glide as smoothly as predicted, meaning the propulsion system sometimes struggled to start the motion.

Failure Mode and Mitigation

One major failure mode identified during development was the possibility of the cart becoming trapped in magnetic dead zones. At the boundary between adjacent electromagnets, the net magnetic force approaches zero, making it possible for the cart to stall even while a movement command is applied.

To address this issue, the firmware implemented an automatic recovery routine. If the cart remained stationary while inside a dead zone, the controller first applied a timed burst of alternating attraction and repulsion to generate movement. If the cart still failed to move, the system entered a rapid "jiggle" mode that repeatedly alternated magnetic polarity to shake the cart free. A movement watchdog continuously monitored travel during operation and triggered the same recovery behavior if a stall was detected elsewhere on the track. This recovery logic significantly improved reliability during testing and allowed the system to continue operating even under inconsistent friction or imperfect alignment conditions.

Team Roles and Contributions

- **Ari:** Testing: Evaluated electromagnet options, tested subsystem performance, and assisted with full-system validation, soldering, assembly, and troubleshooting.
- **Dan:** Electronics: Assembled, soldered, and tested the electrical hardware, including the driver circuits and power distribution system.
- **Josh:** Housing and Integration: Designed and manufactured housings and mounting structures for the electromagnets, electronics, and time-of-flight sensor, and coordinated subsystem integration.
- **Sam:** Electronics / Project Management: Assisted with electronics assembly and testing while coordinating overall subsystem organization and integration efforts.

Bill of Materials (BOM)

This BOM only considers materials present in the final product. It excludes materials bought during testing, but omitted in the final construction.

Quantity	Item Name	Cost
5	LOVIMAG Powerful Neodymium Bar Magnets, Rare Earth Metal Neodymium Magnet - 60 x 10 x 3 mm, Pack of 24	$89.95
As needed	PLA	$0
As needed	Acrylic Sheet	$0
10	SN754410 Quadruple Half-H Drivers	$0 (Detkin)
1	Arduino Mega R3	$49.90
2	Adafruit VL53L1X Time of Flight Distance Sensor	$0 (Detkin)
1	Analog 2-axis Thumb Joystick W/button	$0 (Detkin)
1	Adafruit 1.9" 320x170 Color IPS HX8357D	$0 (Detkin)
2	Breadboards	$0 (Detkin)
As needed	Jumper cables	$0 (Detkin)
20	100 nanofarad ceramic caps	$0 (Detkin)
10	100 microfarads electrolytic caps	$0 (Detkin)
2	Copper wire coils	$78.48
As needed	Resistors	$0 (Detkin)
Total:		$218.33