Model Maglev Train

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Abstract

The goal of this project was to build a model maglev [magnetic levitation] train. The train would be propelled by a linear motor system and would be levitated by a diamagnetic material over a magnetic track. The linear motor was built, but due to time and budget constraints the levitation system was not added. Overall the train was very powerful, achieving an acceleration of roughly 5.4 m/s/s, but it was also highly inefficient, achieving an efficiency of roughly 9%. To make the train more efficient in the future, superconducting electromagnets should be used so that a high current could be obtained without losing energy to heat dissipation. The train and track were built so that a levitation system could possibly be added in the future. Though powerful, the train and track were highly expensive to build, and more cost-effective technology would be necessary to make maglev trains feasible.

Motivation

The idea for this project came from an article in Scientific American [1] that described proposed maglev systems around the world and their potential use for mass transportation in the future. The goal of this project was to gain a better understanding of maglev trains and to assess their advantages in speed and efficiency relative to current train systems as well as their disadvantages in cost and design.

Introduction

High-speed rail has proved to be a very practical source of long-distance transportation. The first high-speed train line opened in Japan in 1964, connecting Tokyo and Osaka at speeds of up to 200 km/h [2]. Current high-speed rail technology can achieve speeds of about...
270-350 km/h [1, 3], making it comparable to air travel in terms of speed over short distances of about 700 km [1]. In fact, trips on high-speed rail are often shorter than trips by plane because rail trips are not delayed by weather. More importantly, high-speed rail is an environmentally friendly mode of transportation that uses only a fraction of the energy planes and cars require, using clean electricity instead of fossil fuels as its source of energy [1]. Yet despite the huge success high-speed trains have achieved throughout the world, researchers are still trying to develop new technologies to make rail travel even faster and more efficient.

Maglev trains have been the main technology of interest to researchers in this field. They were first proposed in the 1960s by two physicists at Brookhaven National Laboratory, whose vision led to large-scale research projects in Japan and Germany [1]. Since then, maglev test tracks have been built in countries all around the world, and the first commercially operating maglev train opened in Shanghai in 2004 [4]. Maglev is defined as a “family of technologies in which a vehicle is suspended, guided, and propelled by means of magnetic forces” [1]. Generally, magnets and electromagnets are oriented so that the train levitates off the track just enough to avoid frictional contact. This same magnetic system or a separate one is also used to propel and guide the train (see Theory of Operation, below).

The major advantage of maglev trains is speed (up to 580 km/h [3]), which increases the range in which rail travel is comparable to air travel. Other advantages include much greater energy efficiency, since levitation eliminates all friction normally created by rails; reduced noise pollution, again due to reduced friction; and faster acceleration, which further reduces the travel time. The major disadvantage, which has been the primary obstacle to maglev projects throughout the world, is cost, because unlike with conventional high-speed rail, completely new infrastructure must be built. The cost for this can reach $100 billion [3].

This project was chosen to investigate maglev trains. The design for this maglev train was not based on any current maglev technology, nor does it seek to improve on any current technology. Rather, the pur-
pose of this project was to build a working model of a maglev train in order to better understand the principles behind magnetic levitation and propulsion. Efficiency and power were other factors investigated over the course of this project. Though the efficiency and power of the train built in this project were not improved upon after building the model, possible improvements were brainstormed, and they are discussed later in this paper.

**Theory of Operation**

The propulsion system used is known as a linear motor. Unlike a conventional motor, a linear motor creates linear rather than circular motion. As mentioned above, the major principle behind its operation is magnetic repulsion.

Permanent magnets on the rails directly next to the electromagnets (Figure 1) exert a magnetic field $B_p$. Electromagnets also exerts a magnetic field $B_e$. $B_e$ can be approximated as:

$$B_e \approx \mu_0 n I$$

where $n$ is the number of coils, and $I$ is the current [5]. (The actual equation is slightly more complicated, but this equation is used to show that $B_e$ is roughly proportional to the current.) The direction of these magnetic fields can be seen in Figure 1a. Since these magnetic fields are opposing each other, there is a repulsive force that pushes the electromagnet away. The electromagnet experiences two repulsive forces, one from the electromagnet on each rail. As can be seen in the figure, the direction of these repulsive forces is away from their respective permanent magnets; and since the two permanent magnets are opposite each other, in theory the two repulsive forces would cancel each other out and the net force would zero. However, the probability that the electromagnet is lined up exactly with the permanent magnets is extremely low. If the electromagnet is even the slightest bit off center—for example, if the electromagnet is below the center (see Figure 1b)—the force from the left permanent magnet will have a right and a downward component, while the force from the right permanent
magnet will have a left and downward component. Though the left and right components cancel each other out by symmetry, there is still a net downward component, giving the electromagnet, and therefore the train, a net acceleration downwards.

When the train is started the electromagnet will in all likelihood not be perfectly lined up, so there will be a net force downwards. Also, if the train has some velocity, it will have enough inertia to move to this point where it will feel the net downward force, and so will continue to move even faster downwards. Furthermore, the train will be in the magnetic field $B_{p2}$, which is the field due to the set of permanent magnets directly below the first set, and as seen in Figure 1c, the fields are pointing in the same direction. So there is an attractive force downwards, and by the same symmetry arguments used above, the train is also accelerated downwards by this second set of forces as well.

When the train moves to the next set of magnets—the ones that it is attracted to—there will be an attractive force that resists motion. However, a sensor in the circuit senses the change in magnetic field, which sends a signal that causes the current to reverse (see Appendices A and B for circuit information). Thus the magnetic field of the electromagnet is in the opposite direction, the attractive force becomes a repulsive force, and the propulsion cycle continues.

Since both the permanent magnets and the electromagnets are dipoles, it is very difficult to calculate the exact force experienced by the cart. Furthermore, many of the components, especially the permanent magnets, are not laid out perfectly on the track, which would cause any such calculations to be only approximations. However, it is shown in the equation above that $B_e$ is proportional to the current going through the electromagnet, and it can be assumed that when $B_e$ increases, the forces of repulsion/attraction due to the permanent magnets also increase (most likely $B_e \sim F$). Thus the force experienced by the train is roughly proportional to the current going through the electromagnet. Current can be calculated using Ohm’s law: $I = \Delta V/R$, where $\Delta V$ is the potential difference across the power source and $R$ is the resistance of the electromagnet.
Linear motors have one key advantage that makes them much more powerful than conventional motor/engine-based propulsion systems: they don’t rely on friction. In cars, for example, to convert rotational motion into linear motion there must be friction between the wheels and the ground so that the wheels can push the car forward. Yet friction also reduces the efficiency of the car because as the car moves, work is done by friction, generating heat and reducing the kinetic energy of the car. With a linear propulsion system, friction is not required to propel the vehicle because magnetic attraction and repulsion do the job. So in fact the friction between the vehicle and the ground could be zero, which would give the vehicle vastly greater efficiency. If the vehicle were to levitate off the ground there would be no friction, and the only force the vehicle would be combating would be air resistance. This is in fact what maglev trains do: they levitate off the ground in order to achieve almost zero friction.

**Figure 1:** Magnetic fields of the permanent magnet and electromagnets and the resultant force. 1a) When magnets and electromagnet are perfectly lined up, the repulsion forces on the electromagnet oppose each other and cancel each other out. 1b) With a slight perturbation, the sideways component of the forces will cancel each other out, but the downwards components add to create a net force downwards. 1c) The attractive forces downward caused by the next magnets in the series also result in a net downwards force, making the downwards pull even stronger.
To create levitation, a magnetic repulsion force is used to counteract the force of gravity. The appropriate magnetic material must be used to achieve levitation. Magnetic materials are classified into three categories: paramagnetic, diamagnetic, and ferromagnetic (see Figure 2) [6]. Paramagnetic materials are materials that, when placed in a magnetic field, experience an attractive force toward the source of the field. In a paramagnetic material, the atoms, which are magnetic dipoles, are able to rotate and orient themselves in the direction of the permanent magnet. The result is a net magnetic field produced by the material in the same direction as the permanent field, resulting in an attractive force.

Diamagnetic materials are essentially opposite to paramagnetic materials. If placed in a permanent magnetic field they will experience a repulsive force. When the material experiences a change in magnetic field, a current is induced in the material. According to Lenz’s law, the magnetic field induced must oppose the direction of the other magnetic field (see Figure 3) [5]. Since current interacting with a perpendicular magnetic field produces a net force perpendicular to both of them [5], the fringing magnetic field interacts with the current to produce a net force away from the magnet (see Figure 3 for an explanation with vectors). Thus the diamagnetic material is repelled from the source of the magnetic field. Diamagnetic materials are the rarest of magnetic materials, because for a material to be truly diamagnetic, it should experience a repulsion even when the magnetic field inside is not changing [6]. In most circumstances this would require the current to continue flowing even when no current is being induced on the material. This in turn requires very low resistance. Because of this, superconductors—materials with an electrical resistance of effectively zero—are the most effective diamagnetic materials. Non-superconducting diamagnetic materials are more practical (since superconductors are rare and require supercooling to acquire superconductivity), but because they do not have superconductivity their diamagnetism is weaker.

Ferromagnetic materials are essentially permanent magnets. In these materials, quantum effects cause the “spin” (which is what causes a magnetic moment) of the electrons to always be oriented so that there is a net magnetic dipole [6]. Thus these materials always produce a magnetic field.
It might seem that magnetic levitation could be achieved by simply taking two permanent magnets (ferromagnets), or a combination of them, and orienting them so that they repelled each other. Magnetic levitation is much more complicated than that, however. Samuel Earnshaw proved in 1842 that it is impossible to create any sort of stable levitation using stable “charges” that rely on any classical inverse square force [6]. In terms of magnetism, Earnshaw’s theorem states that it is impossible to stably levitate a permanent magnet using other permanent magnets. A proof for this theorem can be found in Appendix D.

Figure 2: Diagrams explaining the different types of magnetism. Ferromagnetic materials are permanent magnets, diamagnetic materials are repelled when put in a magnetic field, and paramagnetic materials are attracted when put in a magnetic field. (Image taken from source [6]).
Figure 3: Model of a diamagnetic material repelling a magnet. The diamagnetic material is the disk in the center. A changing magnetic field induces a current in the material that opposes the magnetic field. In this example, current flows clockwise. Due to the fringing magnetic field from the permanent magnet, there is a field component on the same plane as the current flow. By the right hand rule, a force is felt perpendicular to the plane of current and field. In this example, this force is up. In all cases, the force will be pointing away from the magnet. (This can be shown using deduction analogous to this). Thus a diamagnetic material will always repel a permanent magnet or any type of net magnetic dipole.

However, this does not imply that magnetic levitation is impossible. If non-ferromagnetic materials are used to levitate a permanent magnet, the assumption of the theorem is false and therefore the theorem does not hold. Obviously, paramagnetic materials cannot be used to create levitation, because levitation relies on a repulsive force while paramagnetic materials only undergo an attractive force. Diamagnetic materials, on the other hand, can be used. The diamagnetic material repels all of the magnetic field lines it encounters. Thus, if a diamagnetic material is placed above a magnet, the sideways component of the repulsion force is exactly zero by symmetry. Only a net force upwards is felt, resulting in levitation.
Prototype

See Appendix A for drawings. A diagram for the prototype track and propulsion system can be seen in Figure 4. The track used a linear motor propulsion system as described above in the theory section. Magnets were placed so that there were alternating pairs of magnets (see Figure 4). There were two walls with magnets so the train would experience a symmetrical force on both sides. A plastic rail was used to guide the train. Originally, a levitation prototype was also to be built, but due to time and budget constraints this did not happen.

Figure 5 is a diagram of the circuit used to drive the train. The electromagnets were hooked up to a relay that would reverse the direction of the current when switched. The relay was triggered by a Hall effect sensor hooked up to a transistor. When the train moved from one set of permanent magnets to another, the Hall effect sensor sent a signal to the transistor, which switched the relay. This caused the current to reverse, which, as mentioned in the theory section above, changed the direction of the magnetic field in the electromagnet, allowing the train to continue repelling the permanent magnets and so keep moving. See Figure 5 for circuit specifics.

Final Design

See Appendix B for diagrams. The final track was built based on the prototype track. Due to time constraints, a levitation system was not added. This would have required additional research and testing that could have taken months to complete. Originally, a circular track was to be built, but due to budget constraints a smaller track design was needed. A long, straight track was chosen as the final design, similar to the prototype design. The design was made flexible so that in future projects a levitation system could be added and the track expanded.

The track (Figure 6) was made out of HPDE plastic. This material was chosen because it is sturdy and durable but also easy to cut and mold. It has a low coefficient of friction against the wheels of the car used, allowing for little energy to be lost to friction. The magnetic propulsion system was exactly the same as in the prototype system, with \( \frac{1}{4} \)" magnets alternating in polarity every other magnet. The two rails with
magnets were placed at the optimum position so that they would be as close as possible to the electromagnets without being attracted to their iron core. This allowed for the maximum repulsive force.

The circuit used on the final design (Figure 7) was the same as on the prototype, with only a few minor tweaks (see the description of Figure 7). The only major change was using electromagnets with lower resistance. Though this increased the power dissipated by the electromagnets in the form of heat, it increased their strength and so allowed for greater acceleration.

Results

Table 1 is a specification sheet for the final track.

<table>
<thead>
<tr>
<th>Mass</th>
<th>0.375 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>See Appendix A</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>9V</td>
</tr>
<tr>
<td>Average current (at 9.00V)</td>
<td>1.56A ± 0.03A</td>
</tr>
<tr>
<td>Power input (at 9.00V)</td>
<td>14.0W ± 0.3W</td>
</tr>
<tr>
<td>Average acceleration (with 9.00V input voltage)</td>
<td>5.4 m/s/s ± 0.3 m/s/s</td>
</tr>
<tr>
<td>Average power output (with 9.00V input voltage)</td>
<td>1.3W ± 0.1W</td>
</tr>
</tbody>
</table>

Table 1: Specification sheet

Data for the electrical measurements was collected using a multimeter. Power was calculated using the equation $P = IV$. Measurements for the average acceleration and the power output were calculated using a motion detector that recorded position, velocity, and acceleration as a function of time (see Appendix C, Figure 8). The average acceleration was found by finding the slope of the linear best-fit line on the velocity vs. time graph. The average power output was found by finding the final kinetic energy of the train using the equation $K = \frac{1}{2}mv^2$ and then dividing over the total time the train was in motion to get the average power.
As seen from this data, the train achieved remarkable performance. It had a very large acceleration, which could easily have been improved upon if stronger magnets were used, or if the magnets were placed closer to the track, or if more current was flowing through the electromagnets. If a levitation system were added to the track (assuming that the train had an aerodynamic design and minimal air resistance), acceleration would not decrease until air resistance became a significant factor, which would only happen at very high speeds. Thus the train could, in theory, achieve speeds much higher than those attained by conventionally propelled trains.

As seen in the results, the efficiency for this particular train is rather low, roughly 9%. At first it would appear that friction or air resistance were the biggest factors for this inefficiency, but the force of friction was measured to be insignificantly small and the train was not traveling fast enough for air resistance to be a significant factor. Rather, this inefficiency can be blamed on heat dissipation in the electromagnets. The electromagnets have high current constantly running through them, and since they have resistance, power is dissipated across them in the form of heat proportional to the total current squared. Since current is always running through the circuit, the electromagnets are always dissipating power. Yet the efficient work done by the system occurs for only a small period of time, that is, when the direction of current in the electromagnets is switched. For the train to run continuously, the magnetic field in the electromagnets must change directions so as to constantly change the magnetic attraction forces into magnetic repulsion forces. This requires work, provided by the battery, but the work creates useful energy. This only accounts for a fraction of the energy used, however. Power is dissipated through the electromagnets the whole time the train is running, yet it is doing useful work only in the split second when the direction of the current is reversed.

To improve on this design and to make it more efficient, superconducting electromagnets should be used. As mentioned above, superconducting materials have a resistance of effectively zero, and current can run in them even when they are not hooked up to a potential difference. The direction of current can be easily switched via a battery, but once a suitable current has been obtained no power is needed to main-
tain the current. So a superconducting electromagnet can still have a magnetic dipole movement even when no power is being sent through it. If these were used instead of conventional electromagnets, power would only need to be fed through the system when the direction of current needed to be changed. Though this would require energy, its output would be almost entirely useful energy, and the efficiency of the train as a whole would be much higher, probably close to optimum efficiency.

Conclusion

Maglev trains prove to be a promising technology for the future. Though a levitation system could not be built in this project, the linear motor that was built proved to be very powerful. If a levitation system were to be built and superconducting electromagnets used instead of conventional electromagnets, the train would be not only very powerful but highly efficient as well.

To improve on this design in the future, efficiency should be optimized by adding a levitation system and using superconducting electromagnets to prevent any energy loss due to friction or heat dissipation. In the future one could also improve the circuit, possibly using sensors and a microcontroller, to regulate energy use. The microcontroller could tell the electromagnets to turn off once a certain velocity is reached and turn back on again only when needed to maintain the velocity. Future projects could add these features to the track and train.

Nevertheless, the most important and most difficult improvement that must be made to this project is to cut down on the costs. Permanent magnets are very expensive, and building a linear propulsion system requires a lot of magnets. Even for a 36” track, over $30 was spent on magnets alone. If a levitation system were added, the costs would be even greater. If an actual maglev train were to be built, the costs would be much too high for it to be reasonably implemented. The design in this project was not intended to minimize cost; however, for maglev trains to become feasible, the technology would need to become much more cost effective.
Acknowledgements

I would like to thank, first and foremost, Dr. James Dann for giving me ideas and suggestions, and for giving me feedback and keeping me on track (no pun intended) with my project. I would also like to thank Jeremy Pope for his help with the circuit design, Chase Blokker for sharing with me his experiences from a similar project, and Menlo Facilities for their help with cutting the material for the final track. Finally, I would like to thank Menlo School for the opportunity to take the Applied Science Research class.

Appendix A: Prototype Track and Circuit

Figure 4: Prototype of track. Note this diagram only shows the propulsion system. The levitation system was not implemented. A wheeled train (not shown) was used on this track. Darker disks represent magnets with north pole facing forward; lighter disks represent magnets with south pole facing forward. [For a color version of this figure, see the online version of the article available at http://roundtable.menloschool.org.] Two electromagnets will be placed on the train, which (controlled by the circuit) will change the direction of current so that they will always repel the permanent magnets they are in front of, causing propulsion. UPDATE: On the first prototype, like poles were positioned directly across from each other on the two rails. This was modified so that opposite poles are across from each other (as seen in the picture, e.g. south poles are across from north poles). This was so that a single electromagnet (see Figure 3 for the positioning of the electromagnet) could be used to get a repulsive force from both rails at the same time, instead of one side being attracted to the rails and the other side being repelled.
Figure 5: Circuit used in prototype. A Hall chip (HC) sends a signal to the transistor with a sensed change in magnetic field that causes current either to flow or cease to flow in the transistor. This current is sent through a relay, which, when switched, reverses the direction of current in the output. The output is to be sent to two electromagnets in parallel that were built for the prototype (one of which is roughly 50Ω, one of which is roughly 10Ω), which will be placed on either side of the train. UPDATE: The 15Ω resistor that was originally attached to the relay's switch was removed to give more power to the electromagnets.

Appendix B: Final Track and Circuit

Figure 6: Final track design. This design was modeled after the prototype design, except it was roughly tripled in size. Track was made out of HPDE plastic, and instead of using pre-made external rails, the plastic was shaped so there would be rails built onto the track. There are a total of 48 holes on each side for the magnets (not shown). The magnets used were $\frac{1}{2}$” diameter neodymium magnets, spaced 0.75” apart and oriented in the same way as on the prototype (every other one alternating). Both sides of the track are symmetrical, but with the magnets oriented in opposite directions, as on the prototype. The same wheeled cart was used with a similar circuit. NOTE: The final product's dimensions do not perfectly match those of the drawing, but they are close.
Figure 7: The final circuit. Similar to the prototype, with minor changes. Smaller resistors were used in conjunction with the Hall effect chip circuit (the 8.3KΩ and the 16Ω resistors) so that the chip would be able to switch the relay even if less than 9.0V was fed through it. Also, the LEDs were taken out of the circuit because the current running through the circuit caused them to burn out. The output voltage was hooked up to two roughly 12Ω electromagnets, for a total resistance of about 6Ω.

Appendix C: Example Data

Figure 8: Velocity vs. time graph for the train moving down the track. This data was collected by a motion detector. Total run took 0.20s. The best-fit line represents the average acceleration. From this, the final kinetic energy was calculated using the final velocity value, and from this the average power output was calculated.
Appendix D: Proofs for Theorems

Earnshaw’s Theorem

Note: This proof only proves the case for magnets/magnetic fields. The proof for any other classical inverse square law is analogous. The following proof was taken from source [7].

Gauss’s law for magnetic fields states:

\[ \int \mathbf{B} \cdot d\mathbf{A} = 0 \]

This is true because permanent magnets are only found as non-changing dipoles, and so the net “magnetic charge” within a given surface must be zero. Written in differential form, Gauss’s law is:

\[ \nabla \cdot \mathbf{B} = 0 \]

It can also be shown by Gauss’s law that the curl of the magnetic field is zero as well.

For there to be a point where magnetic levitation is stable using permanent magnets, the potential energy must be at a minimum. There can only be a local minimum for potential energy \( U \) if \( \nabla^2 U > 0 \), where \( \nabla^2 U \) is the laplacian of \( U \) (the sum of the second order non-mixed partials). However, since \( U = -\mathbf{M} \cdot \mathbf{B} \) (where \( \mathbf{M} \) is the dipole moment of the magnets):

\[
\nabla^2 U = \nabla^2 (-\mathbf{M} \cdot \mathbf{B}) = -\nabla^2 \left( M_x B_x + M_y B_y + M_z B_z \right)
\]

\[
= - \left[ \frac{\partial^2}{\partial x^2} \left( M_x B_x + M_y B_y + M_z B_z \right) + \frac{\partial^2}{\partial y^2} \left( M_x B_x + M_y B_y + M_z B_z \right) + \frac{\partial^2}{\partial z^2} \left( M_x B_x + M_y B_y + M_z B_z \right) \right]
\]

\[
= - \left[ M_x \left( \frac{\partial^2 B_x}{\partial x^2} + \frac{\partial^2 B_y}{\partial y^2} + \frac{\partial^2 B_z}{\partial z^2} \right) + M_y \left( \frac{\partial^2 B_x}{\partial x^2} + \frac{\partial^2 B_y}{\partial y^2} + \frac{\partial^2 B_z}{\partial z^2} \right) + M_z \left( \frac{\partial^2 B_x}{\partial x^2} + \frac{\partial^2 B_y}{\partial y^2} + \frac{\partial^2 B_z}{\partial z^2} \right) \right]
\]

\[
= - \left[ M_x \left( \nabla^2 B_x \right) + M_y \left( \nabla^2 B_y \right) + M_z \left( \nabla^2 B_z \right) \right]
\]
The laplacian of each of the magnetic field components can be calculated to be zero, as shown below. $\nabla^2 B_x$ was calculated in this example. Calculations for the other components can be done analogously to this example.

$$\nabla^2 B_x = \frac{\partial}{\partial x} \frac{\partial}{\partial x} B_x + \frac{\partial}{\partial y} \frac{\partial}{\partial y} B_x + \frac{\partial}{\partial z} \frac{\partial}{\partial z} B_x$$

Since the curl of $B$ is zero:

$$\frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} \quad \text{and} \quad \frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial x}$$

Therefore:

$$\nabla^2 B_x = \frac{\partial}{\partial x} \left( \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} \right)$$

$$= \frac{\partial}{\partial x} \left( \nabla \cdot \vec{B} \right)$$

But Gauss's law states that $\nabla \cdot \vec{B} = 0$.

Therefore: $\nabla^2 B_x = 0$, $\nabla^2 B_y = 0$, $\nabla^2 B_z = 0$. And therefore, $\nabla^2 U = 0$, so there is no local minimum of potential energy. Thus stable levitation cannot be achieved.

Of course, this proof only holds true for permanent magnets (ferromagnets). If diamagnetic materials are used, Gauss's law cannot apply, since it assumes that the enclosed magnetic dipole moments are constant and not changing [7]. This is why diamagnetic materials can cause magnetic levitation—the theorem is not violated. Also, this theorem only holds true for classical inverse square laws. When dealing with instances on the quantum level, it is possible to achieve electrostatic or magnetic levitation, because the inverse square laws break down at the quantum level [6].
Appendix E: List of Ordered Parts

The following is a list of parts purchased for the project, including parts bought but not actually used. Other parts were used that are not listed here, but they were either previously owned parts or spares. The prototype track and the electric circuit were all built with previously owned materials. The train itself was a spare part from home. The magnets and the HPDE plastic were the only purchased parts used on the final track.

<table>
<thead>
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<th>Part Description</th>
<th>Used in:</th>
<th>Cost</th>
<th>Store/Website Purchased From</th>
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<tr>
<td>5 cm x 5 cm x 3 mm pyrolytic graphite (diamagnetic material)</td>
<td>Levitation system experimentation (not used in final design)</td>
<td>$55.00</td>
<td>K&amp;J Magnetics</td>
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<tr>
<td>1/2” dia. x 1/4” thick axially magnetized neodymium magnets (100)</td>
<td>Propulsion system for final track</td>
<td>$18.00</td>
<td>Magnets 4 Less</td>
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<td>HPDE plastic (18” x 36” x 1”)</td>
<td>Final Track</td>
<td>$80.00</td>
<td>Taft Plastics</td>
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References


