Electromagnetic Train

Final Report

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Revised: December 5th, 2017

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1. Introduction

1.1 Project Statement

The primary goal of this project is to design a simple electromagnetic train. The second goal is to use this model to help us understand some of the fundamental concepts and the physics behind the electromagnetic train.

1.2 Purpose

Several EE/CprE students at ISU have expressed their frustrations with the concepts of electromagnetics. The concepts are too difficult, unintuitive, and uninteresting to many students. Professor Song has proposed designing a simple electromagnetic train to help recapture the students' interest in electromagnetics.

1.3 Goal

Our primary goal with this project was to design an electromagnetic train that would complete at least one complete circuit around the track. The train would not slow down, stop, or get stuck (in the track).

1.3.1 Goals Accomplished

- Successfully designed a working prototype
- The train could complete several circuits around the track
- The train did not slow down
- The train did not stop or get stuck

2. Deliverables

At the end of this project, we have managed to achieve the following:

- A working electromagnetic train prototype
- Force calculations of the system
- A report containing all of the required specs for our project
- A powerpoint explaining the physics that allow our train to run.

3. Design Standards

3.1 System Specifications

3.1.1 Non-Functional Specifications

Coil

- Turns ratio needs to be optimized to balance between speed, current, and visibility.
- Size and distance should be constant.
- The cost needs to be considered when deciding its gauge size.

- **Battery**

  - Should be replaceable but reusable.
  - Should provide enough energy to power the system.

- **Magnets**

  - Should be as strong as possible.
  - Able to stay intact on the battery.

- **Force**

  Need to get the exact amount of force generated by the system and explain it.

3.1.2 Functional Specifications

Coil

- Change the number of turns per inch.
- Determine wire resistance to limit the current.

- **Battery**

  - Commercially available rechargeable batteries.
  - Fully charged

- **Magnets**

  - Strongest commercially available permanent magnets.

- **Force**

  - Use knowledge from electromagnetism class to calculate the force

3.2 Design

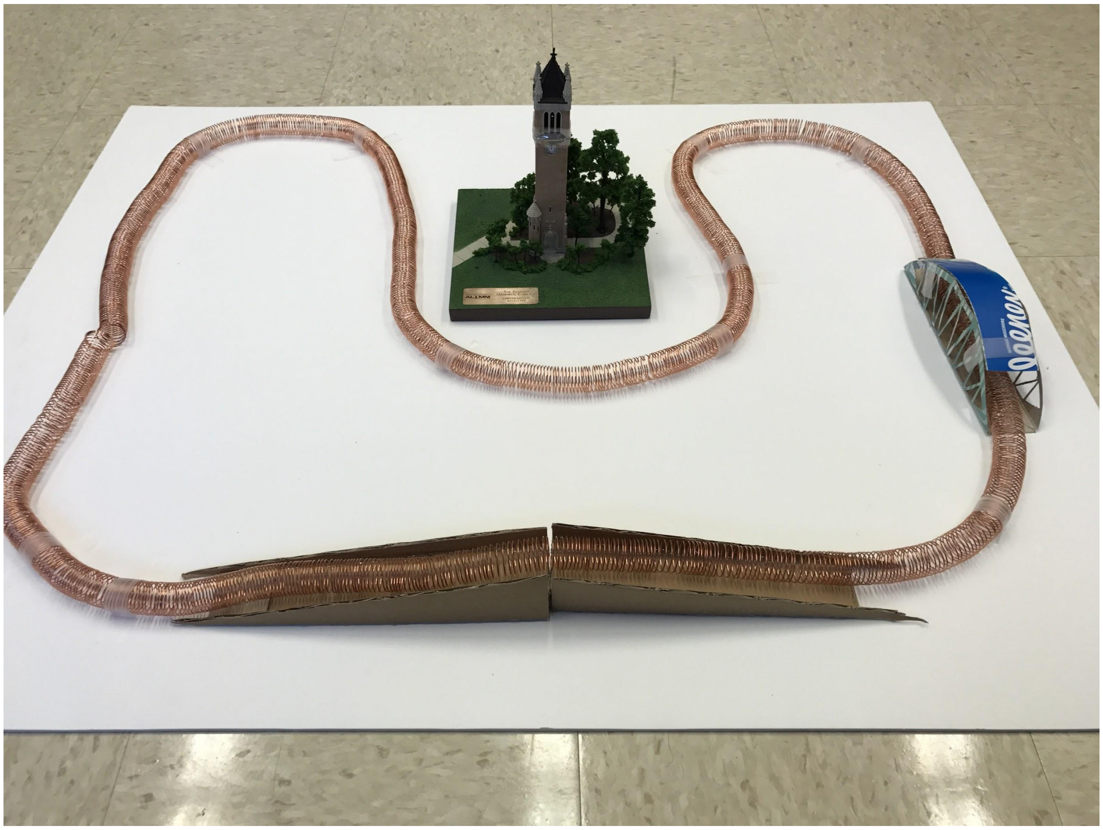


Figure 1: Circuit Design for the project

The main purpose of our project is to collect several different types data from a simple electromagnetic train. The data would be collected by observing how the coil's turn ratio and the number of magnets used would affect the speed and energy efficiency of the train. We would then use that data to help us optimize our design.

Cost:

Given that we had a limited budget of $100, we had to limit our major cost factor, wire size, to a gauge size of AWG18 (this was the cheapest size we could find, given our design constraints). The cost for this wire size was around $50 per track. We wanted to work with different wire thicknesses, but we also wanted to minimize our costs. So we selected a wire that was the most cost efficient by having the lowest resistance per dollar, and being malleable enough to turn into coils.

Battery Voltage:

We used rechargeable AA Nickel Cadmium batteries as the main body and power source for our train. We tested fully charged AA and AAA batteries and had them run the tracks until they ran out. We went along with AA batteries. The reason is that the terminals on the AA battery have a larger area of contact compared to the terminals on the AAA battery. This allows the AA battery to maintain better contact with the magnets as compared to the AAA battery.

Data Collection:

We calculated the force on the train by finding the mass of the train, the distance between the two magnets and battery system, the number of turns enclosed in the magnet-battery system, the average radius of the coils, and measuring the acceleration of the train. The resulting force is then cross-referenced with the Lorentz force and the gradient of dipole potential energy. They should be equal, with a small allowance due to friction, eddy currents, and the Lorentz force in the opposite direction.

Visibility:

We limited our turns ratio to 9 turns per inch. We chose this limit so that we could see the train as it traveled through the track. This limit was also chosen as the increase in number of turns has no significant effect on the efficiency of the train. Less turns allowed us to get a better measurement of the speed of the train as well.

Calculation:

After determining that the motion of the train is due to the force on the magnetic dipole in a non-uniform magnetic field, we did the calculations for the force exerted upon the tracks. This was the Lorentz force. We used this force to prove the force equivalency by Newton’s Third Law of Motion. We then verified this value by calculating the force exerted by the train by measuring its acceleration. This force is less than what we expected as we did not account for the frictional force induced by the tracks.

4. Implementation (Development)

4.1 Interface Specifications

A user must be able to assemble the train easily with batteries, copper wire, and a couple of neodymium electromagnets. After the train is assembled, a user must be able to place it on the track and operate the circuit.

4.2 Hardware/Software Specifications

Copper wires:

The copper wires used in this project are size 18 AWG wires. The reason why smaller AWG wires are not used in because the wires will be too thick, thus making the wire harder to be coiled. On the other hand, if the wires are too thin with a larger number of AWG, the number of turns needed to coil will be increased which will make it harder to have a clear vision when the train moves. The wires also have a resistance of 0.2095mΩ/cm to limit the current.

Battery:

Rechargeable AA Nickel-Cadmium battery is used as a power source for the train. This is because the power consumption is high when the train ran continuously on the track. The velocity of the train will be reduced after a couple of rounds on the tracks and replacement of the battery is needed for a more accurate data. Therefore, having a rechargeable battery can save the cost of replacing the battery when it has been depleted. Moreover, the reason why AA battery is more favourable than AAA battery in this project is that it supplies more power to the train which increases its velocity.

Magnets:

N52 neodymium permanent magnets are used in this project. The magnets have to be strong enough to generate sufficient magnetic fields. The strongest magnets available commercially is N52 neodymium magnets which makes it a suitable magnet for this project. Furthermore, the dimension of the magnets used are 5/8 inch because the diameter of the magnets are slightly larger than the diameter of the AA battery. This can prevent the magnets to slip off the battery while also allow electrical contact between the magnets and the coils.

4.3 Process

Coils:

The number of turns per inch used for the coils is 9 turns per inch. We have tested out the velocity of the train. We notice that the velocity of the train varies with different turn ratios of coils. They are as follows, in terms of number of turns per inch: 7, 8, 9, 10, 11. The train is the slowest in the coils that have 7 turns per inch while being the fastest when it have 11. However, 11 is not used in our project because the visibility on the train is at the worst at 11. So, to find a balance between the velocity and visibility on the train, we used 9 turns per inch.

Magnets:

The number of magnets used in this project is 3 on both sides. We have tested out the time taken to complete 1 cycle of the track for 2, 3, and 4 magnets on both sides. The longest time taken to complete the track is the train with 2 magnets. When the train with 4 magnets is used, the length of the train is too long which makes the train harder to turn and decreases its velocity. Thus, 3 magnets are the most suitable number of magnets used for our project.

5. Testing Processes & Results

Mass Calculation

The mass of the whole system, which includes the battery and the magnets are measured as it will be taken into account of the calculation of the force acting upon it and by the train. The mass of the magnets and the battery are first measured and weighed by using a weighing scale. This measurement is the compared to the combination of the magnet attached to the battery weigh. Since the magnets are higher grade magnet we took precaution steps in measuring the mass of both items as the magnets affect the reading of the scale.

Force Acting on The Battery

The force acting on the battery, which causing the battery to move is calculated. We are focusing on the two forces, which are the Lorentz force and the gradient dipole potential energy. The Lorentz force is the force acted upon the coils while the gradient dipole potential energy acts upon the system. The dipole force calculation is shown as below:

$$F = CI,$$

where

$$C = \frac{\mu_0 m N}{L}\left[\frac{1}{R} - \frac{R^2}{(L^2 + R^2)^{3/2}}\right].$$

Where ;

i) L is the distance between the two magnets and battery system.

ii) N is the number of turns within L

iii) R is the average radius of the coil

The Acceleration of The Train

The train acceleration of the train is calculated manually by using frame rate per second (fps) in video format. The train movement in completing one full cycle is recorded by using a mobile phone camera with 30 fps. The delay in every frame is the used to calculate the acceleration of the train. This step is repeated for a few times to get a consistent measurement of acceleration.

Impact of "Turn Ratio"

Before the complete prototype of our train is built, we have tested several "turn ratio" to see the impact on the train speed. We have come up with 7 turns per ratio, 9 turns per ratio, 12 turns per ratio and 14 turns per ratio. As we compared the time to complete the distance of 0.3m at each ratio, the 9 turns is the optimum turns per ratio.

As the number of turns increase the duration of completing the cycle decrease, however, due to the customer requirement, which the train must be viewable in between the gap of the coil turns, 9 turns is the best alternative. However, the train speed cannot be calculated as there are too few frames and the samples are too short in length. But it still provides significant results.

Number of Magnets Used

The train is also tested with different number of magnets, in order to determine the optimum number of magnets that suits the needs of our track and our customer requirement.

Minimum Voltage

The minimum voltage is calculated by using a fully charged AA battery (capacity ~1.5V) to run a full course of the train coil. For every cycle, the battery completed the cycle, the voltage drop is measured and recorded. This step is repeated to get a consistent value and the values are compared.

Results

The total mass of the magnets and battery is 0.143 kg. While the force acting upon the battery are shown below:

The Lorentz Force	-2.8 N
The Gradient Dipole Potential Energy	2.8 N

The acceleration of the train to complete a cycle of the coil with distance 1 metre and 9 turns per inch is 0.16 ms-2. The minimum voltage that the battery needed in order to complete one cycle is 1.274 V. Based on the prototype demonstration, the train can move up to 22 complete cycles that approximately 22 meters with the elevated ramp of 12.6 % steepness. We managed to create a working prototype and tests several variables to come out with this prototype.

6. Timeline

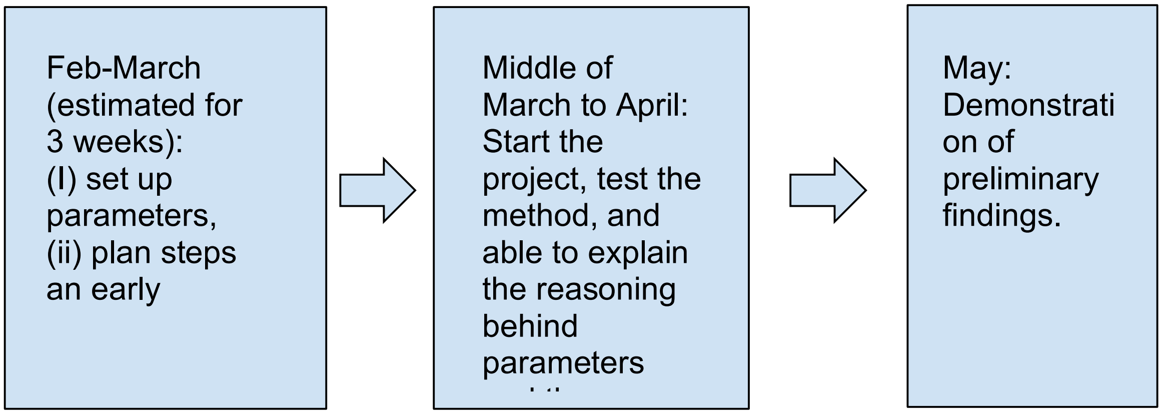


Figure 2: Timeline for last semester

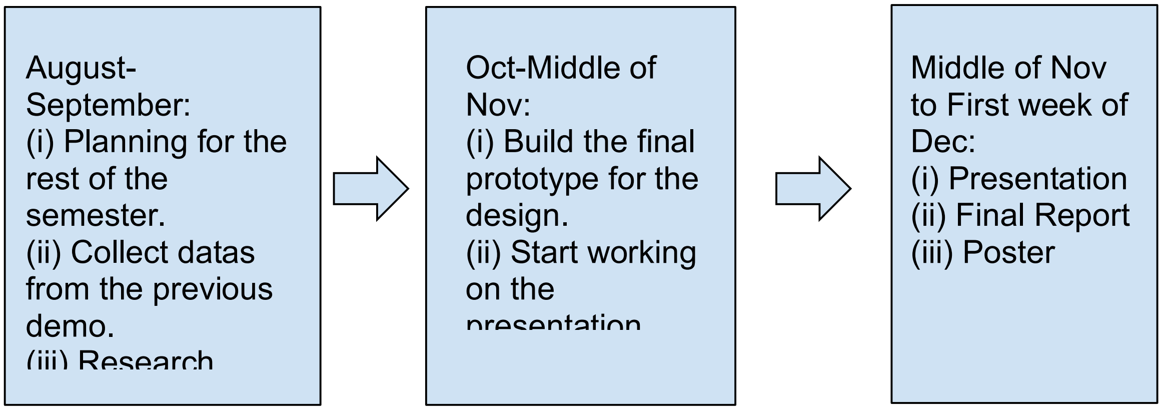


Figure 3: Timeline for this semester

6.1 First Semester

Based on Figure 2, a large model should be done by the end of this semester. This is explained in the chart above.

6.2 Second Semester

Based on Figure 3, a final prototype of the project, presentation and poster for the project will be done by the end of December.

7. Conclusions

To sum it all, our plan for is to create an electromagnetic train that can travel at a fast speed while being efficient at the same time. Our goal is to produce a prototype for the electromagnetic train and understand the principle behind it. Moreover, we need to find the optimal level of both the velocity and efficiency of electromagnetic train. There are a few factors why we are using 9 turns per inch for building the track using the copper wire and 3 magnets at both sides for building the train. We got to improve the speed and efficiency of the train from these designs. Moreover, we explained the physics of the train both overall quantitatively and qualitatively. Lastly, we built a new circuit in the second semester.

8. Appendix

Appendix I: “Operational Manual”

Setup

Train:

The train is made out of a battery with three magnets attached on each terminal of the battery. The magnets have to be position in such a way that the same poles of the magnets make contact with both terminals of the battery. This means that either the south pole of the magnets will face towards the battery or the north pole. To check the poles of the magnets, we placed the magnets of both ends close to one another. If the magnets repel one another, we then know that the poles are the same and vice versa. The two scenarios which can occur which are shown in Figure 4and 5 below.

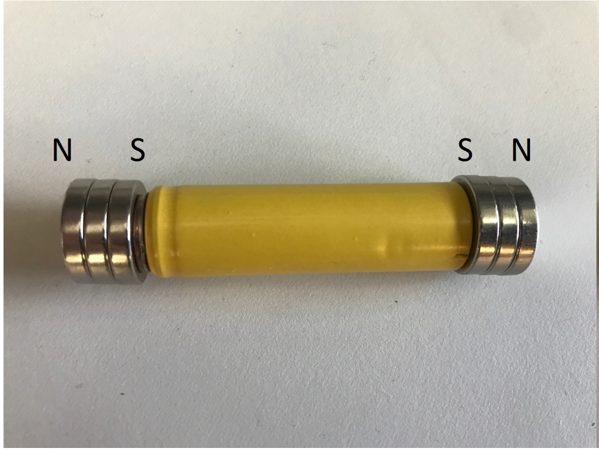


Figure 4

Figure 5

For the positive side of the battery, a washer is placed in between the magnets and the battery. This is to prevent the magnets to go out of position when the train travel through the coils. The setup of the train is as shown in figure 6 below.

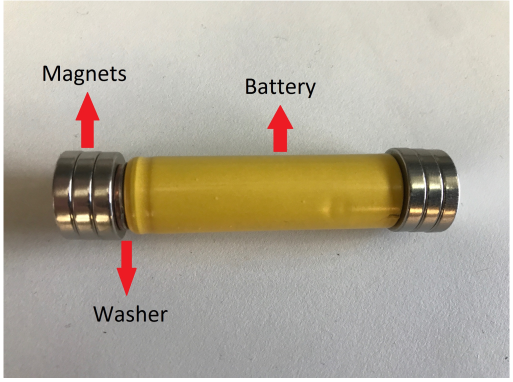


Figure 6: “Train”

Track:

The copper wires used for the track are size 18 AWG wires. The coils are turned by hand on a ½ inch PVC pipe that has outer diameter of 0.840 inch. The turns ratio are kept at 9 turns per inch which is as shown in figure 7 below. When the length of the coils have reached the intended length, the coils can then be arranged to be used as the track for the train as shown in Figure 8 below.

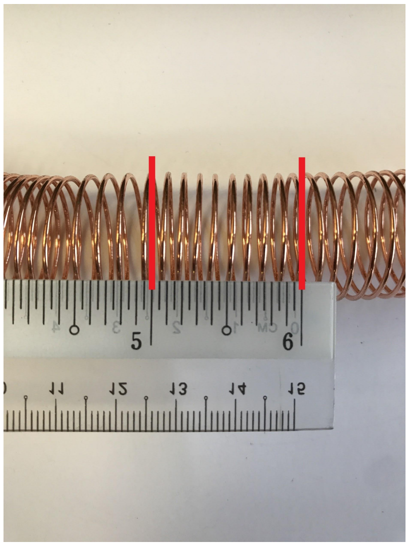


Figure 7: “turn ratio”

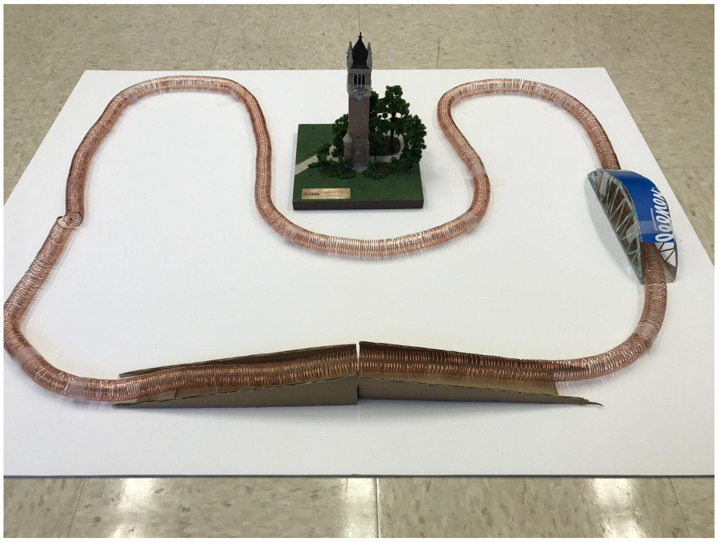


Figure 8: “ Completed track”

Demo

After the train and the track have been setup, the system is then ready for demo. To do so, the train is placed into one end of the track. When both ends of the magnets have physical contact with the coils, the train will either move through the tracks or be repelled. If the train has been repelled, simply flip the ends of the train and place it into the track once again.

Appendix II: “Alternative/ other initial version”

Versions that resulted in failure to achieve

Hot Glue:

At the first version of the prototype, we tried to use hot glue to stick the track onto the board. But the train got stuck and hit the glue while traveling through the track. In this case, we decided to use transparent cellophane tape to tape the track onto the board.

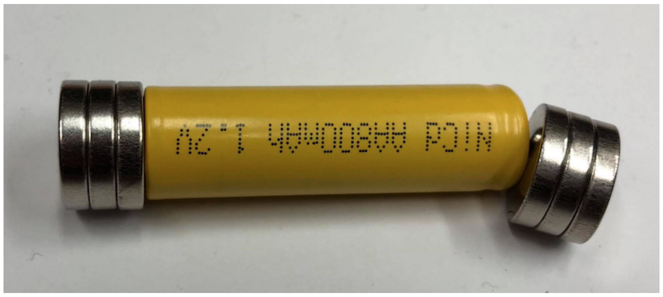


Figure 9

Cellophane tape:

During the first semester, we tried to use cellophane tape to tape the magnets and the positive terminal of the battery. The train will not move because there are no electric contact between magnets and coil. In the semester, we use a washer to support the magnets from tilting as shown in Figure 9. Not all type of washer could move the train, the only type of washer we could use is magnetis washer as shown in Figure 6.

Appendix III: “Other Considerations”

Figure 10

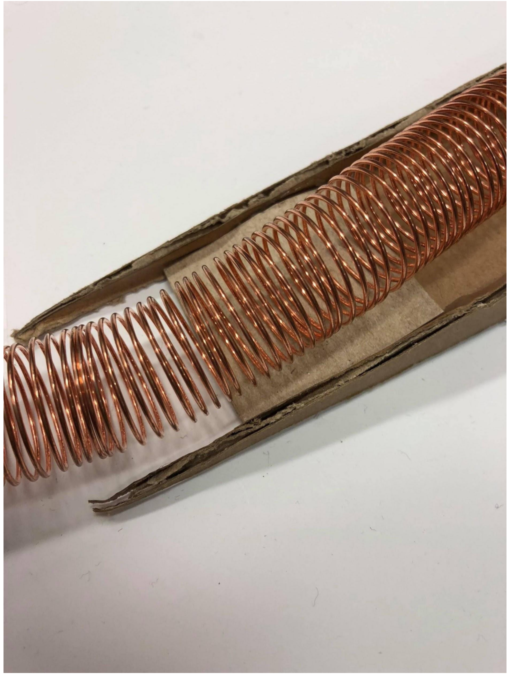
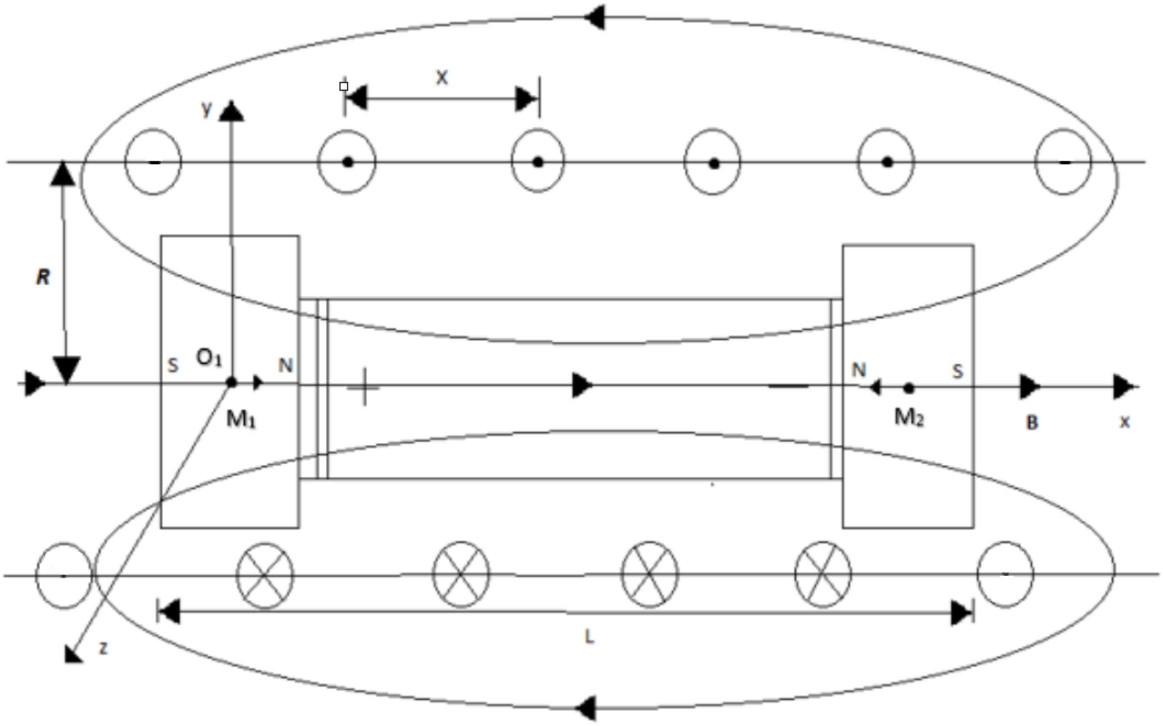


Figure 11

In Figure 10, we could see there is a level at the beginning of the bridge. So we add a small pieces of paper at the beginning of the bridge to avoid the train get stuck at the beginning of the bridge and make sure the train pass through the track without any problem.

We tested the train with multiple magnets, We noticed that it had a higher chance of getting stuck as we added more magnets to the system. We found that 3 magnets on each side of the battery gave us the best results. If we added any more, then the train would sometime get stuck in the track.

Appendix IV: “Calculations”



Gradient of Dipole Potential Energy

In the middle part of the train, where the battery is located, the field lines are exactly parallel thus the system feels no net force. However at the ends of the coil, where the field lines diverge, the magnets will be either pulled into the coil or pushed out of the coil depending on which way round you insert it. The system makes a circuit that generates a magnetic field just in the vicinity of the battery. The geometry means the two magnets are automatically at the ends of the generated magnetic field, where the field is divergent, so a force is exerted on the magnets. The magnets have been carefully aligned so the force on both magnets points in the same direction, and the result is that the magnets and battery move. But as they move, the magnetic field moves with them and you get a constant motion. The calculations below show the calculations for force produced.

- Assume magnets length h radius r and Magnetization M
- $B = -\frac{\mu_0 M}{2}$[5] with magnitude equal to residual magnetism B_r = 1.45T
- Magnetic dipole moment: $m = \pi r^2 ML$
- Potential energy: $U = -m . B$
- Magnetic dipoles: m_1 = (m,0,0), m_2 = (-m,0,0)
- Take B = magnetic field of coil = (B_1,B_2,B_3)
- $U = -mB_1$ $U = mB_2$

- Using Biot-Savart law as the magnetic field is at the point (x,0,0) at the axis of the helix:

which gives the output of: $\boldsymbol{B} = \frac{\mu_0 I}{4\pi} \int_h \frac{dx' \cdot (x-x')}{|\mathbf{x}-x'|^3}$

$$\boldsymbol{x}' = (x', -Rcos(kx'), -Rsin(kx'))$$

- k = 2π/s and s = L/N, the first component of the integral gives

$B_1(x) = \frac{\mu_0 IN}{2L}(\frac{x}{\sqrt{x^2+R^2}} - \frac{x-L}{\sqrt{(x-L)^2+R^2}})$

$$F(0) = -\frac{dU(x)}{dx}\bigg|_{x=0} = \frac{m\left(dB_1(x)\right)}{dx}\bigg|_{x=0}, F(L) = -\left(\frac{dU(x)}{dx}\right)\bigg|_{x=0} = \frac{mdB_1(x)}{dx}\bigg|_{x=0}$$

- Since they are both equal, the total force is F = CI

$$C = \frac{\mu_0 mN}{L} * [\frac{1}{R} - \frac{R^2}{(L^2+R^2)^{\frac{3}{2}}}]$$

The final force calculated is 2.8N after factoring in the variables that we have measured.

The Lorentz Force

The Lorentz force is the force induced by the tracks according to Newton's Third Law. Therefore, it is supposed to be the negative of the force produced by the gradient of dipole potential energy.