Design of a linear motor-based magnetic levitation train prototype

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ABSTRACT

This study explores the modelling of a magnetic levitation train and its implementation using a microcontroller. Magnetic levitation (maglev) is a technology that enables vehicles to levitate and move without wheels. Maglev research has been conducted globally, but maglev trains haven't received much attention. Due to the sophisticated linear motor technology for contactless transit, building a maglev train requires enormous investments. This paper is crucial for understanding the linear motor technologies necessary for levitation and propulsion. The primary objectives of this study include creating a model of the maglev train using a linear motor circuit, investigating the maglev effect concerning different coil and magnet types, and monitoring the train's propulsion and levitation using a microcontroller. This work constructs a linear motor system for the maglev train, comprising a mechanical structure with a permanent magnet for levitation and electromagnets for propulsion. A microcontroller is employed to sense the magnetic field, produced by the permanent magnet and electromagnets. In summary, this paper successfully designed a maglev train prototype using a linear motor circuit to establish the repulsive mechanism for both levitation and propulsion, with levitation~1 cm from the track and demonstrated the ability to move along a 30 cm track.

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1. INTRODUCTION

The conventional train is a vehicle connected in series and moves along a railway track to transport people to their destination. The traditional train relies on the wheels and rail to move the train by exerting friction but by applying this can cause a decrease in operational efficiency. Friction must be reduced or eliminated to increase operational efficiency. The magnetic levitation (maglev) train appears to be a viable option for meeting those needs since the maglev train uses the high technologies of the linear motor system by applying superconducting magnets as the electromagnets into the system to levitate the train over the track and creating propulsion without any contact [1], [2]. Even though the maglev train has become the preferred mode of transportation in Japan, South Korea, and China, having one in Malaysia requires a high cost to build [3].

Maglev trains employ maglev to levitate a short distance of the train's body from a guideway. Electrodynamic suspension (EDS) and electromagnetic suspension (EMS) are two types of maglev technologies. EDS technology relies on the repulsive force that repels the superconductive magnet throughout the whole track surface to maintain a levitation gap greater than 10 mm. However, maglev trains using EDS structure must travel at a particular speed to ensure that the repulsive force is sufficient to lift the train. Because this technology does not require active control and is an essential open-loop stable system, it can attain significantly greater speeds [4], [5] than EMS. On the other hand, EMS used the magnetic attraction force provided by electromagnets mounted at the bottom of the train with the guideway to achieve levitation. When compared to EDS, EMS is easier since it can levitate the train at zero or low speeds, which is hard to perform with the EDS type [5].

For a high-speed maglev train, a powerful linear motor system is required as a propulsion device [6]. To move, the maglev train does not utilise any mechanical connecting parts. Furthermore, compared to rotary motors, a linear motor system's structure is more straightforward and more robust. Linear motors are based on the operating concept of rotary motors that have been sliced open, flattened, and placed on a guideway [7]. A linear motor also has a stator and rotor, but instead of "stator" and "rotor," the standard terms "primary" and "secondary" are used to describe a linear motor system. The primary is attached to the guideway while the secondary is attached to the bottom of the train's body in maglev trains. A linear induction motor is typically used for low-speed maglev trains like the high-speed surface transport (HSST) of Japan and the urban transit maglev (UTM) of Korea. While high speed maglev trains such as the superconducting maglev train (SCMaglev) of Japan and the Shanghai maglev train of China travel at roughly 600 km/h using a linear synchronous motor [7], [8]. Next, Guidance is the idea that maintains the train centered over the guideway. The necessary forces are provided in a manner equivalent to the suspension forces, which might either be attractive or repelling to maintain the train's position [9].

This paper mainly focuses on building the maglev train model using a linear motor circuit and controlled by a microcontroller. The Hall effect sensor detects and controls the magnetic force between permanent magnets and electromagnetic coils, resulting in a net force that propels the train forward. The change in the number of coils wrapped around the electromagnets is considered because the number of coils wrapped is directly proportional to the magnetic force produced by the electromagnets and affects the train model's speed. This project proposed building a simple linear motor circuit model for a maglev train to achieve levitation and forward movement.

This paper comprises an introductory section, background context, and an exposition of the research inquiry regarding maglev train model using microcontroller. Following this is the methodology section, which elucidates the research techniques and data collection methods employed in maglev train electromagnetic system. Subsequently, the paper presents results and discussions that explain the study's discoveries pertaining to magnetic field strength of different magnet type used for levitating and propelling the train. In conclusion, this paper offers a summary of the system's accuracy in pinpointing the availability of the Maglev train to levitate and propel in order.

2. THEORITICAL BACKGROUND

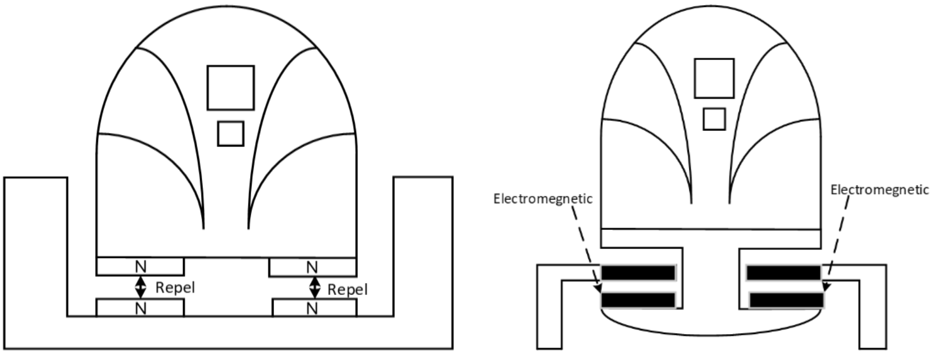
Maglev involves suspending a train car above a U-shaped concrete guideway using superconducting magnets. These magnets repel one another when their corresponding poles are facing one another, much like regular magnets do. Simple metallic loops embedded in the concrete walls of the maglev guideway interact with these magnetic fields. Since the loops are formed of conductive materials like aluminium, a magnetic field passing by causes an electric current to flow, which in turn produces a new magnetic field.

Three different loop types are placed into the guideway at predetermined intervals to perform three crucial functions: one provides a field that causes the train to hover 5 inches above the guideway; the other maintains the train's horizontal stability. The train car is kept in the ideal position by magnetic repulsion in both loops; the farther away from the guideway's center or the nearer the bottom it is, the more magnetic resistance pushes it back on course. The third set of loops is a propulsion system run by alternating current power. Here, the train car is propelled along the guideway by both magnetic attraction and repulsion. Put a magnet on each corner of the box to represent its four magnets. The magnets in the front corners have their north poles facing out, and the ones in the back corners have their south poles facing out. By electrifying the propulsion loops, magnetic fields are created, which propel the train forward from both the front and the back [10]–[12].

2.1. Levitation

The maglev train uses maglev to levitate a short distance from the train's body from a guideway. Shown in Figure 1 are the two types of maglev technologies, EDS and EMS. EDS technology uses the repulsive force that repels the superconductive magnet throughout the entire track surface to maintain a levitation gap greater than 10 mm, as shown in Figure 1(a). However, the maglev train that uses the EDS structure needs to reach a certain speed to ensure the repulsive force is enough to levitate the train. By using

EDS a much higher speed can be achieved because this technology does not require active control and is an essential open-loop stable system. On the other hand, EMS exploited the magnetic attraction force created by electromagnets installed at the bottom of the train with the guideway to accomplish the levitation, as shown in Figure 1(b). EMS is easier compared to EDS because it can levitate the train at zero or low speeds which is difficult to achieve using EDS [4], [13].

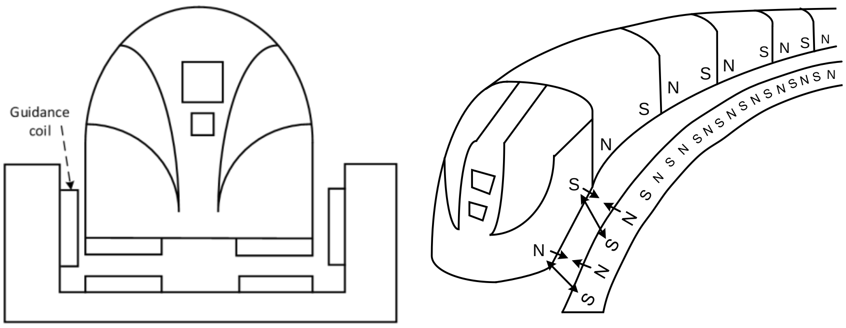


(a) (b)

Figure 1. Maglev technologies in (a) EDS and (b) EMS

2.2. Guidance and propulsion

To move the maglev train, the guidance and propulsion concept are used. Figure 2 shows the guidance and propulsion concept. Shown in Figure 2(a) is the sideward forces necessary to make the vehicle follow the guideway are referred to as guidance. In simple terms, guidance is the concept that keeps the train centered over the guideway. The requisite forces are given in an exact analogy to the suspension forces, which can be either attracting or repulsive. Employing the same onboard magnets that provide lift for guidance or separate guidance magnets is possible [4]. Shown in Figure 2(b) is the maglev train propulsion concept. A powerful linear motor system is necessary as a propulsion device for high-speed maglev trains. Maglev train does not use any mechanical coupling part to move. Furthermore, the linear motor system structure is simpler and more robust compared to rotary motors. The linear motor also has a stator and rotor same as the rotary motor because the linear motor system came from the working principle of the rotary motor system that has been cut open and flattened and placed on the guideway [14]. In describing a linear motor system, the standard term "primary" and "secondary" is used instead of "stator" and "rotor".



(a) (b)

Figure 2. Maglev train in (a) guidance concept and (b) propulsion concept

In maglev trains, the primary is placed on the guideway, and the secondary is attached to the bottom of the train's body. The maglev train was classified by speed, and mainly for the low-speed maglev train such as HSST of Japan and UTM of Korea use a linear induction motor. While the high-speed maglev train, such as the SCMaglev of Japan and the Shanghai maglev train of China, operates at speeds of about 600 km/h using a linear synchronous motor [15].

3. RESEARCH METHOD

This work involves the construction of a linear motor system for the maglev train mechanical structure, which includes a permanent magnet for the train's levitation system and electromagnets for propulsion. To obtain the best result for levitation and propulsion, the electromagnetic field strength and type of magnet used are studied. The microcontroller part is used for sensing the magnetic field produced by the permanent magnet and electromagnets.

3.1. Mechanical structure and control mechanisms

The levitation and propulsion system (permanent magnets and electromagnets) are paramount to hover and move the train forward [16] with the help of linear system using a microcontroller. Shown in Figure 3 is the maglev train prototype and its control circuit. Figure 3(a) shows the levitation magnet mounted on the track and the bottom of the body train help the train model to levitate in the air for almost 1 cm above the track. Twelve permanent magnets are used to create the levitation system of the train model. Twenty of them are mounted vertically at the side of the guideway so that the electromagnets will interact with the magnetic field produced by the permanent magnets. The generated mechanical force between the electromagnets and the permanent magnets will help propel the train over the track [17]. The correct placement of the permanent magnet can produce a strong repulsive force between the train and the track, and the train will remain levitated in the air even when it is running. For this work, the length of the track is set to 30 cm and the width of the track is 15 cm. The track design consists of five permanent magnets on both sides, with the dimensions of each magnet: 60×10×5 mm. The permanent magnets used in this study are Neodymium magnets (NdFeB) (N38) since it has strong magnetic force compared to regular magnets. The electromagnet is designed using bolts, nuts, and carved plastic sheets. The copper wire is wound over the electromagnet in a specific arrangement. For this study, 100, 200, 300, and 400 total number of turns are developed to study the effect of number of turns to the magnetic field produced when the current is supplied. The electromagnets are placed inside the train's body.

Figure 3(b) demonstrates the maglev train's control system, consisting of microcontroller, Hall effect sensors, and LED. The process begins by initializing the magnetic field force produced by the magnets. When the system detects the magnet's magnetic field using the Hall effect sensors and sends the signals to the microcontroller. Then, the microcontroller will decide to activate or deactivate the electromagnets to operate the maglev train model. The electromagnets start switching polarity based on the received command [18], [19]. The Hall effect sensor detected the magnetic field from the permanent magnets, and the signal from the sensor was amplified and then digitized by using an analog-to-digital (ADC) converter. The microcontroller receives this digital signal and then activates or deactivates the electromagnets. When the Hall effect sensor detects the magnetic field from the permanent magnets, the signal goes to the microcontroller, and it starts switching the electromagnets based on the received command. This design model uses two electromagnets integrated with the (12 V, 2 A) power supply. The forward movement of the train model is controlled by changing the voltage polarity for the electromagnets. The Darlington transistor negatif-positif-negatif (NPN) (TIP120) acts as power broker or gatekeeper between the Arduino and is suitable for controlling medium-power electronics such as electromagnets. Specified resistor values are used to reduce current and lower the voltage of the circuit to avoid damage to the microcontroller board [20], [21].

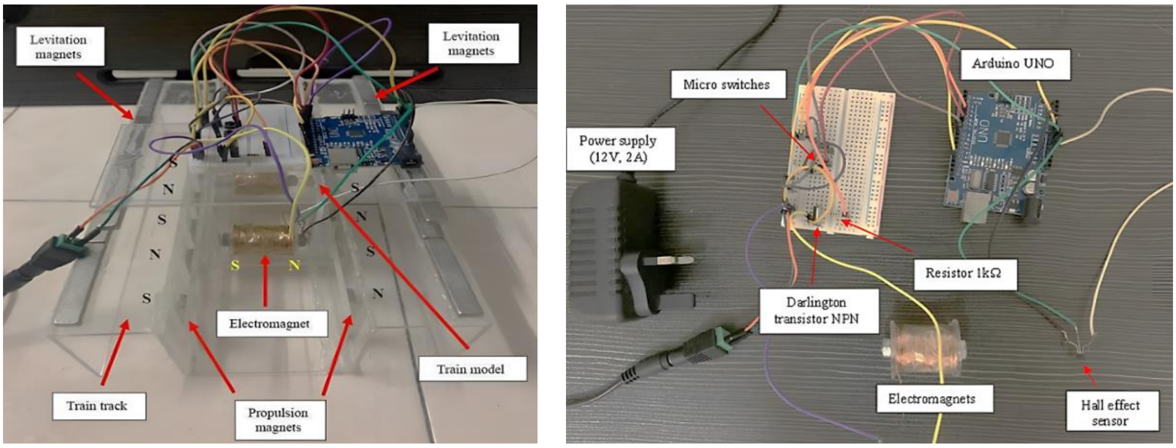
3.2. Electromagnetic magnetic field and magnet type

The magnetic field strength of electromagnets is determined by the number of turns, current, and coil radius [22], [23]. The copper wire used in this work has a diameter of 0.7 mm, the values considered for N are 100, 200, 300 and 400, I equal to 2 A, L is set to 3 cm, and D is set to 3 cm. According to the right-hand rule, when a current flows through the coil, it will become electromagnetic with north and south poles. The magnetic field strength of the electromagnet can be calculated according to [24] using the (1).

$$B = \mu NI/L = \Phi/A \quad (1)$$

B=is the magnetic induction or magnetic flux density produced by the electromagnetic coil in tesla (T); M=is the permeability of air and is equal to 1.25663753×10^{-6} T m/A; N=are the total number of coils turns; I=is the current used to energize the coil to produce the desired magnetic field; and L=is the coil length.

This study of magnetic field strength is done to choose the most suitable magnets for levitation and propulsion. The magnetic force of the permanent magnets must be strong enough to create the lift force and propelling force [25], [26]. The magnetic field testing are run using the Hall effect sensor. In this paper, two type of magnet are considered; the bar magnet and the Neodymium magnet.



(a) (b)

Figure 3. The maglev train model using a linear motor circuit in (a) prototype and (b) its control circuit

4. RESULTS AND DISCUSSION

The experimental results from the maglev train prototype are presented in this section. The findings of the coil turns relationship with magnetic field strenght produced and the best magnet type to be used will be discussed. This section include the results of levitating and propulsion of the maglev train ptototype as well as its tracks.

4.1. Magnetic field strength

The relationship between the number of coil turns (N) and the magnetic field strength produced by the electromagnets are validated by the calculation using the (1). The current supply through the coil is set to 2 A. The total number of coil turns is divided into 100, 200, 300, and 400 turns. The value of magnetic field strength produced by each electromagnet is shown in Table 1. As expected, magnetic field strength increases with numbers of coil turn [16]. This magnetic field strength affects the propulsion of the maglev train.

Table 1. The value of magnetic field strength produced by each electromagnet

Number of coils (N)	Magnetic field strength (T)
100	0.008377583
200	0.016755167
300	0.025132751
400	0.033510334

4.2. Type of magnet

The levitation and propulsion of the train model can be affected by the type of magnets chosen [17]. In this part, two different types of magnets were tested at various distances from the Hall effect sensor ranging from 0 cm to 5 cm and at different polarities to observe how the data readings changed when the Hall effect sensor detected the south and north poles. Both regular and Neodymium magnets were employed in this test. Table 2 shows the value of hall voltage and percentage difference produced between regular magnets and Neodymium magnets for the north and south pole.

Table 2. Hall voltage differences for north and south poles of the magnets

Distance (cm)	North poles Hall voltage (m^3/C)		Percentage difference (%)	South poles Hall voltage (m^3/C)		Percentage difference (%)
	Regular magnet	Neodymium magnet		Regular magnet	Neodymium magnet	
5	504	511	1.38	501	493	1.61
4	505	519	2.73	499	488	3.24
3	508	533	4.80	496	475	4.33
2	516	568	9.59	489	439	10.78
1	537	689	24.80	460	306	40.21
0	737	863	15.75	211	174	19.22

The highest Hall voltage obtained by Neodymium magnet is at 863 m^3/C when nearest to the Hall sensor for north pole. For the south pole, the value for Hall voltage is opposite of north pole result. It has the highest value the furthest from the sensor. This is because the south pole needs to turn OFF when north pole is ON. It shows that Neodymium magnet has the lowest value, 174 m^3/C when nearest to the Hall effect sensor. In conclusion, the Neodymium magnets are much stronger than regular magnets because they have the highest and lowest value of hall voltage and are more suitable for this work.

4.3. Propulsion and levitation

Achieving simultaneous propulsion and levitation in a maglev train is challenging. Numerous prototypes have been designed to test it. Electromagnets and permanent magnets provide powerful, attractive, repulsive forces that drive the vehicle forward or backward. In the proposed design, the train model's propulsion is achieved with a microcontroller system. In this system, two electromagnets and two Hall effect sensors are mounted inside the train's body. The first electromagnet is connected to the first Hall effect sensor while the second electromagnet is connected to the second sensor. The first sensor was programmed to switch ON the electromagnets when the sensor detects north pole and will be switched OFF when it detects south pole of the permanent magnets. The second sensor has been programmed to switch OFF the electromagnet when it detects the north pole and will switch ON the electromagnets when it detects the south pole of the permanent magnets.

Figure 4 shows how the propulsion of the train model is achieved. When the first sensor detects the north pole of permanent magnets, the first electromagnets will have the north pole on the right side and the south pole on the left side of the electromagnet. The interaction between first electromagnet and the permanent magnets will result in a net force moving the train model forward because the net force of the first electromagnet is higher than the second electromagnet because it has been switched off. Next, after the train model reaches the next position, the second electromagnet will be switched on because the second sensor detected the south pole and will produce a higher net force compared to the first electromagnet that has been switched off due to the first sensor that detected the south pole of the permanent magnets. This process will be repeated so the net force will continue in a forward direction.

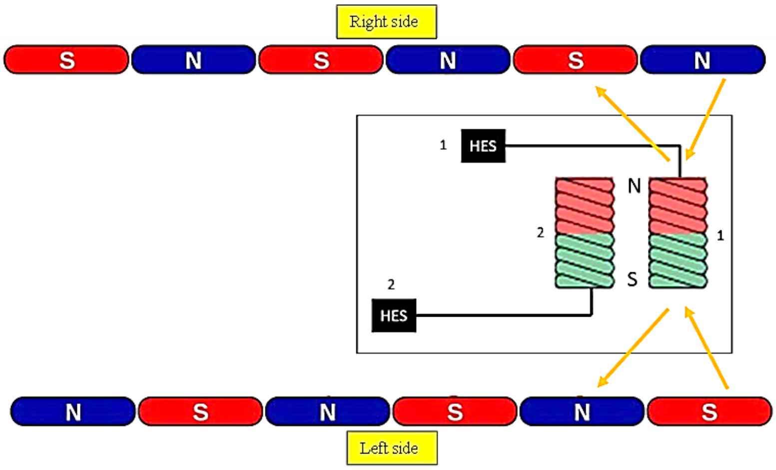


Figure 4. Propulsion working condition

5. CONCLUSION

In conclusion, this paper successfully designed a maglev train prototype using the concept of a linear motor circuit to create the repulsive mechanism for levitating and propelling the train model, reaching a levitation ~ 1 cm from the track and can move the train model along the 30 cm track. The control mechanism proposed for a maglev system by switching the electromagnet and allowing the maglev train model to propel forward is also a success. In this control mechanism, electronic components are embedded onto the breadboard, and an Arduino board is integrated with the Hall sensor to detect the magnetic field of permanent magnets and switch the electromagnet's polarity. The study shows that the number of coils wrapped around the electromagnets and the type of magnets used in this project affects the levitation and propulsion of the train model. The test was conducted using four electromagnets with different coil turns starting from 100, 200, 300 and 400 turns. The result shows the magnetic field's increasing value as the number of coils turns increases. Lastly, the test result for two different magnets also showed that the Neodymium magnet is more suitable to be used in this project because it can produce more magnetic field strength than regular magnets. However, there are a few recommendations that can be made for future research. For example, the maglev train model can be upgraded by adding a remote control so it can control the movement of the train across the track in forward and backward direction. Additionally, the stronger Neodymium magnets can be used in design prototype so it can levitate the train higher and can support the electrical component mounted on the train model. This prototype enables students to gain a fundamental grasp of the maglev train.

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