Closed Loop Control of Halbach Array Magnetic Levitation System Height
(CLCML)

Functional Description and Complete System Block Diagram

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Background

Magnetic levitation (maglev) has been used in transportation as an alternative to traditional methods. Using maglev, an object can be lifted and propelled eliminating friction thereby producing faster acceleration and velocity.

The key component to maglev is the magnetic repulsion between the object and the track. An object can be made with a special arrangement of magnets so that the magnetic fields only exist below the object and are canceled above the object. This arrangement is called Halbach array. Fig. 1 shows an example of the Halbach array magnetic fields. Notice the alignment of the polarity of the magnets and how it creates a magnetic field on just one side of the magnet. The Halbach array arrangement causes a more powerful field than magnets with only a one-way alignment, making it more practical on a large scale.
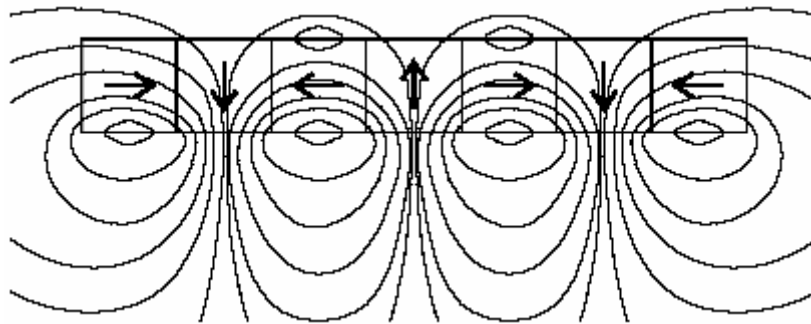

Fig. 1. Halbach Array Magnetic Fields

Just as alternating current induces a magnetic field, a changing magnetic field induces current. As a Halbach array moves across a conductor, it changes the magnetic field around the conductor and induces current in the conductor. The induced current in the conductor will be changing as well, thus creating its own magnetic field. Fig. 2 and Fig. 3 show the Halbach array device and its magnetic field (red and blue) and the inductrack's induced magnetic field (pink and light blue). At low velocity as shown in Fig. 2, these fields are not aligned; however, at high velocity, the current induced begins to lag, and the magnetic fields align as shown in Fig. 3. Therefore, when the device moves at a certain high velocity, the device induces current strong enough to create a magnetic field capable producing lift. These are the basic principles of an inductrack.
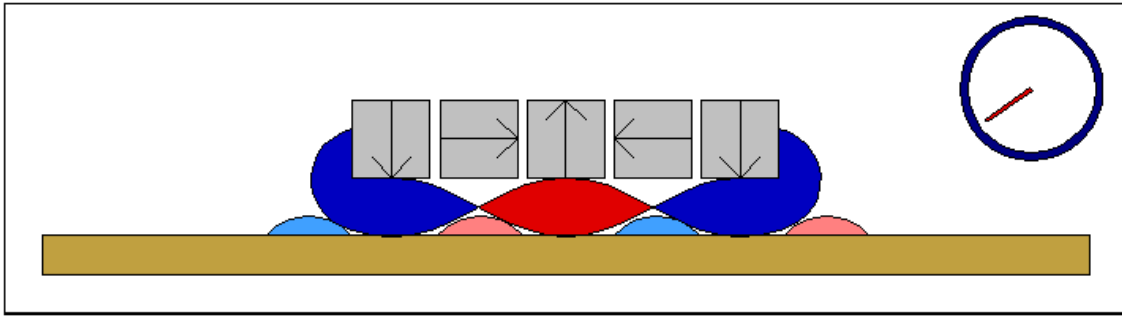
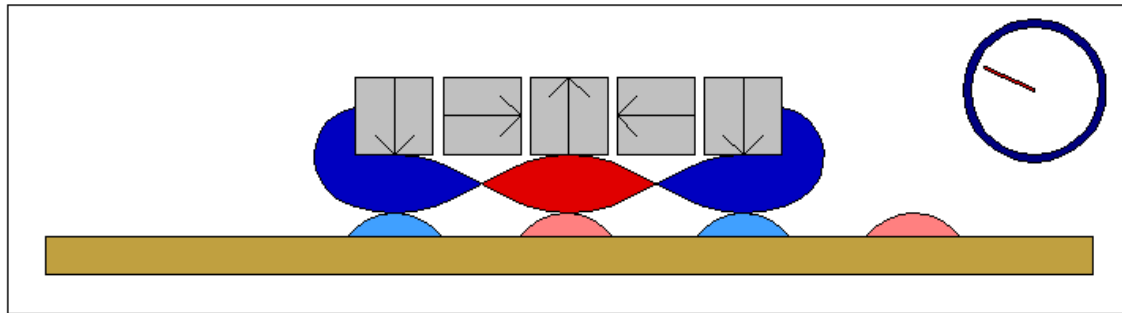Fig. 2. Inductrack and Halbach Array Interaction at Low Velocity

Fig. 3. Inductrack and Halbach Array Interaction at High Velocity

An inductrack can be made from aluminum or copper. Instead of propelling the device, a rotary inductrack can be used to lift the device. The rotary inductrack will produce a magnetic force that is proportional to the tangential velocity to create levitation. Therefore the rotational speed of the track can be used to control the levitation height of the Halbach array device.

Introduction:

This project will extend the previous years' progress to demonstrate closed loop control of Halbach array magnetic levitation system height on a rotary inductrack. Fig. 4 shows the current magnetic levitation device which was designed by Dirk DeDecker and Jesse VanIseghem. The device can achieve 0.37cm vertical displacement at a rotary track tangential velocity of 10.09 m/s. A small piece of plexiglass shields the user from the rotary track. The current system implements open loop control of levitation height.
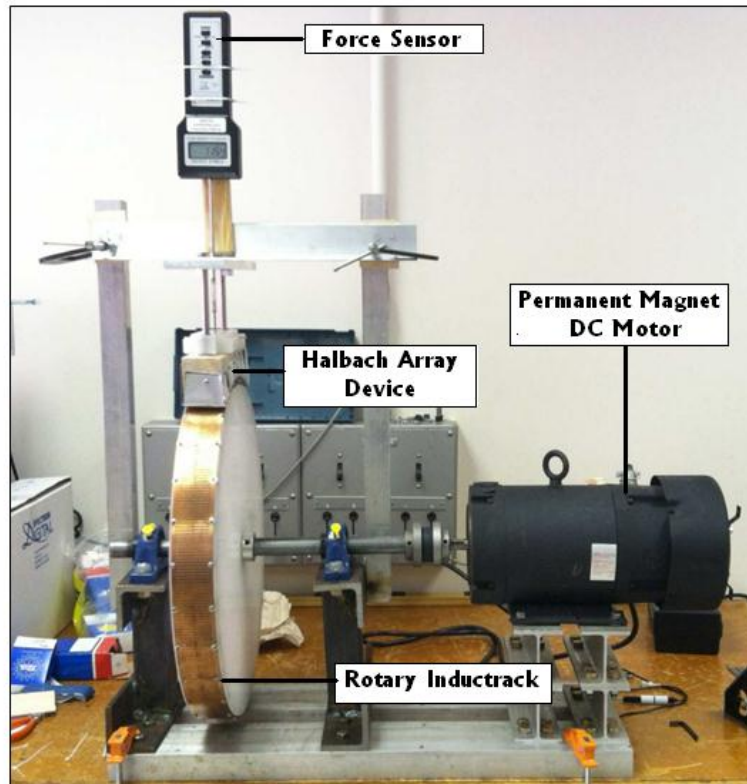

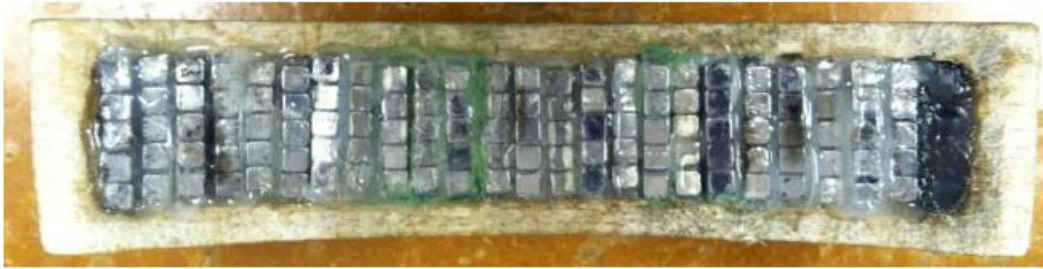Fig. 4. DC Motor, Inductrack, and Halbach Array System as of 9/1/2012

Halbach Array Device

Fig. 5. DeDecker-VanIseghem Designed Halbach Array Device

The current Halbach array device built by last year's team shown in Fig. 5 has an arrangement of 5x25 magnets. The magnetic flux density generated by this arrangement can be calculated using equation (1)

$$B_0 = B_r(1 - e^{-k*d})\sin(\pi/M)/(\pi/M) \text{ Tesla} \quad (1)$$

where $k = 2\pi/\lambda$,
M = # of magnets,
Br = magnet strength,
d = thickness of each magnet.
λ = wavelength of the Halbach array

Mr. DeDecker and Mr. VanIseghem [1] found their designed Halbach array device to have the following magnetic flux density:

$$B_0 = 0.8060 \text{ Tesla}$$

Inductrack

Fig. 6 Copper Inductrack Spun Around the Rotating Wheel

The inductrack shown in Fig. 6 was made with copper sheets. This design allows for levitation at low velocities. The Inductrack can be modeled as a series R-L circuit. The inductance and the resistance of the track are given by equations (2) and (3)

$$L = \mu_0 w/(2kd_c) \text{ H} \qquad (2)$$
$$R = P_c R_c/(N_t * c * N_s) \text{ } \Omega \qquad (3)$$

where d_c is the center to center spacing of conducting strips and w is the track width and R_c is the resistivity. The phase shift of the system relating drag and levitation forces is given by equation (4).

$$\text{Lift/Drag} = \omega * L/R \qquad (4)$$

To maximize lift, a large amount of inductance and a low resistance is desired. Mr. DeDecker and Mr. VanIseghem [1] found their inductrack to have the following properties:

$$L = 7.532 \text{ x } 10\text{-}8 \text{ H}$$
$$R = 1.9 \text{ x } 10\text{-}5 \text{ } \Omega$$

Dr. Post and Dr. Ryutov [4] demonstrated that the magnetic force experienced by the device can be separated into two dimensional components corresponding to lift and drag forces given by equations (5) and (6) respectively:

$$<F_y> = B_0^2 w/2kL * [\text{ } 1/(1+(R/\omega L)^2)] * e^{-2k*y} \qquad (5)$$

$$<F_x> = B_0^2 w/2kL * [(R/\omega L)/(1+(R/\omega L)^2)] * e^{-2k*y} \qquad (6)$$

where $\omega = kv$ and y is the distance between the device and the inductrack.

Project Description:

The first objective will be to improve the previous years' progress by properly balancing the wheel for improved stability at higher RPM. As shown by equation (5), operating at a higher RPM will allow for more magnetic force and therefore vertical displacement. Currently, it is deemed only safe to operate in the range of 500 RPM, but the motor could operate around in excess of 1000 RPM. Additionally, a more complete safety enclosure must be fabricated. Physical dimensions will be measured to place plexiglass around at least three sides of the system.

After the system has been modified to meet our safety and stability requirements we will begin modeling the DC motor and the Halbach Array system shown in the high level system block diagram in Fig. 7. An attempt will be made to find the data sheets of the 20-year old motor, but if they cannot be found, the motor will be modeled through experimentation. The inductrack and Halbach array system will be used to determine how much rotational velocity is needed to vertically displace the device. These models will be analyzed and used in the design of a closed loop control system utilizing the vertical displacement as the feedback signal.

Once the models of the two physical systems are made, we will design a controller that will modify the motor's RPM to maintain desired displacement. The controller will be designed based on the closed-loop transfer function of the system to fit certain specifications. Maximum percent overshoot, rise time, and settling time will be specified later when a more precise specification can be given. The controller will be implemented on a microcontroller. The exact microcontroller will be determined later.
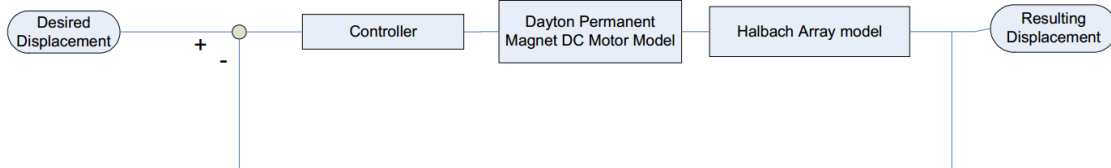

Fig. 7. High Level Overall System Block Diagram

After achieving these objectives, a linear track with a linear synchronous motor and a new Halbach array device with guidance and propulsion capabilities will be fabricated. The linear synchronous motor will propel the Halbach array device. This objective will require additional research to determine the most effective method of implementation and fabrication for our specific needs.

Goals:
- Improve safety and stability of system used in previous years.
- Model the physical systems of the DC motor and the magnetic levitation device.
- Effectively show levitation height control through closed-loop feedback using a microcontroller.
- Design, fabricate, and implement linear track and Halbach array to accommodate linear motion.

Conclusion:

      The functional system built by previous years will provide us with a foundation on which we can build and improve. The first goal of the project is to address the safety and stability concerns of the current system. Once the appropriate improvements have been made modeling and control design will begin with the goal of controlled levitation height. If time permits, we will design, build, and implement a linear track that will accommodate magnetic propulsion and levitation.

Works Consulted:

[1] Dirk DeDecker, Jesse VanIseghem. Senior Project. "Development of a
      Halback Array Magnetic Levitation System". Final Report, May 2012

[2] Glenn Zomchek. Senior Project. "Redesign of a Rotary Inductrack for
      Magnetic Levitation Train Demonstration". Final Report, May 2007.

[3] Paul Friend. Senior Project. Magnetic Levitation Technology 1. Final Report,
      May 2004.

[4] Post, Richard F., Ryutov, Dmitri D., "The Inductrack Approach to Magnetic
      Levitation," Lawrence Livermore National Laboratory.