Control of Halbach Array Magnetic Levitation System Height

Senior Project Proposal

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Project Summary:

This project will demonstrate magnetic levitation using a rotary inductrack and a device with Halbach array magnets. The project is an extension of projects completed in previous years, building on Paul Friend's 2004 project [1] and Glenn Zomchek's 2007 project [2]. These projects were able to show successful levitation, but only to a maximum height of 0.45 mm. These projects and their findings will be used to start this year's project.

This year, all of the parameters will be recalculated. This will lead to a new experimental set up, including the magnets, Halbach array, Maglev device, wheel, and motor. A 5 by 5 Halbach array will be used for initial testing. A new device will then be made and testing will be completed with a 5 by 13 Halbach array.

System Block Diagram:

The overall system block diagram is shown in figure 1.

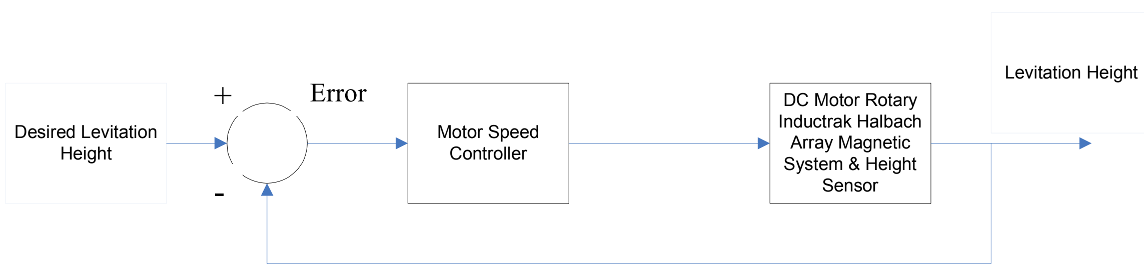

Figure 1: High level overall system block diagram

The first goal of the project will be to demonstrate levitation. Once successful levitation is demonstrated, a closed loop control system will be implemented as shown in figure 1. The measured levitation height from the displacement sensor will be compared to a desired levitation height that is entered by the user. The desired and actual levitation heights will be compared, and the motor speed controller block will use the difference between these signals and adjust the speed of the motor to achieve desired levitation height. The output from the motor speed controller block will be sent to the DC motor, which will drive the Inductrack. The motor's speed will be adjusted by this signal, causing the track velocity to change, thereby adjusting the levitation height.

Previous work completed:

Dr. Sam Gurol and Dr. Post have worked on "The General Atomics Low Speed Urban Maglev Technology Development Program" utilizing the rotary track and Inductrack methods [5]. This program is working to design an urban transportation system for the United States that will use the Inductrack to levitate the trains at low speed.

Dr. Richard Post was the head scientist for the magnetic levitation program at Lawrence Livermore National Laboratory. Dr. Post pioneered the Inductrack method of magnetic levitation in the 1990's [3]. The Inductrack method is now being researched by NASA for launching rockets into space.

Previous work has also been completed by Bradley University electrical engineering students in previous senior projects. The first of these projects was by Paul Friend in 2004. Paul Friend helped to obtain all the levitation equations and wrote the code for the Matlab GUI to run simulations. In 2007, Glenn Zomchek designed a Maglev system using the rotary inductrack method. Zomcheck obtained successful levitation to 0.45 mm.

The previous work of individuals on magnetic levitation will be of great assistance while working on the magnetic levitation project this year.

Physics of the Inductrack System:

For the project, two different size Halbach arrays will be used. The Halbach array is shown in figure 2.

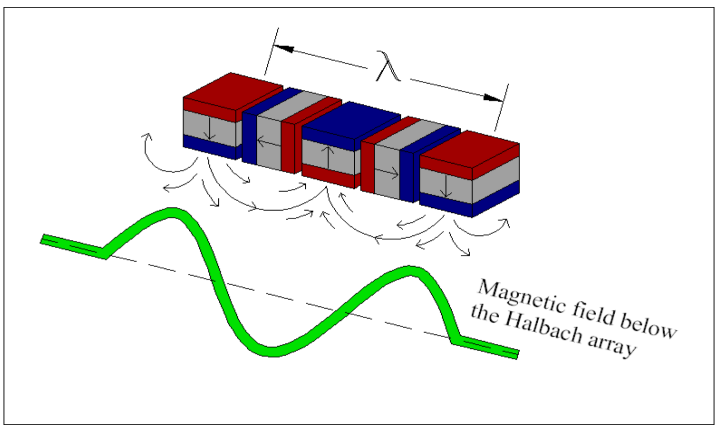

Figure 2: Halbach array

The Halbach array was designed by Klaus Halbach. The arrangement of the polarities of the magnets creates a strong magnetic field on one side of the array, while canceling most of the magnetic field on the other side. The peak strength of the array is given by:

$$\mathbf{B_0=B_r(1-e^{-kd})\sin(\pi/M)/(\pi /M)} \text{ Tesla} \qquad \mathbf{(1)}$$

where $k = 2\pi/\lambda$, M = # of magnets, Br = magnet strength,
d = thickness of each magnet [3].

The track will be of the Inductrack design, using close-packed conductors, made utilizing thin aluminum or copper sheets. This design allows for levitation at low velocities. The Inductrack can be modeled as an R-L circuit, shown in figure 3. The transfer function will have a pole at –R/L.

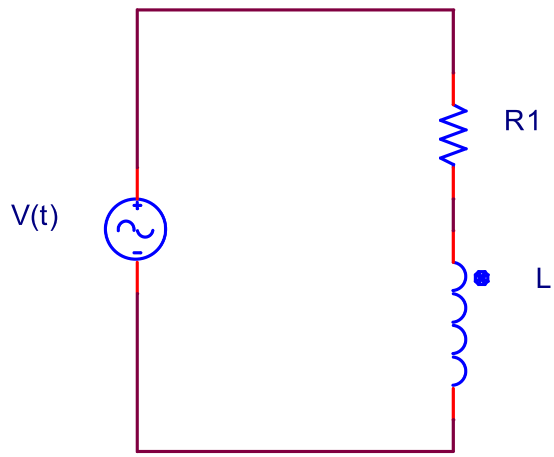

Figure 3: R-L circuit representation of Inductrack

The Halbach array moving at velocity, v [m/sec], over the inductrack generates flux linking the circuit. The flux is $\boldsymbol{\varphi_0 \sin(\omega t)}$, where φ_0 [Tesla-m2] and:

$$\omega = (2\pi/\lambda)v \ \ \text{rad/sec} \qquad (2)$$

The voltage induced in the inductrack circuit is the rate of change of flux given by:

$$V(t) = \omega\ \varphi_0 \cos(\omega t) \qquad (3)$$

From figure 3, the Inductrack R-L circuit current equation is given by:

$$V(t) = L*di(t)/dt + R*i(t) \qquad (4)$$

Dr. Post and Dr. Ryutov [3] used the induced current, i(t), which is the solution of (4), and magnetic field to derive equations for the lift force and drag force.

Lift force:

$$<Fy> = B_0^2 w^2/2kL*1/1+(R/\omega L)^2*e^{-ky1} \qquad (5)$$

Drag force:

$$<Fx> = B_0^2 w^2/2kL*\ (R/\omega L)\ /1+(R/\omega L)^2*e^{-ky1} \qquad (6)$$

where y1 is the levitation height in meters.

The phase shift of the system relates to drag and levitation forces.

$$\textbf{Lift/Drag} = \omega * L/R \qquad \textbf{(7)}$$

To maximize lift, a large amount of inductance and low resistance is desired. The inductance of the track is given by the equation:

$$L = \mu_0\, w/(2kd_c) \qquad \textbf{(8)}$$

where d_c is the center to center spacing of conducting strips and w is the track width.

The equation for L shows that it is desired to have the narrow transverse slots on the track as wide and close together as possible to maximize L.

The force needed to levitate the device is given by:

$$F = m*9.81 \text{ Newtons} \qquad \textbf{(9)}$$

where m is the mass of the device.

Solving Lift/Drag equation (7) for velocity, the breakpoint velocity of the system is given by:

$$v_b = \lambda\omega/(2\pi) \text{ m/sec} \qquad \textbf{(10)}$$

Functional Requirements:

Rotary Wheel Requirements:

- A new wheel shall be fabricated with a radius of 9 inches.
- A new aluminum Inductrack shall be fabricated with 4 to 5 mm conducting strips with 0.5 mm spacing between the strips.

Maglev Device Requirements:

- Two new devices shall be fabricated out of balsa wood to house the Halbach arrays.
- The device shall have a breakpoint levitation velocity of less than 30 m/s, corresponding to a motor speed of 1253 RPM. At our simulated speed of 10 m/s, the power will be approximately 257 watts.

Halbach Array Requirements:

- 6 mm cube magnets shall be used to create the Halbach arrays.
- Each magnet shall have peak strength of 1.21 Tesla.
- A Halbach array of 5 by 5 magnets shall be constructed using 6mm cube magnets.
  - The length of the Halbach array shall be 34 mm.
  - The width of the Halbach array shall be 34 mm.
  - The total area under the Halbach array shall be 1156 mm^2.
  - The wavelength of the Halbach array shall be 28 mm.
  - The Halbach array peak strength shall be 0.80595 Tesla.
- Another Halbach array of 5 by 13 shall be constructed.
  - The length of the Halbach array shall be 90 mm.
  - The width of the Halbach array shall be 34 mm.
  - The total area under the Halbach array shall be 3060 mm^2.
  - The wavelength of the Halbach array shall be 28 mm.
  - The Halbach array peak strength shall be 0.80595 Tesla.

Motor Requirements:

- For initial testing, the Reliance motor model 437698-KW shall be used.
  - The motor shall have 1/3 horsepower.
  - The motor shall be rated at 1725 RPM.
  - The rated current of the motor shall be 3 amps armature current and 0.4 amp field current.
  - The rated voltage of the motor shall be 115 volts.
- For further testing and set up with closed loop control, the D&D ES-10E-33 DC motor shall be used.
  - The motor shall have peak horsepower of 17 horsepower and continuous horsepower of 8 horsepower.
  - The motor shall be a 48VDC Separately Excited Motor.
  - The motor shall be rated at 3000 RPM.

Performance Specifications

- The controller to be used has yet to be determined.
- The maximum overshoot of the system shall be <10%.
- The steady state error shall be less than 0.2 cm.
- The rise time shall be less than 13.9 ms.
- The settling time shall be less than 55.6 ms.

Preliminary Lab Work:

The following tasks have been performed this semester in lab:

- Checked Glenn Zomchek's equations
- Checked equations against Paul Friend's GUI
- Ordered Magnets
- Determined and indicated polarity of magnets
- Determined specifications for initial testing
- First draft of wheel diagram for fabrication, shown on the next page in figure 4

After checking the design equations against the outputs of the GUI, the GUI was used for simulation. The simulation GUI parameters and graphs showing levitation force, drag force and levitation height versus velocity are shown in figure 5. The simulation results were used to specify the Halbach array requirements.

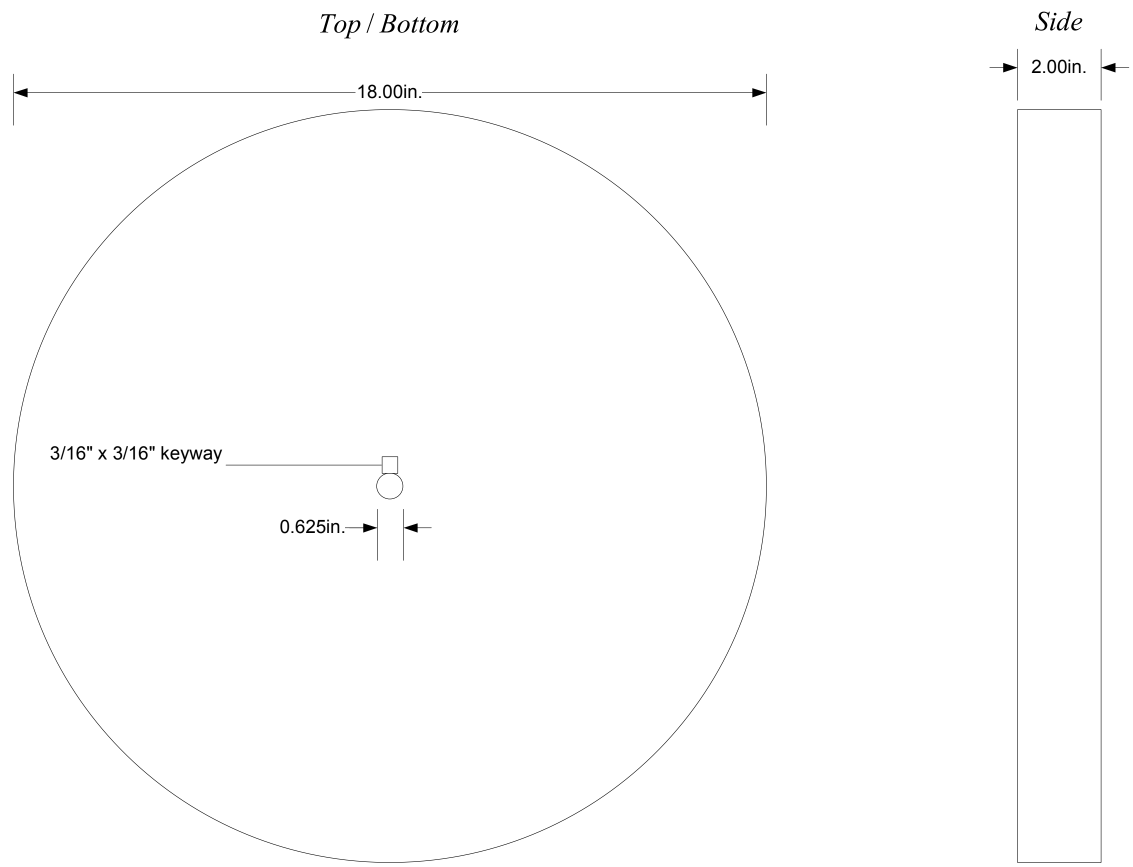

Figure 4: Diagram of wheel to be fabricated

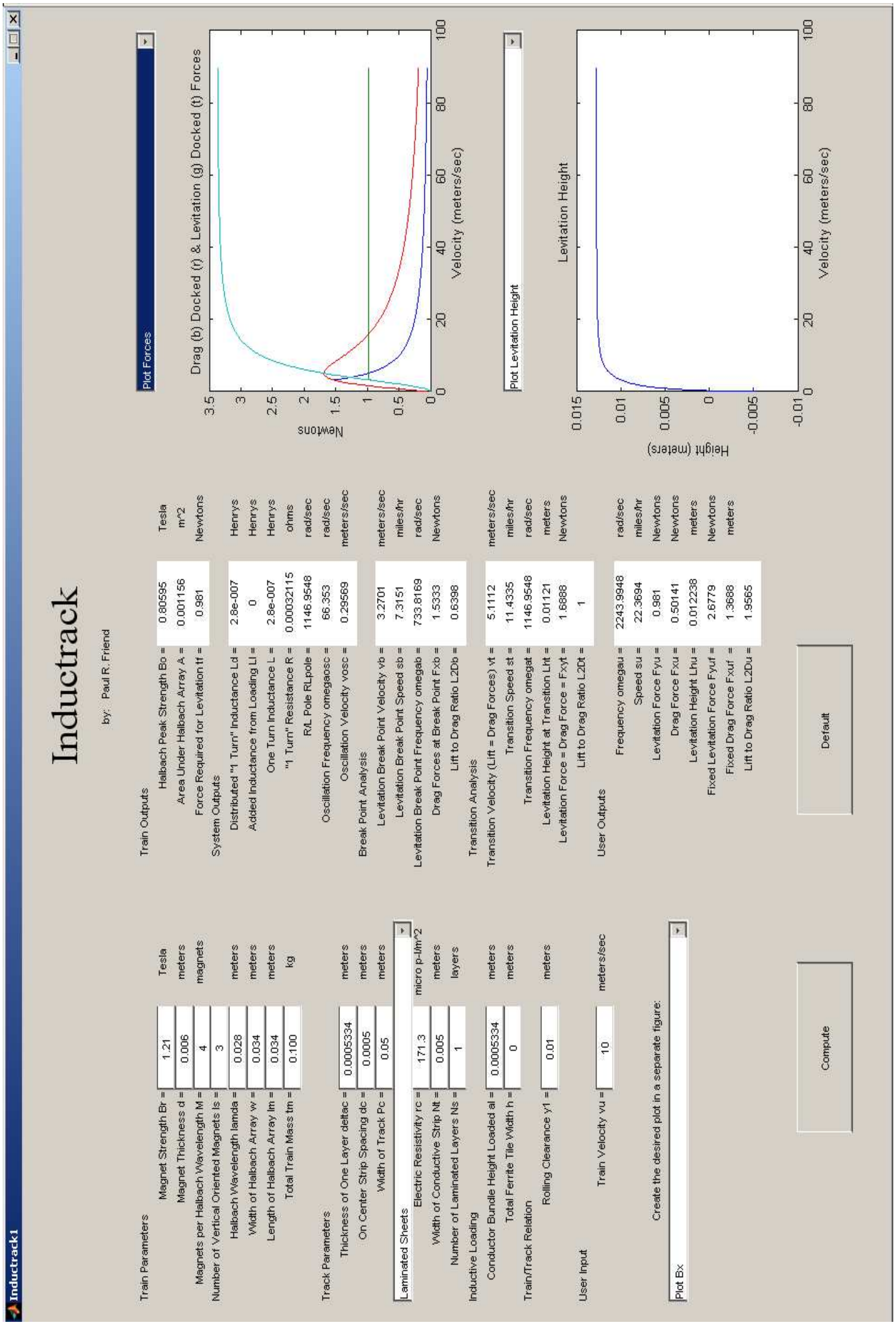

Figure 5: Matlab GUI for Simulation

Schedule:

- **Week 1** – install system will all new fabricated parts
- **Week 2** – modeling of the current motor for open loop testing with the new wheel and Halbach array
- **Weeks 3 & 4** – testing of system for levitation
- **Week 5** - compare simulation results with experimental results
- **Weeks 6 & 7** – Testing and modeling of new motor and Halbach array system
- **Weeks 8 & 9** – Design of closed loop controller for Halbach array system
- **Week 10** – Testing of the closed loop system
- **Week 11** – Student expo
- **Week 12** – Preparation of senior project presentation
- **Week 13** – Preparation of senior project report
- **Week 14** – Senior Project Presentations

Equipment List:

- 9" radius polyethylene wheel, with a width of 2"
- 90 - 6mm cube neodymium magnets
- 2 balsa wood structures to house the 5x5 Halbach array and the 5x13 Halbach array
- Structure to hold Halbach Array device that enables it to levitate
- 1 – 57"x2" sheet of thin conducting strips
- Reliance motor model 437698-KW
- D&D ES-10E-33 DC motor
- Motor Controller (to be determined later)
- Digital Force Gauge Model: 475040
- Displacement Transducer Model: MLT002N3000B5C

Applicable Patents:

- Coffey; Howard T.
  Propulsion and stabilization for magnetically levitated vehicles
  U.S. Patent 5,222,436
  June 29, 2003

- Coffey; Howard T.
  Magnetic Levitation configuration incorporating levitation, guidance and linear synchronous motor
  U.S. Patent 5,253,592
  October 19, 1993

- Levi;Enrico; Zabar;Zivan
  Air cored, linear induction motor for magnetically levitated systems
  U.S. Patent 5,270,593
  November 10, 1992

- Lamb; Karl J. ; Merrill; Toby ; Gossage; Scott D. ; Sparks; Michael T. ;Barrett; Michael S.
  U.S. Patent 6,510,799
  January 28, 2003
- Richard F. Post
  Magnetic Levitation System for Moving Objects
  U.S. Patent 5,722,326
  March 3, 1998

- Richard F. Post
  Inductrack Magnet Configuration
  U.S. Patent 6,633,217 B2
  October 14, 2003

- Richard F. Post
  Inductrack Configuration
  U.S. Patent 629,503 B2
  October 7, 2003

- Richard F. Post
  Laminated Track Design for Inductrack Maglev System
  U.S. Patent Pending US 2003/0112105 A1
  June 19, 2003

Bibliography:

[1] Paul Friend, “Magnetic Levitation Technology 1”, Senior Project Final Report, 2004

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

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

[4] Post, Richard F., Ryutov, Dmitri D., “The Inductrack: A Simpler Approach to Magnetic Levitation,” Lawrence Livermore National Laboratory.

[5] Post, Richard F., Sam Gurol, and Bob Baldi. "The General Atomics Low Speed Urban Maglev Technology Development Program." Lawrence Livermore National Laboratory and General Atomics.

[6] Sam Gurol, E-mail (Private Conversation)