Magnetic Levitation - MAGLEV

Julio Arias, Sean Mawn, William Schiller, Leo Sell

College of Engineering and Computer Science, University of Central Florida, Orlando, FL, 32826, USA

***Abstract* — This project investigates an alternative technology for mass land transit travel. The paper presented introduces techniques for creating a small-scale version of current industrial versions in use today. The group chose this project as a method to explore this relatively obscure technology in the hopes of informing and educating.**

***Index Terms* — Magnetic Levitation, Electromagnetics, Electromagnetic fields, Magnetic fields, Hall Effect, Neodymium, Permanent magnets.**

I. INTRODUCTION

Magnetic levitation or otherwise known as "maglev" technology is a system where levitation and propulsion are achieved through manipulation of magnetic fields. This technology does not use any mechanical method of propulsion such as wheels or axles, nor does it use similar methods for levitation. Our design is that of a scaled-down version of the maglev train technology that is in its infancy today. This technology is in use overseas, albeit, most of the breakthroughs that are related to maglev are strictly experimental. Commercial maglev rails are few and far between as there are only 2 rails in existence today that transport people.

Our maglev rail will feature a modified version of the Inductrack maglev design as well as Electromagnetic Suspension design ideas. The vehicle will feature a 3-phase linear motor mounted on the underside. The vehicle will also be equipped with permanent magnets that will react with the track to create levitation.

For levitation, the track will be outfitted with two rows of permanent magnets, arranged in a Halbach array. This arrangement will direct the magnetic field towards the underside of the vehicle. The on-board permanent magnets will react with the track as stated above, and will result in levitation. The 3-phase motor will react with the Halbach rows to create propulsion. This track is a long straightaway to demonstrate the basic capabilities of maglev technology.

The vehicle will be controlled via a mobile device. The mobile device will interface with a Bluetooth module on the vehicle and will be able to be controlled wirelessly from the device.

II. DESIGN METHODOLOGY AND SPECIFICATIONS

In the initial stages of designing the project, the group focused on replicating the technology in use today. The propulsion system is based off of the JR-Maglev design seen in Figure 1. The group used the rows of alternating magnets to facilitate propulsion when interacting with the linear motor.

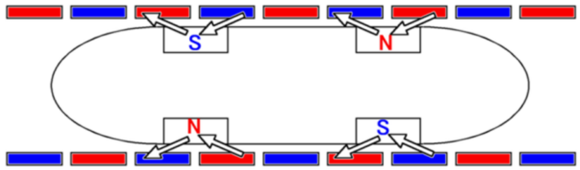

Fig. 1 JR-Maglev propulsion diagram. Reprinted with permission under the Creative Commons License

For propulsion, passive magnets are placed both on the top side of the track and the underside of the vehicle. This is a modified version of the Inductrack's levitation design shown in Figure 2 which uses passive coils embedded in the track that react with permanent magnets arranged in a Halbach array to facilitate levitation.

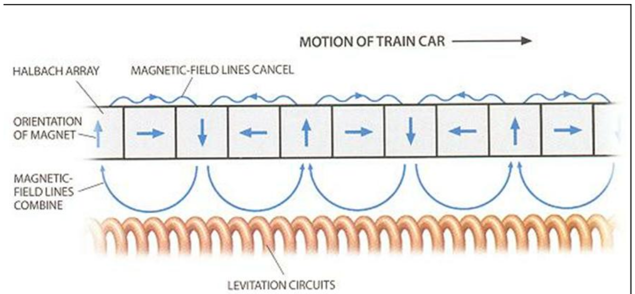

Fig. 2 Inductrack levitation design. Reprinted with permission under the Creative Commons License

The specifications for the project are listed below

Track	2'x 5.5"
Power Supply	One 9V and one 12V
Wireless Connectivity	RN-42 Bluetooth Module
Magnetic field detection	3x A1301 Hall Effect Sensors
Linear Motor	3x Air-core Solenoids
Wireless Device	Android
Vehicle	5" x 5.5"
Propulsion Magnets	32 1" x 0.5" x 0.125" N45 60 1" x 0.25" N48 Cylinder
Levitation Magnets	22 2" x 0.5" x 0.1875" N48 10 1" x 0.5" x 0.125" N45

III. Propulsion and Levitation

Propulsion and Levitation are the key elements to the project as the project is based off of these elements, performing both without conventional means. The first element explored is propulsion, more specifically, the Halbach Array.

A. Propulsion - Halbach Array

A Halbach array is an arrangement of magnets that localizes a magnetic field in one direction and reduces the field on the other side to near 0 [1]. These arrays are created by arranging the magnets in a rotating pattern as shown in Figure 3.

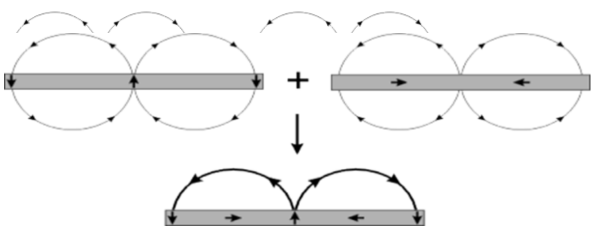

Fig. 3 Halbach array theory. Reprinted with permission under the Creative Commons License

For the solenoids to work and drive the vehicle, the hall-effect sensors must be able to read the pole of the magnet at each drive magnet. With 32 drive magnets, the fields from both the N pole and the S pole will start to converge and cause discrepancies in the hall-effect sensor readings. This is where the Halbach array does its job, by nullifying the fields emanating from the face of the magnet that faces away from the solenoid and intensifying the field from the face that faces the solenoid. Shown in Figure 4 is a flux diagram of a Halbach array.

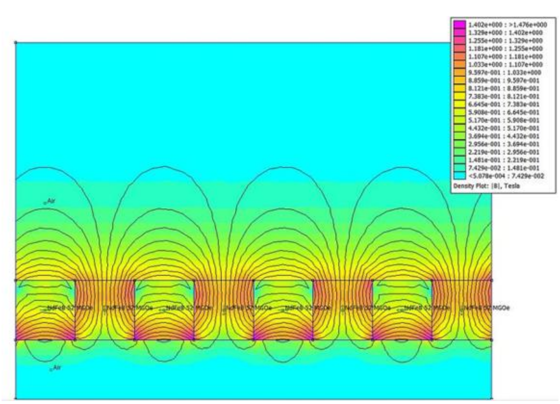

Fig. 4 Flux diagram of Halbach array. Reprinted with permission under the Creative Commons License

The Halbach array for the drive straights are constructed using 1” x 0.25” diameter N48 cylindrical magnets. These magnets are magnetized axially and are placed in between each of the 1” x 0.25” x 0.125”, which are magnetized through the 0.25” thickness.

B. Passive Levitation

In order to get the vehicle to levitate, the vehicle is subjected to a magnetic field of the same polarity as the magnets equipped on the vehicle. Since there are two arrays of magnets that are attached to the track (the levitation array and the propulsion array), the flux is minimized in all other directions besides upwards via the spacing of the levitation magnets and the drive magnets. If the magnetic field from the levitation array were to cross the magnetic field from the propulsion array, there would be interference which could compromise the entire vehicle. Shown in Figure 5 is the repelling strength of the passive track magnet and the passive car magnet respectively.

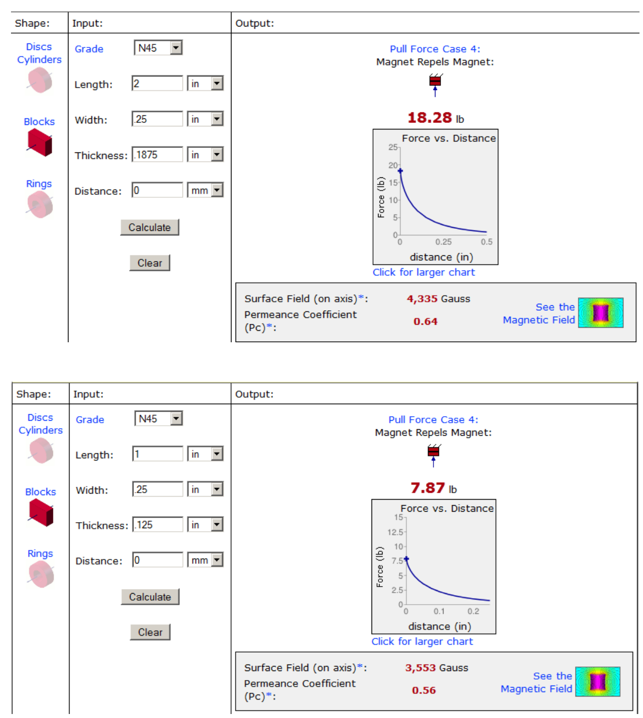

Fig 5 The track levitation magnet and the car magnet repulsion strength respectively. Reprinted with permission from K&J Magnetics

The Halbach arrays on the sides of the track help to nullify the S face of the 1” x 0.25” x 0.125 inch drive magnet, so that field will not interfere with the passive levitation.

A caveat with passive elements providing levitation is the effect of the magnetization reacting with the opposite pole. While the passive magnets on the car repel the passive magnets on the track, the edges of the passive magnets will experience a slight moment of attraction when the magnet on the car passes over the levitation magnet on the track. This can cause a brief period of lateral de-stabilization which necessitates extra methods of lateral stability. To circumvent this, the group has placed an extra row of passive magnets on the car to create a larger surface of magnetic contact, as well as adding two guides to prevent the fields from attracting each other at the tips of the repelling magnets.

IV. System Components

There are three major components to our system, three hall-effect sensors, two quad H-Bridge drivers and one Atmega328 MCU. The sensors and the MCU operate on a 5V DC supply with a separate 12V external supply to Drive the H-Bridges.

A. Hall-effect sensor

The Hall-effect sensors we are using are the Allegro A1301 IC's. The A1301 is a linear, 3-pin, through hole continuous-time Hall-effect sensor. We decided to use this sensor because of its sensitivity rating at 2.5mV/G. The way the sensitivity is calculated is shown in this equation.

$$Sensistivity = \frac{Vout(+B) - Vout(-B)}{2B} \quad (1)$$

The quiescent voltage of the sensors is 2.5V when the supply voltage is at 5V. This value will increase towards the supply voltage of 5V when an S-polarity magnet comes in range and decrease towards 0V when an N-polarity magnet approaches. The magnet arrangement on the track is described in the section 3.

B. H-Bridge Drivers

The IC's used are TI's SN754410 a 16-pin DIP chip, the important specifications when considering the solenoid drivers were the output current, number of states and external supply voltage range. The supply voltage range is 4.5V – 36V, it can accommodate 1A output-current per driver and has 3 state outputs. Shown below in figure 6 is the state outputs important to our project

1,2 EN (Pin1)	1A (Pin 2)	2A (Pin 7)	Function
1	0	1	N-S
1	1	0	S-N
1	0	0	Solenoid off
1	1	1	Solenoid off
0	X	X	Solenoid off

Fig. 6. Truth table of the three state outputs of the H-bridge functions

C. Solenoids

The car has three electromagnets located in a 5 ½'' long x ¾'' wide aluminum C channel. The wire used for the windings is 30 gauge enamel coated copper wire. The solenoids have air cores made of ¼'' inside diameter plastic tube. Two small square sheets of aluminum are placed on the ends of the solenoid to hold the wire in place. The square sheets fit snuggly on the inside of the aluminum C channel. The total clearance length of the solenoids is 1 ½'' from the base to the end of the solenoid.

V. Vehicle

The vehicle design is a T-shape, with a wood foundation. 5 neodymium magnets are placed on either side of the vehicle for levitation on like polarity magnets located on the two track rails. Figure 7 is a Solid works model of our car design. The PCB is mounted on top of the main foundation; the three slots in the channel represent the placement of where the solenoids are located.

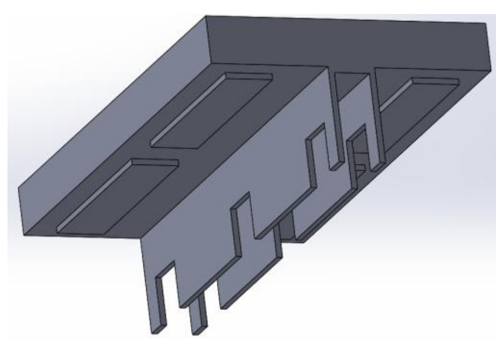

Fig. 7. Solidworks part drawing of the vehicle

The aluminum channel and the aluminum solenoid inserts act like a heat sink would on a CPU. The heat generated from the solenoids is dispersed through the extent of the channel body.

A technical drawing of the vehicle with dimensional outlines is shown in figure 8. The overall size of the vehicle is 5.5'' x 5''.

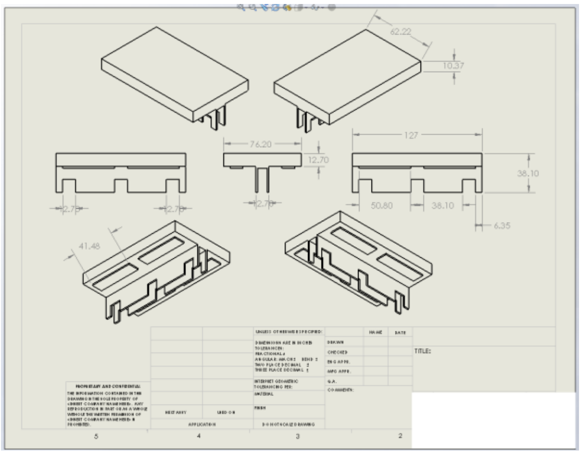

Fig. 8. Solidworks Tech dimensional drawing

VI. Hardware Integration

This section details the interconnection of all the components in the hardware design and shows the PCB layout that ultimately wasn't used because a through hole point-to-point perf board is more convenient and less costly. The group couldn't afford to spend an extravagant amount on PCB manufacturing due to the costs of all the magnets required for the track.

A. Sensor functionality

The sensors readings are read in through the analog pins of the Atmega328 MCU. The voltage values 0-5V are then converted through programming functions to gauss values between -1024 to 1024. The three sensors are set up in such a way on the channel that a three-phase time-linear signal is sent back to the MCU and are utilized to determine polarity of our electromagnets.

B. H-Bridge Connections

The H-bridge has 16 pins current will be sent either left or right through the two drive pins which represent polarity change. figure 9 shows the pins of significance for the project. Six digital logic pins are connected to the Atmega328 for solenoid polarity control. The enable pins are always high logic level because we are tying them to the 5V power rail on the PCB perma-proto board. The wiring to the solenoids goes up from female headers soldered to the perf board and down through the C channel.

Pin	Function
1	Enables 1^{st} solenoid tied to 5V rail
2	Digital logic pin (high or low)
3	Connects to 1^{st} solenoid wiring
6	Connects to 1^{st} solenoid wiring
7	Digital logic pin (high or low)
8	12V Solenoid driver Power supply
9	Enables 2^{nd} solenoid tied to 5V rail
10	Digital logic pin (high or low)
11	Connects to 2^{nd} solenoid wiring
14	Connects to 2^{nd} solenoid wiring
15	Digital logic pin (high or low)
16	IC power supply 5V

Fig. 9. Pin functionality of the h-bridge drivers

C. Solenoid power draw

The solenoids each draw .6 amps from the 12V DC power source. So according to ohms law the solenoids equate to 20 ohms apiece. The h-bridges function perfectly within this output range, but as a safety precaution heat sinks were attached to the IC's because 7.2 W can generate a significant amount of heat that has the potential to fry the h-bridge if it exceeds its temperature rating of 180 degrees Celsius.

D. PCB design

The overall PCB design is shown is Figure 10. This is what we would have ordered if point-to-point soldering wasn't a viable and preferred option.

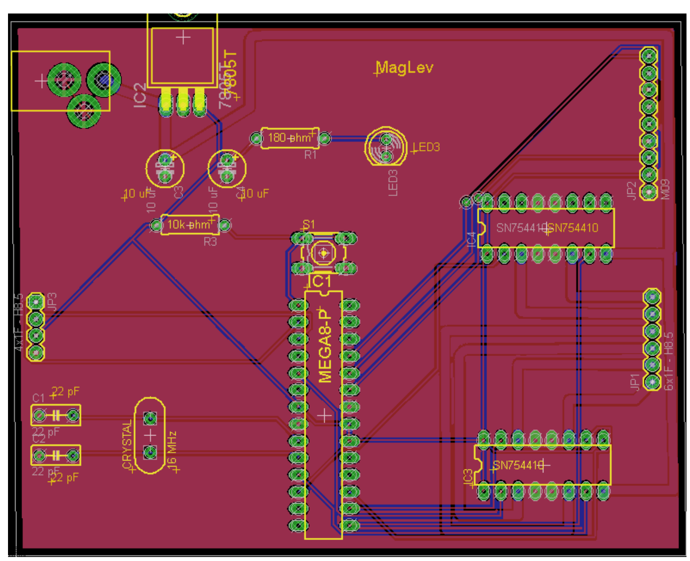

Fig. 10. PCB Board layout done in EAGLE CAD

VII. Remote Controller

The remote controller is the main interfacing device between the user and the vehicle system. The remote controller sends wireless signals to the microcontroller unit to initiate the movement of our vehicle. It will need to send several commands to the vehicle, which will control the entire movement of the magnetic levitation system. There are three main commands that are sent which include forward and backwards motion as well as stop. The remote controller not only sends commands to the microcontroller but receives input to monitor the speed of our vehicle.

Speed is a parameter that will be available on the remote controller. So the remote controller has the ability to establish a wireless connection between the system and the remote itself, send and receive commands through this network, and has capabilities to monitor the speed of the vehicle in real time, which require access to a real time clock, giving us a time parameter for the calculation in velocity. The other parameter of displacement is calculated by the controlling system of the magnetic levitation vehicle and sent as an input to the remote controller.

The chosen device to serve as a remote controlling is an android powered smartphone. Other choices included using wireless analog controller or a laptop pc. The smartphone was chosen as it is an already possessed device, it is mobile and compact, a smartphone provides wireless communication capabilities through either Wi-Fi or Bluetooth, and it possesses a great platform to develop an application and interface.

VIII. Android Application

The application's purpose is to establish a wireless connection between the remote controller, the smartphone itself, and the magnetic levitation vehicle, more specifically the microcontroller which will be sending the signals to the vehicle.

A. Developing the App

To begin developing the application for Android, one needs to use the Android Bluetooth APIs (Application Programming Interface) which allows the access of Bluetooth functionalities already encompassed in the Android smartphone. These APIs allows users to scan for other Bluetooth devices, query the local Bluetooth adapter for paired Bluetooth devices, establish RFCOMM channels, connect to other devices through service discovery, transfer data to and from other devices and manage multiple connections. These APIS are available in the *android. Bluetooth* package.

For the application to be able to use the features of this library, at least one of the two Bluetooth permissions needs to be declared either Bluetooth or Bluetooth_Admin. The Bluetooth permission is used for connection purposes such as requesting and accepting a connection as well as transferring data through the connection. Through this permission, the application can put the device in device discovery mode. This mode will actually allow the smartphone to search for as well as be found by any Bluetooth enabled devices within the probable range.

B. App Interface

The application's interface is designed using XML (Extensible markup Language) and the ADT tools downloaded for the Eclipse Environment. These tools allow developers to design the interface of the application by either drag/drop or using the cursor and changing widget displays, by using the side menus, or by editing the actual XML code behind the interface.

Then the three main commanding buttons will be in the center of the screen. These will send outputs read by the microcontroller to give our vehicle commands. The two commands that will allow the user to put the vehicle in motion are forward and back. The Stop button will allow the user to bring the vehicle to a stop when the device is in motion. All of these commands will be handled by the microcontroller which will be pre-programmed to execute specifically on the vehicle depending on each command. At the bottom of this interface will be displayed a meter that will show the vehicles speed as it moves about the track, in mph.

IX. Wireless Communication

Wireless communication is a growing field with more and more technologies available for this form of communication including infrared, Wi-Fi, Bluetooth, and other relevant technologies. For the magnetic levitation system that the group proposes to design, two of these technologies are the most prominent and best suited for this type of system. These are both Wi-Fi and Bluetooth Wireless Communication. Both of these technologies provide an ample medium through which the remote controller and the system can communicate.

A. Wi-Fi Connectivity

Since the smartphone has Wi-Fi capabilities, this would be a prospective connection to use to communicate with the vehicle's microcontroller. Using Wi-Fi would limit the connectivity to the Wi-Fi connection strength and signal depending on the testing environment in which the system is not only tested, but presented as well.

Although Wi-Fi allows for longer ranges of interfacing between systems or devices, such as 300 feet from the networking node, this is not really a pro with this particular system. The user in this system will not be any farther from this system than a probable 10 feet, making this Wi-Fi advantage over Bluetooth a light one. Wi-Fi connectivity can be seen as more secure network with numerous securities.

B. Bluetooth Connectivity

Communication between our remote controller and our magnetic levitation vehicle system will happen through a wireless Bluetooth connection between the smartphone and the microcontroller. It will allow our smartphone to use as little power needed to send commands to our microcontroller. Our Bluetooth connection between our remote and our system will allow for as minimal interruption as possible using a communication frequency between 2.402 GHz and 2.480 GHz, which has been set aside by international agreement for the use of industrial, scientific and medical devices (ISM). Our smartphone will send out a small signal of about 1 mill watt, limiting the range of connection between our remote and vehicle to about 10 meters or 32 feet, as well as the odds of other devices in the area of testing or presentation that might have the ability to interfere with our system and device.

C. HC-06 Bluetooth Module

The HC-062 is a Bluetooth module device used to connect or add Bluetooth capabilities to a microcontroller unit or processor. The device is programmed by simple ASCI command language. The general specifications can be seen in Fig. 11 below:

Feature	**Specification**
Bluetooth protocol	v2.0+EDR
Frequency	2.4GHz ISM band
Modulation	GFSK(Gaussian Frequency Shift Keying)
Emission power	<= 4dBm, Class 2
Sensitivity	Asynchronous: 2.1 Mbps(Max)/160kbps, Synchronous: 1Mbps/1Mbps
Security	Authentication, Encryption
Profiles	Bluetooth, Serial Port
Power Supply	+3.3 V DC, 50 mA
Working Temperature	-20 ~ +75 Centigrade
Dimensions	26.9 mm x 2.2 mm

Fig. 11. HC-06 Specifications

The HC-06 will be connected to the Atmega328 processor via the Tx, Rx, Vcc, and Grnd Pins. The Tx and Rx will allow the serial communication between these two peripherals. The purpose of the Bluetooth Module is to allow the MCU to wireless communicate with the Android Smartphone App through its Bluetooth capabilities.

X. INTERFACING MICROCONTROLLER AND REMOTE

In order for the remote controller to interface and send commands to the vehicle, it must consolidate with the microcontroller which will be directly handling the vehicle's motion and directly connected to the HC-06 Bluetooth Module from which UART communication happens.

A. Communication through the System

The maglev vehicle will be on the magnetic track and levitates by magnetic levitation, controlled by the Atmega328p which will be powered by a 12 volt battery. In order for the microcontroller to support Bluetooth a slave module is added to the board. This module serves as a hallway with the purpose of exchanging information between the smartphone remote controller, and the board. Figure 12 shows an outline of the interaction between each interfacing technology in the entire system and how each of these technologies will work.

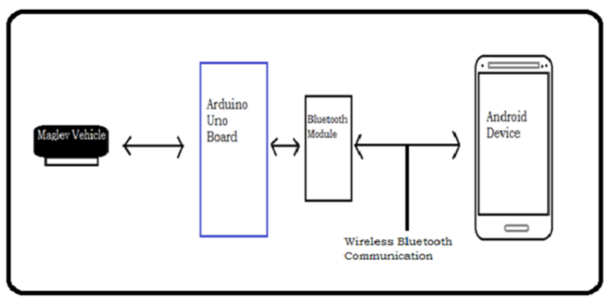

Fig. 12. Communication System Model

The Android smartphone will initiate a connection between itself and the Bluetooth module. The smartphone will send a radio frequency to any Bluetooth supported device in order to establish communication. Once the Bluetooth module is on and ready to receive this signal, a connection can then be made and communication can then take place where the Bluetooth module will serve as the slave and the Android smartphone will serve as the master. This entitlement is appropriate since the smartphone is the controlling device establishing the connection and deciding when to send and retrieve information in a client-server interaction.

XI. Microcontroller Control

Using this Microcontroller, we were able to implement the correct input / output expectation for movement. Table 1 below shows the list of expected input / outputs.

Case #	**Voltage**	**Solenoid**	**State**
1	3.75V	1	N-S
	0V	2	OFF
	3.75V	3	S-N
2	5V	1	OFF
	1.25V	2	N-S
	1.25V	3	S-N
3	3.75V	1	S-N
	3.75V	2	N-S
	0V	3	OFF
4	1.25V	1	S-N
	5V	2	OFF
	1.25V	3	N-S
5	0V	1	OFF
	3.75V	2	S-N
	3.75V	3	N-S
6	1.25V	1	N-S
	1.25V	2	S-N
	5V	3	OFF

Table 1 – Expected Input / Output Cases

By taking three analog inputs from the Hall Effect sensors we will know which outputs we need for the H-bridge to give us the intended solenoid polarity. Once we know which outputs need to change we will toggle the digital outputs heading from the atmega328 to the TI SN754410. The intended output is numerically determined by following the table above, but is explained physically by the flowchart in figure 13. Once the Microcontroller sends the signal to the H-Bridge, the solenoid should be the correct polarization. There are three expected solenoid orientations; N-S, S-N, and off. If used in the correct pattern, these three orientations will move the vehicle smoothly in the direction we intend.

A. Pass N-Oriented Magnet

Since the solenoid just passed an N polarized magnet, we changed the switch values to match what they would need to be in order to create movement. As shown in Figure 13, the N oriented magnet will push the vehicle, while the S magnet ahead, pulls the car forward.

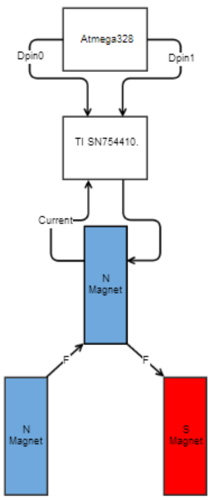

Fig. 13. MCU – H-Bridge Connection

B. Pass S-Oriented Magnet

Above in figure 13, we can see what the expected solenoid polarity output will be if it has just passed an N-magnet. Similarly, if the solenoid has just passed an S-magnet then the solenoid will turn S oriented. The orientation looks like figure 1 except the magnets will be opposite polarity. This will cause a similar pushing away from the magnet behind it, and pulling towards the magnet in front.

C. Adjacent to S or N magnet

If the solenoid is adjacent to either type of magnet on the track, it will be turned off. Sending the same signal out of Dpin0 and Dpin1 will allow this to happen. When the solenoid passes a magnet on the track while off it will smoothly move past without pulling itself down or in the wrong direction.

XII. Movement Control

The functioning of the microcontroller is a crucial portion of the project. The MCUs job is take the input it received from the Hall Effect sensors and convert that information into digital outputs that will be in charge of controlling the solenoid magnet polarities. Below in figure 14 there is a small portion of the microcontrollers programing that displays the logic of how our vehicle reads the current magnetic field and directs the circuit.

```
if(gauss0>630){          // gauss is converted magnetic field
    delay0++;            // delay used for adjacent off time
    if(delay0>100){        // solenoid is no adjacent, it
      OPass_N=Pass_N;       // used for magnetcount
      Pass_S = 0;          // for "if" statement later
      Pass_N = 1;          // use to established digital outputs
    }
    else{
      digitalWrite(dpin7, LOW); //turns off solenoid until
      digitalWrite(dpin8, LOW); // it is no longer adjecent
    }
    if(OPass_S != Pass_S){
      Magnetcount_f=Magnetcount_f+1; //f is for front
    }
  }
```

Figure 14

In the code above we see that when the gauss value is higher than 630, our MCU will acknowledge that the solenoid is adjacent to an N-polarized magnet on the track and therefore turn off until the solenoid has passed the track magnet. Gauss is a value that our group used to identify the magnetic force being measured by the Hall-Effect sensors.

Once it has passed the track magnet we want the solenoid to be N-S oriented in order to move in the correct direction. When it is N-S oriented it will move forward

A. Backward Movement

One of the signals that can be sent from the Bluetooth controller is to drive the opposite direction. This means that the same process will happen, just in reverse

Similar to forward movement, the MCU controls backward movement by keeping track of which polarity magnet is being passed.

B. Brake

Whenever we receive a signal of "brake" from the Bluetooth controller we need to set the solenoids polarity to whichever magnet is closest to it. This will create a pull towards one spot on the track and hold it there.

REFERENCES

[1] J. E. Hilton and S. M. McMurry, "An adjustable linear Halbach array," *Journal of Magnetism and Magnetic Materials.,* vol. 324, no. 13, pp. 2051-2056, July 2012

Group Members

Julio C. Arias is a graduating Computer Engineering with interests in Software and Systems Engineering. Julio is currently working at NYSE Euronext as a Software Developer and hopes to eventually work as a Systems Engineer in Missiles and Fire Control for one of the leading military DOD contracting companies.

Sean D. Mawn is a senior in Electrical Engineering at UCF. After graduating, he hopes pursue a career in control systems or power generation and transmission. He is also working towards obtaining a P.E. license.

William G. Schiller is an Electrical Engineering senior at UCF. Upon graduating he wishes to pursue a career related to sound engineering, with an emphasis in signal processing and amplifier design. California will be the ideal location of his future career.

Leo F. Sell is an Electrical Engineering senior at UCF. After Graduating in fall 2013 he hopes to pursue a career in computer vision programming. Leo is also considering continuing education towards a masters or PhD