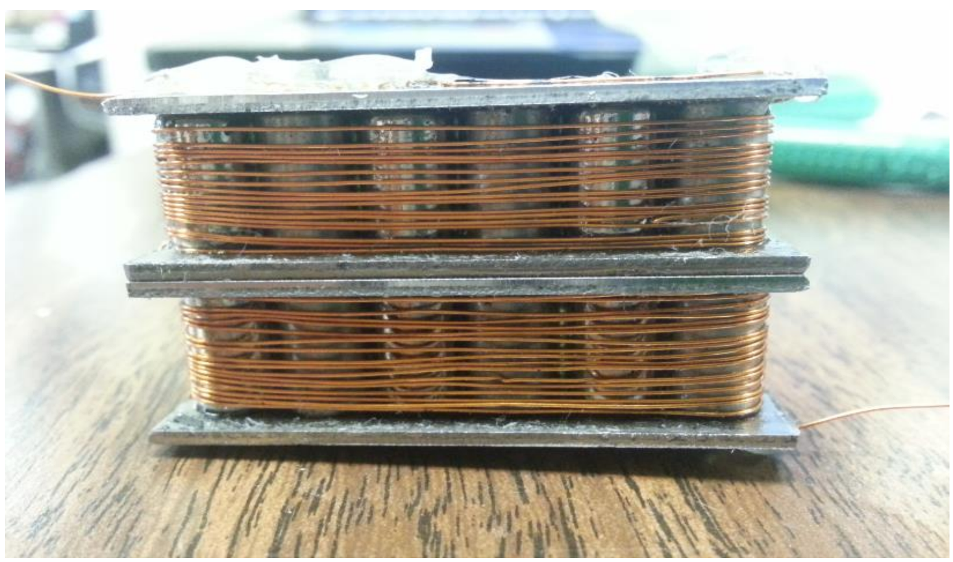
ELECTRO-PERMANENT MAGNETS AS AN ALTERNATIVE TO ELECTROMAGNETS IN THE GIBBOT PROJECT.

YASH SIDDHARTHA



8/19/2013

EECS 399 Capstone Design Project

Advisor: Prof. Randy Freeman

0 ACKNOWLEDGEMENTS

I'd like to thank Nelson Rosa for his invaluable contribution to my proof-of-concept system. There was very little information to go off and talking my ideas through with Nelson helped me immensely. Prof. Lynch's advice through the project was also very helpful. He gave me some good direction on how to proceed in small steps. Prof. Peshkin's help with the relay is also much appreciated.

Thanks to my team-mates, Andrew Griesemer and Jason Mantouzanis for their assistance and feedback through the design process and thanks to Prof. Freeman for being my advisor.

1 TABLE OF CONTENTS

Contents

1.1 TABLE OF FIGURES

2 EXECUTIVE SUMMARY

This project is geared toward examining the viability of an electro-permanent magnet assembly replacing electromagnets in a holding application. Electro-permanent magnets are supposed to offer the benefits of power and space-savings.

This report takes a look at a proof-of-concept design that attempts to ascertain if the electro-permanent magnet can be used within the constraints of the Gibbot design team. These magnets would be used in a future iteration of the robot.

The electro-permanent magnet assembly built by me and Nelson Rosa showed promise as a device that could be optimized further to meet our force requirements while improving on our current solution. Some further experimentation will definitely be required, but the outlook is optimistic on the whole. The force achieved by our current assembly is 1/10th of what we need, but this can be cut by more than half by using higher permeability steel and by raising magnet diameter by 50%. Both of these are easily possible. Further improvements should be possible by fully magnetizing our assembly one way or the other and perhaps implementing a multi-layered structure.

3 INTRODUCTION

An electro-permanent magnet (EPM) is a device that exploits the vastly different coercivities of magnetic materials with similar field strengths. This project used an Alnico magnet (coercivity: 48000 A/m, field: 1.28T) coupled with Neodymium magnets (coercivity: 1000 kA/m, field: 1.25T) [1]. The Alnico magnet's polarity can be switched to reinforce the Neodymium magnet's field, or it can be set opposite to that of the Neodymium to effectively create a net 0 magnetic field.

The Gibbot is a dynamic climbing robot developed for experimental validation of estimation and control of hybrid mechanical locomotion systems. The Gibbot locomotes on a vertical wall and consists of two links, each equipped with a "hand," and a single powered rotary joint connecting the two links. A hand can clamp to the wall at any time, with the link freely pivoting about the clamp. The robot moves by actuating the joint motor and switching between four dynamic regimes: one hand clamped, the other hand clamped, both hands in free flight, or both hands clamped (rendering the Gibbot stationary). The Gibbot prototype climbs on a steel wall, so we use electromagnets mounted in rotary bearings to implement the hand clamping mechanism. [7]

The electro permanent magnet would replace the electromagnets in each "arm." The advantages offered would potentially include savings in power consumption, space and weight. To this end, we proceeded to test the concept of an electro permanent magnet, first with a proof-of-concept experiment and then started to design larger systems approaching the size we would require to implement it on the Gibbot itself. [7]

The tasks required to be completed in order to realize these goals included:

1) Determining if the space and power savings are worth the effort to replace the electromagnet.
2) Finding the appropriate permanent magnetic materials to maximize efficiency and space savings
3) Programming the PIC controller to provide pulses to engage the circuitry and provide a way to disconnect the high-current magnet-switching circuitry from the control.
4) Designing the appropriate circuitry to switch the magnets on and off to allow the robot to swing

There was some prior work done with electro-permanent magnets that was particularly relevant to our project.

The first was a thesis by MIT student, Ara Nerses Knaian titled "Electropermanent Magnet Connectors and Actuators: Devices and their Applications in Programmable Matter". This was of particular help with understanding the theoretical side of the problem and calculating ballpark values for the currents and energies required to switch magnetic systems of a certain length. Chapter 3, "Electropermanent Magnets" was the relevant chapter in this case and provided both theoretical guidance as well as some practical results from experiments conducted by Dr. Knaian. [1]

The second major source we used was based on a Kickstarter project started by Andreas Jochum, to build a 100N electro-permanent magnet based cargo-lift. Andreas was himself a valuable resource to us over email and chat from Nicaragua. He provided us with some of the ideas for circuitry and various tips based on his experiences with trial and error with the process of building a larger-scale EPM. [3]

The final source we used, that served primarily to corroborate the principles we used in designing our EPM assembly was a paper by a UTS students Peter Ward and Dikai Liu, titled "Design of a High Capacity Electro Permanent Magnetic Adhesion for Climbing Robots." This paper served as an important baseline for our understanding of how best to switch an EPM and the dependence of energy required on the length of the magnet, as well as keeper sizes. The coercivity to be taken into account was also obtained from this paper (~180000 A/m). Furthermore, it clarified the best way to amplify force available, by minimizing air gaps and designing keepers of the correct materials. [6]

3 KEY REQUIREMENTS AND CONSTRAINTS

There were a number of requirements and constraints associated this project, some of which are related to the Gibbot itself and others related to ensuring that the EPM is a significantly better option than the electromagnet that is currently being used in the system.

Specifically, the constraints associated were:

1) The EPM assembly must fit in a space 2.37” in diameter and 0.985” in height.
2) The EPM assembly along with associated circuitry must be operable at 48V.
3) The EPM assembly must be capable of switching states in 800-900ms.

Requirements:

1) The EPM assembly must be able to withstand around 100N of force.
2) The EPM assembly must consume less than 5.2W of power per switching process. This is the power used by the electromagnet. (http://catalog.apwcompany.com/Asset/6489.pdf)
3) The EPM assembly must be capable of withstanding constant switching of states.
4) The EPM assembly must be significantly lighter than the electromagnet currently being used.
5) The EPM assembly must be safe for operation within the vicinity of the other electronics being operated in the Gibbot.
6) The EPM assembly must be programmable for various possible motions that the Gibbot may be able to execute in the future.

4 BROADER CONSIDERATIONS

The design basically does exist in the commercial sense. Andreas Jochum's "Kickstarter" project made well over its $10,000 and he has been fielding orders for it ever since. He is also developing smaller and perhaps cheaper systems to implement his cargo-lifter with EPMs.

However, as for widespread use of EPMs beyond the hobbyist market, the paper by Bard and Liu is specifically considering the use of EPM assemblies in lifting very large loads.

Generally, EPMs are beneficial in systems where the holding force is required for long periods of time and time between switching is reasonably large. There is a crossover between when to use EPMs and when to use electromagnets once the number of switching events gets larger and larger. (Knaian) The break-even time is given by the following equation:

$$T_b = \frac{2E_{electropermanent} - E_{electromagnet}}{P_{electromagnet}}$$

EQUATION 1 [1]

Where E represents energy of each type of system. The electro-permanent magnet energy is per switching event and hence multiplied by 2.

P is the power dissipation of the electromagnet.

One of the biggest issues with designing an EPM system is that the currents associated with switching an EPM are very high.

The current I required to switch a magnet of length L, with material coercivity H_{mag} is given by:

$$I_{max} = \frac{H_{mag} L}{N}$$

EQUATION 2: LENGTH OF MAGNET VS. CURRENT [1]

Note: This is presuming an air-gap of 0, which Dr. Knaian's thesis does not necessarily presume.

With Hmag being in the range of 180 kA/m, the current is high for any meaningful length of magnet. We will talk about the reasoning for not raising the number of turns to limit current as well as other factors to be considered in the next section.

5 DESIGN DESCRIPTION

The design process began with one basic goal- Switch the poles of a single AlNiCo magnet. This was perhaps the hardest part of the process, because we were very unclear as to the exact amount of energy/current required to switch the poles of a magnet of a given.

From Equation 2, we knew what the maximum current reached would have to be, but we were unsure-and truly still are- as to how long this current needed to be maintained.

We started with a 1.25" long and 0.25" in diameter magnet.

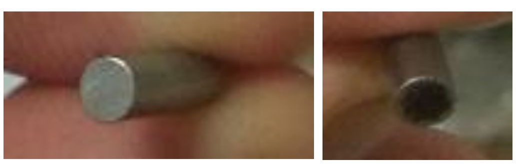


FIGURE 1**. THE ALNICO MAGNET USED IN INITIAL EXPERIMENTS 1**

The magnet was wound with 22 windings of copper wire, of gage 32 AWG. This corresponded to a resistance of 0.4 ohms and an inductance of 4.4 uH.

The length of the magnet, using a value of coercivity of about 48,000 A/m (to demagnetize halfway) [6] meant we needed to apply a field created by 80A worth of current. This corresponded to a required voltage greater than 31.2 V to re-align the poles of the magnet.

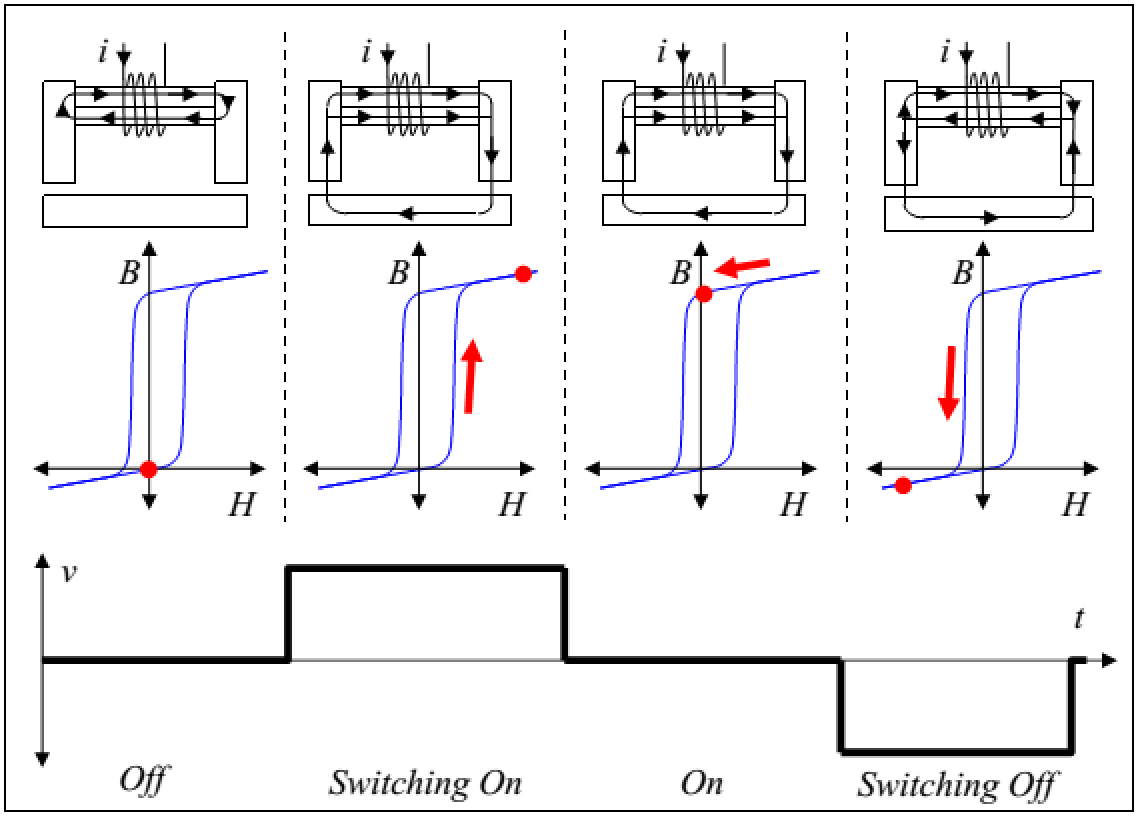


FIGURE 2**: FROM DR. KNAIAN'S THESIS- A DESCRIPTION OF SWITCHING THE POLES OF THE MAGNET. WE ARE ONLY GOING FROM OFF TO ON WITH OUR INITIAL EXPERIMENT- HENCE THE LOWER COERCIVITY VALUE. 2 [1]**

Initially, the circuitry for this was implemented with a 2 way switch. The switch was first used to charge a capacitor up to 32V. Then, it was used to turn that circuit off and activate the circuit that just consists of the capacitor and the magnet with windings. Effectively, we have a LRC circuit with very low impedances- this leads to a fast discharge of high current across the windings of the magnet.

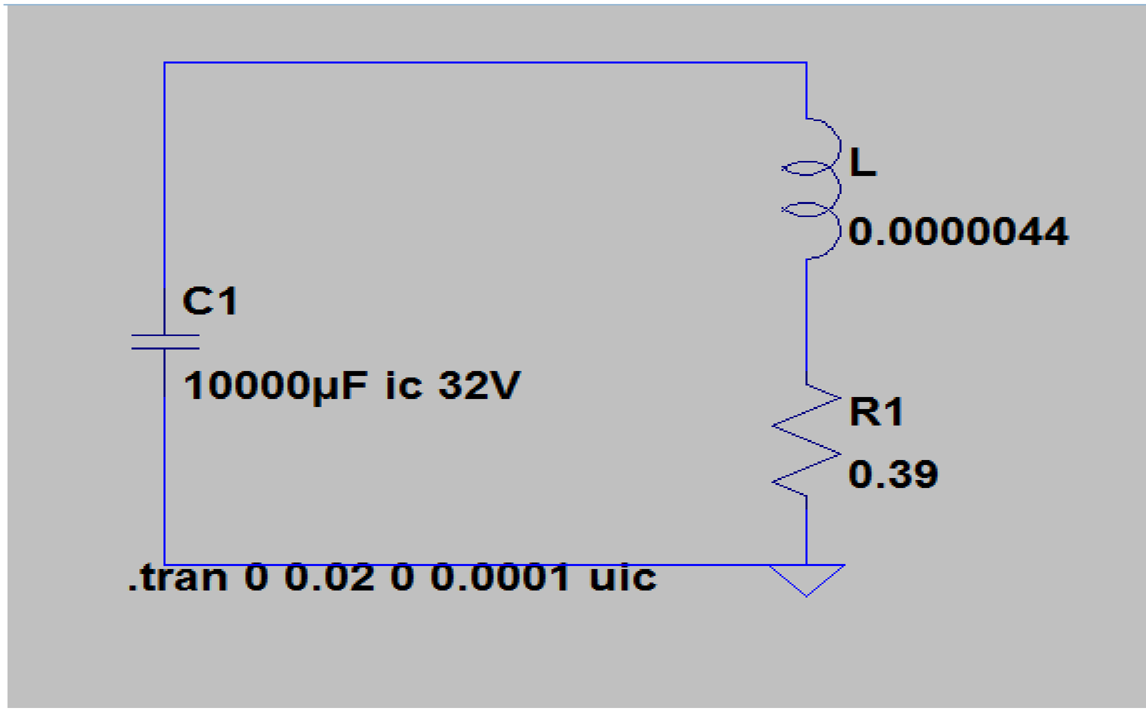


FIGURE 3A**: THE CIRCUIT CAN BE APPROXIMATED TO A CAPACITOR WITH INITIAL CONDITION OF VOLTAGE 32V. 3**

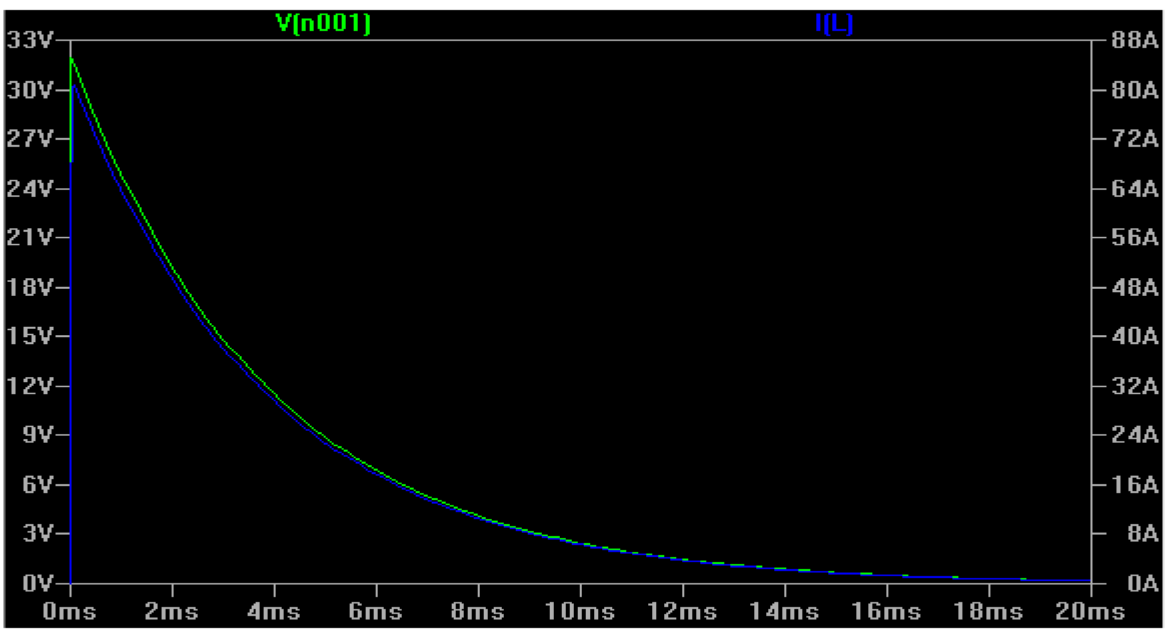


FIGURE 3B **(BOTTOM): THE SWITCH IS CLOSED AND CURRENT AND VOLTAGE ACROSS THE MAGNET ARE AS SHOWN ABOVE. THERE'S A HUGE SPIKE IN THE CURRENT (BLUE) WHICH IS WHAT ALLOWS FOR THE SWITCHING OF THE POLES. 4**

This circuit successfully brought the magnet's field strength down significantly, but our switch was unable to withstand the high currents. We were also quite worried about back EMF from such a large current flow.

Our next iteration of this design was to use a PIC32 to drive a MOSFET that allowed a pair of relays to be turned on in parallel (they were rated for 30A each and 60A in parallel). This was suggested to us by Professor Peshkin. This worked significantly better and we were able to switch the poles reliably and quickly.

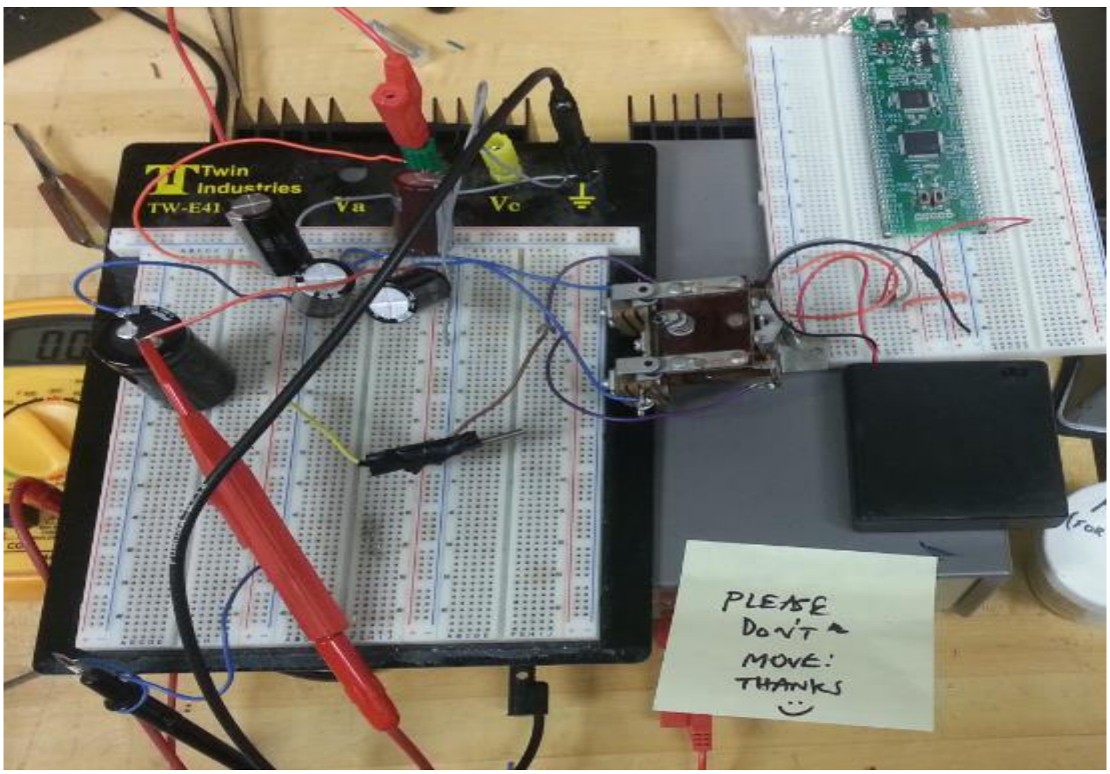


FIGURE 5: **SETUP OF CIRCUIT WITH THE RELAY** 5

The battery pack pictured powers the relay through the FET. When the relay is engaged, the capacitor discharges across the magnet, switching the polarity. The side of the magnet that is to be converted to “north” should be connected to the positive side of the capacitor and the side that’s to become “south” to ground.

The switch was replaced on the charging side with a 100 ohm resistor, which continuously charges the capacitor with the time constant RC. The capacitor used was 10,000uF, which appeared to be necessary to hold the discharge field for long enough to switch the poles. In all likelihood, a higher voltage would also work when applied for a shorter period of time. However, we are constrained by a 48V voltage, which needs to be kept in mind when designing a larger system.

The video of the circuit’s operation is available at:

https://www.dropbox.com/s/58zrfi6uutlmc3d/2013-08-14%2020.22.58.mp4

The black dot represents the initial “north” pole, which is then switched to become a south pole. This concept was sourced from the Kickstarter[8] project and [4].

5.1 FINAL PROOF-OF-CONCEPT DESIGN

Andreas Jochum’s Kickstarter project takes advantage of the fact that the energy required to switch an EPM is proportional to the volume of the magnet, while the force exerted by it is proportional to pole surface area. As a result, by minimizing the lengths of the magnet, while maximizing diameter of the poles (and thus surface area), it is possible to obtain the right force-energy balance to make EPM a worthwhile replacement for the electromagnet. This insight will also be key to obtaining enough force from a configuration that can fit within the space available in the Gibbot’s “hand.”

The relevant equations we took into account when designing a larger system were the force equation for magnets of a certain pole area and equations for current, resistance and hence voltage required for the assembly.

These were obtained from Dr. Knaian's thesis:

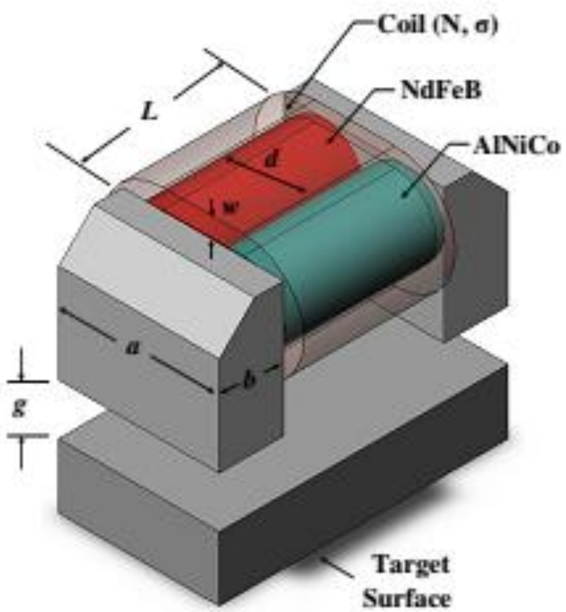


FIGURE **6: A PICTURE DESCRIBING THE PARAMETERS USED IN THE EQUATIONS PRESENTED BELOW.**

$$F = \frac{1}{\mu_0 ab} \left(\frac{\pi B_r d^2 N_{rods}}{4} \right)^2$$

EQUATION 3 [1]

where a,b are dimensions of the metal keeper pieces (preferably silicon steel)

Br = 1.26T for AlNiCo and NeDb approx.

Nrods is the number of magnet pieces being used in the assembly

d is the pole diameter of each piece (And this pi()*d^2/4 is the surface area term) mu is the permeability of free space

$$b = \frac{B_r}{B_{sat}} \frac{\pi d^2 N_{rods}}{4a}$$

EQUATION 4 [1]

This is an equation determining the optimal dimensions of the keeper pieces on sides. b is the thickness of the metal to be used. a is effectively determined by the number of pieces used and their diameters.

Resistance of the windings is a function of the number of windings and the circumference of the magnet pieces.

$$R = \frac{4\rho N^2}{L}\left[1 + \frac{d}{w}\left(1 + \frac{2N_{rods} - 2}{\pi}\right)\right]$$

EQUATION 5 [1]

p is the intrinsic resistivity of the material (copper)

d is diameter of magnet pieces (as before)

w is the width of the wire (the gauge/AWG in mts)

L is the length of the magnet piece

The area available to us was defined by a circle of diameter 2.37”. The largest setup that would fit in such a circle is a square of side 4.24 cms (1.67”). We were going with a rectangular or square setup to mimic Andreas’ work in case we needed a reference point.   The assembly could potentially be expanded and made non-symmetric if additional force is required.

Based on these equations and with Andreas' design as reference, we decided to build a multi-magnet assembly that minimized length while maximizing surface area. This was done by choosing magnets of almost equivalent diameter and length. This involves a tradeoff: Shorter magnets tend to have less "reach", but they also take a lot more current to magnetize in either direction. Longer magnets can surmount larger air gaps, but in our application, air gaps are unlikely to be very large. As a result, it makes sense for us to minimize energy consumption by using shorter magnets. [3]

Based on this, we ordered a number of different magnets of various sizes and diameters to test them out and look at the practical applicability of our hypotheses.

Based on an initial cursory inspection, it was obvious that the magnets of larger diameter were clearly stronger than the thinner ones. Furthermore, the effect of additional length was not significant in terms of magnetic strength.

As a result, we made the decision to proceed with testing 0.25" diameter magnets in a 12-piece assembly (we didn't have enough of the 3/8" magnets to do a full assembly). The 12-piece assembly uses all the space available.

The keeper lengths were determined by the sum of the diameters of each row of 6-piece magnets. (2 rows make up 12). The thickness was then determined by the formula provided in the Knaian thesis. The thickness obtained was in the tenths of a millimeter, which did not make too much sense from a practical standpoint, and hence we went up to 2.2 mm thickness based on availability of steel sheet in the machine shop.

The assembly is put together with the poles being attached to the keepers with the neodymium and AlNiCo magnets alternated in the assembly.

FIGURE 7: **NEDB MAGNETS ALTERNATED WITH ALNICO. BLACK MARKINGS INDICATE A NORTH POLE FOR NEDB – IMPORTANT TO LINE THEM UP. MARK THE SIDE THAT IS NEDB NORTH POLES AS "NORTH" 7**

FIGURE 7.2 8 **: ASSEMBLY OF 12 MAGNETS BEING GLUED TOGETHER WITH LOCTITE. THE "NORTH" POLE PIECES SHOULD BE BONDED FACING EACH OTHER.**

FIGURE 8**: ASSEMBLY WITH WINDINGS OF 28AWG WIRE. REMEMBER TO STRIP THE ENDS – BURN THEM OFF AND WIPE WITH SANDPAPER 9**

This assembly is now ready to get introduced in to a circuit.

Based on our calculations, the requirements to switch this magnet (using equations presented above) were:

Number of turns: 10

Max. Current: 154 A instantaneous

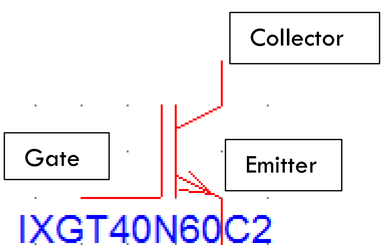
Resistance: 0.18 ohms (measured) vs. 0.04 ohms (theoretical – tends to be about 4 times off every time)

Min. Voltage Required: 27 V

Initially, we began with 34 AWG wire, but with the resistance being off by 400% made it impossible to use. Circuit design now became the next challenge. 154 A is a lot of current and we needed the right device to withstand such a high current, even instantaneously. MOSFETs are not designed to withstand high power. They are considerably better for application with low power and high switching. On the other hand, IGBTs (Insulated Gate Bipolar Transistors) are significantly better for applications where high power is being switched. They tend to be rather unhappy with high frequency switching though, so depending on the application, it makes sense to choose between the two semiconductor devices. [9]

In this design we decided to go with the IGBT. While MOSFETs of this rating are available, they are far and few between and tend to be quite expensive. Furthermore, we won't be switching very often, which lends itself to using IGBTs anyway.

We proceeded to replace the relay from our original test circuit with an IGBT. Initially, since it was a device we had not used very much before; we set up a test circuit with a resistor being used as the load (pictured below)



Taken from pSpice Schematics Editor

FIGURE 9A**: IGBT CIRCUIT SYMBOL. 10**

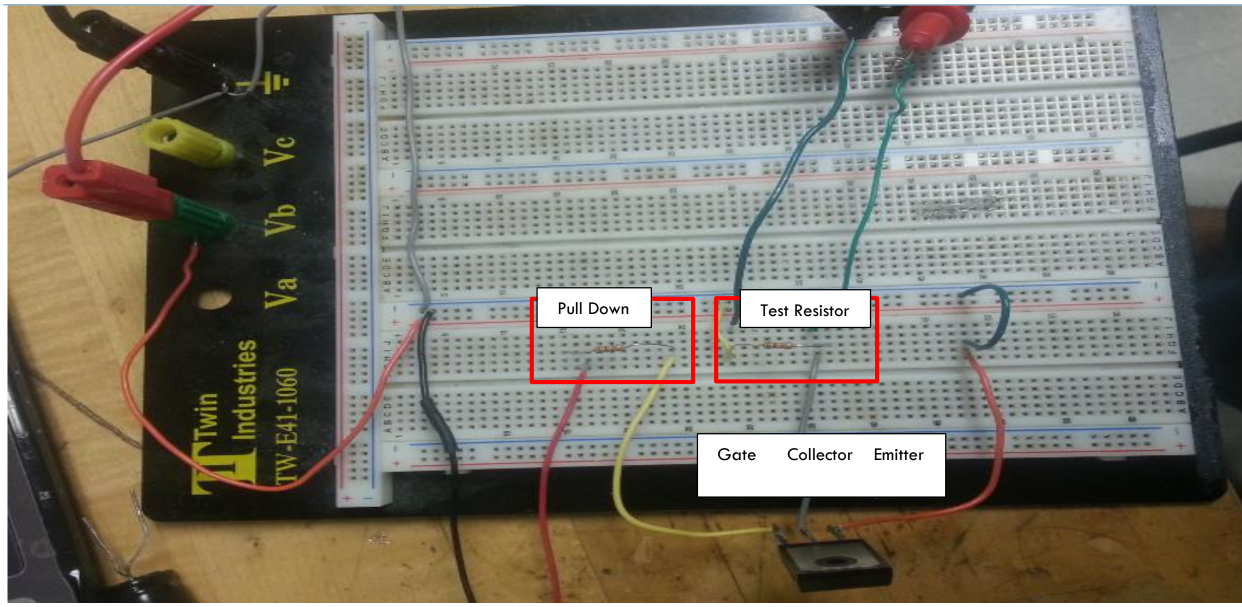


FIGURE 9B**: IGBT TEST CIRCUIT. BATTERY PACKS (12V) WERE USED TO POWER THE GATE. MINIMUM V_{GS} = 5V AND OUTPUT GOES UP SIGNIFICANTLY AS V_{GS} GOES UP. 11**

One of the biggest problems we faced was with turning the IGBT off even when Vgs=0. This was solved by adding a pull-down 1k resistor to the gate, which took care of the floating gate problem. The IGBT then switched reliably. All that was left to do was to switch the IGBT on and off via the PIC32 and the MOSFET from the previous circuit and then replace the test resistor with our EPM assembly in the correct orientation. A simulation of the circuit was run in pSpice. The schematic used, and results are on the next page.

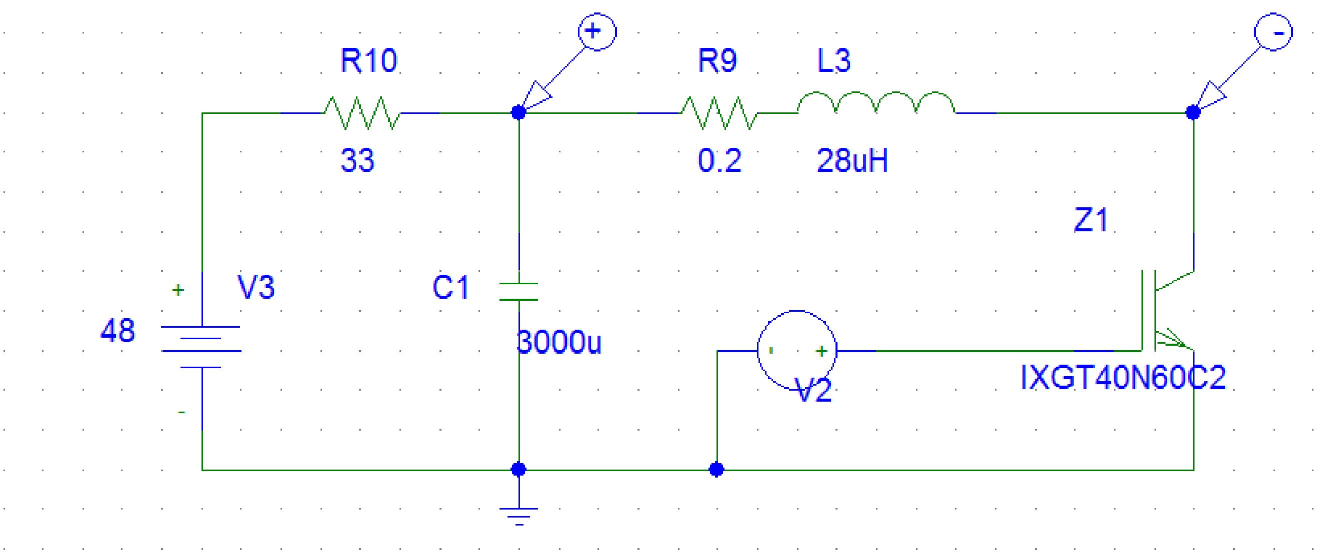


FIGURE 10**: SCHEMATIC FOR FINAL CIRCUIT. V2 IS A 12 V SOURCE CONTROLLED BY THE PIC.12**

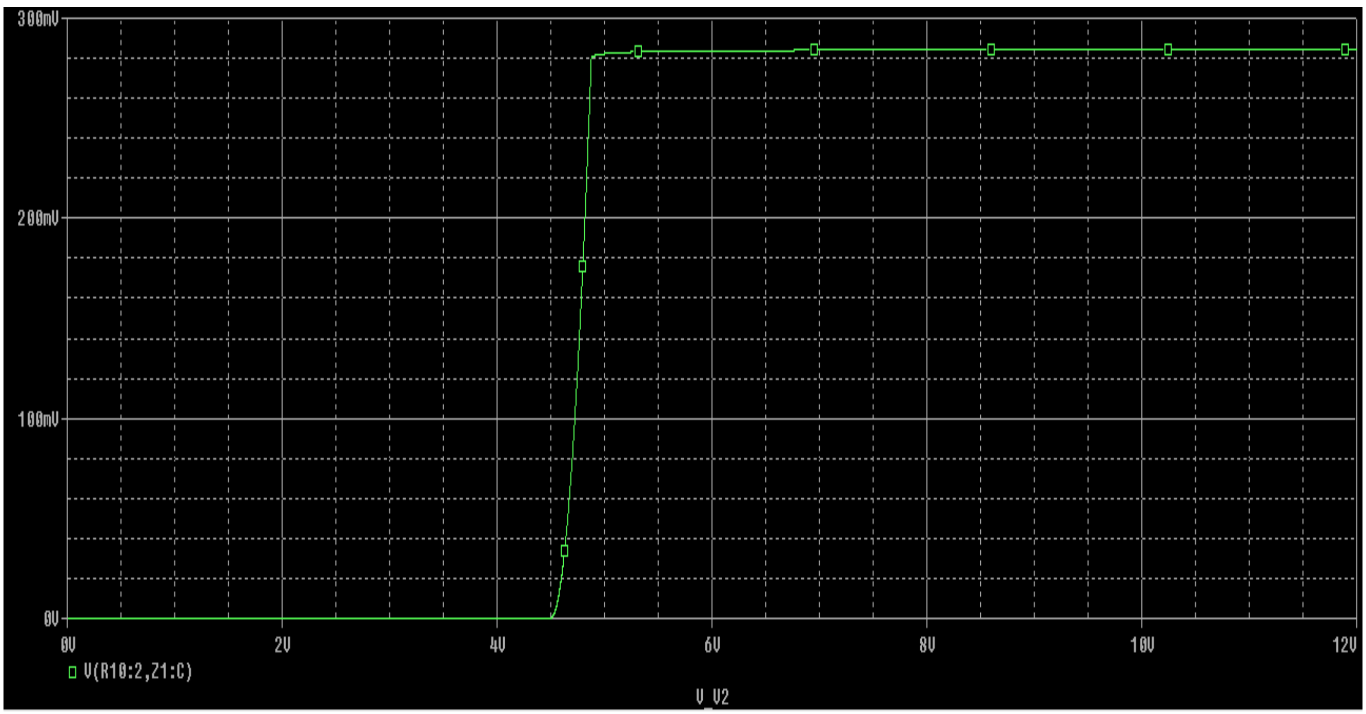


FIGURE 11**: ONCE THE VOLTAGE AT THE GATE GOES ABOVE 5V, THERE IS A VOLTAGE DROP ACROSS THE RESISTOR AND INDUCTOR. IN THE CASE OF CONTINUOUS CIRCUIT OPERATION, WHICH IS WHAT HAS BEEN SIMULATED, THERE IS A VOLTAGE OF 300 MV CONSTANTLY ACROSS THE RESISTOR-INDUCTOR. 13**

The objective with this simulation was to ensure the IGBT was functioning as required.

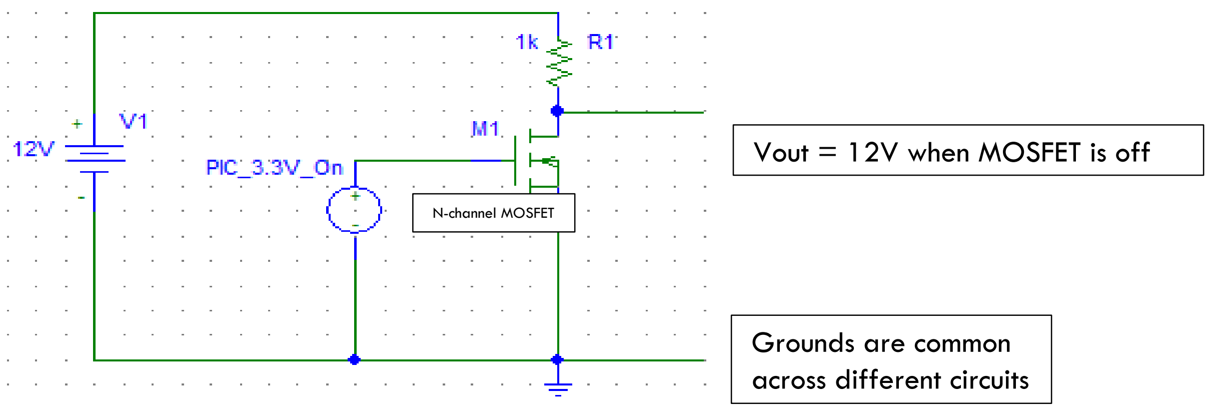


FIGURE 12**: THIS IS THE CONTROL PART OF THE CIRCUIT. THE PIC TURNS ON THE MOSFET, AND IS NORMALLY ON. THUS WHEN THE MOSFET IS** OFF**, 12 V IS AVAILABLE TO THE IGBT'S CIRCUIT. THE PIC'S 3.3V INPUT IS TURNED OFF BY USER. 14**

6 TESTING RESULTS

The final concept design was tested against a number of weights and performed reasonably well in terms of holding force. There is, however, some ways to go in terms of switching the magnet quickly and completely. It was able to lift up to 2.5lbs in weight, though this was diminished to some extent after switching once.

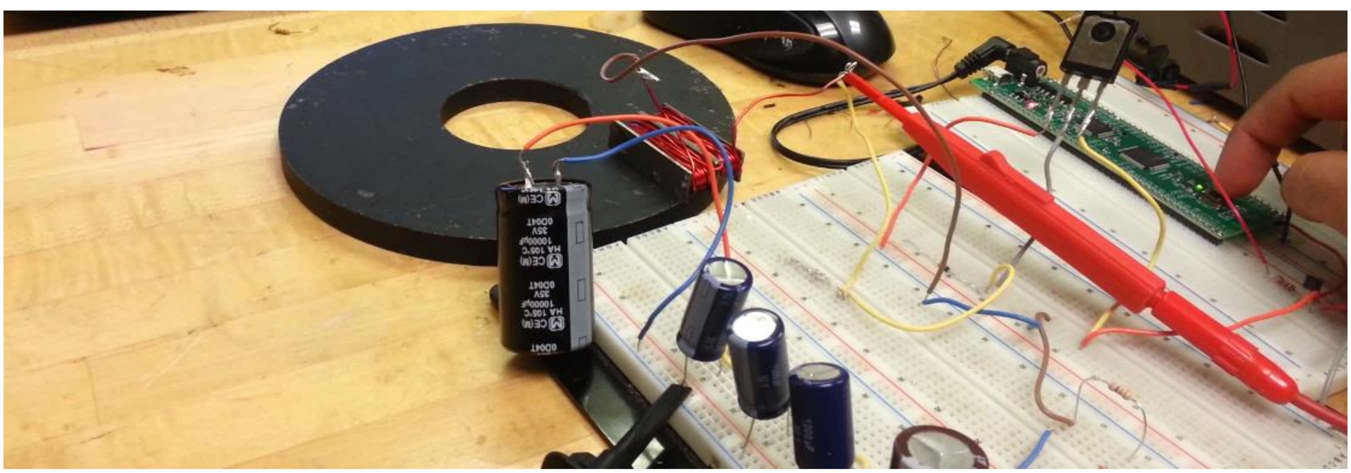


FIGURE 13**: TEST SETUP WITH THE 2.5LB WEIGHT. THE IGBT IS THE LARGE THREE-PRONGED DEVICE. 15**

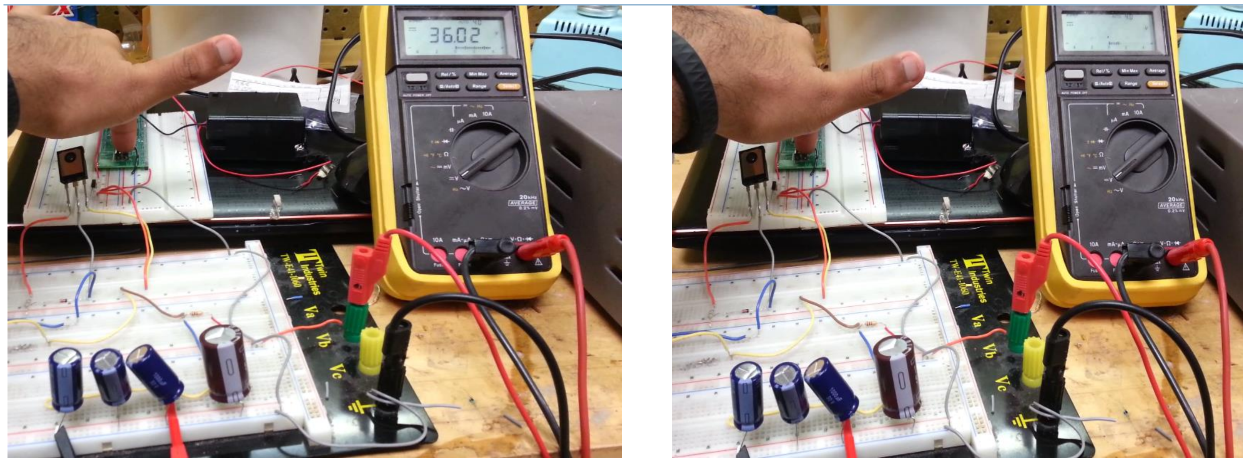


FIGURE 14**: MEASURING VOLTAGE ACROSS THE CAPACITOR BANK 16**

Left: before PIC 32 button is pressed   Right: While it is being held down.

Testing mostly consisted of applying the current pulse to the assembly and then testing its holding force against a 2.5lb weight. There were a number of observations from these rather simple tests:

1) Initially, we used higher gage wire which gave us a resistance that we couldn't support in terms of voltage and minimum current requirement.
2) One of the biggest issues with using wire of higher gage was the size of the keepers required to ensure wires do not interfere with holding force.

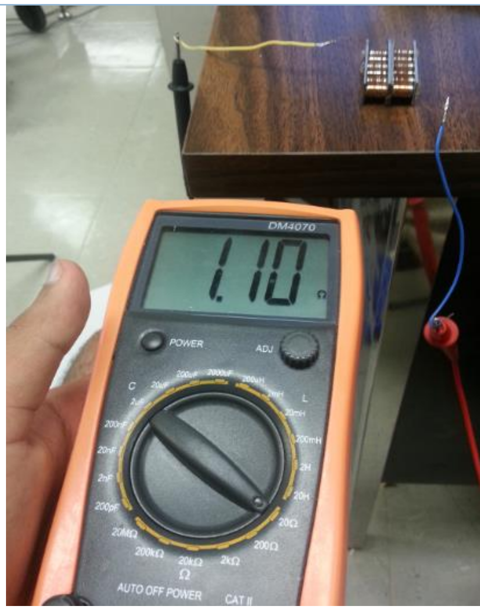


FIGURE 15**: INITIAL HIGH RESISTANCE 17**

3) With voltages higher than the minimum required voltage (36 as opposed to the required 32), a large capacitance was still needed to effectively switch the magnet, especially in one shot. We performed some analysis to figure out if it would be more advantageous to apply higher voltage and lower capacitance or the other way around from an energy standpoint. This will be presented a little later on.
4) It might also be advantageous to use a lower number of windings if a switching device of a higher rating can be found. Our current IGBT can withstand 200A for 1ms. Very high current tends to be difficult to deal with however (Andreas Jochum)
5) The back EMF from the closing of the LRC circuit creates a high current that damages regular resistors. Resistors with higher power ratings need to be used for the charging circuit.
6) With bigger winding wire, there is a concern with the use of 2 windings in opposite directions which would be used alternatively to switch poles one way or the other. This eliminates the

need for building an H-Bridge or a similar device to reverse current. However, it might be difficult to get enough space for the windings on such a small magnet.

7) The circuit itself worked reliably in terms of switching and the IGBT had no problem withstanding high current. The only potential problem occurs when switching is done too fast, but this should not be a problem for our design.

7 CONCLUSIONS

The objective behind this experiment was to prove that an EPM assembly is a viable alternative to electromagnets for the Gibbot project. Some of our takeaways and next steps for this project include:

1) As evidenced by our experiments and circuit design within the parameters of the project, it is definitely a strong possibility that the Gibbot project will be able to implement an EPM assembly.
2) Andreas Jochum's Kickstarter project uses a 300V power supply into the magnet, but only a 60uF capacitor. This only works out to an energy of 2.7J which is given by the capacitor energy equation. While we are currently trying to implement a circuit with a voltage supported by the Gibbot's power supplies. That may not be energy-efficient in terms of holding the current (and thus the polarizing field) for long enough and we might be forced to step up the voltage. The details of this are discussed in the appendix.[8]
3) Currently, the magnet isn't magnetized fully by the current pulse and furthermore, there is considerable uncertainty as to how long a pulse is truly needed. This needs to be cleared up to optimize the design to the fullest.

4) There is a lot of optimization to be done with regards to the design itself in terms of physical characteristics. The keepers need to be redesigned with steel of a higher permeability; silicon steel being the best.
5) The optimal size of magnets needs determining with a closer diameter-length match expected to be the right way to go. (same as in the Kickstarter) [3]
6) The space available could also potentially be better used with a circular arrangement in the future.
7) Photoflash capacitors can be used to maximize efficiency, since they are built to provide high currents. [Andreas Jochum, 3]
8) The switching of magnets, their material properties and inconsistency in the exact sizes of the magnets leaves room for slightly higher or lower magnetic fields than expected. In the case of a non-zero net field when we are trying to disengage from the wall, there needs to be a system in place to push off from the wall.
9) If the AlNiCo-NeDb concept works well, an extension of this project could be to take AlNiCo magnets from full magnetized in one direction to zero in the other. This eliminates the need for Ne magnets and thus, with a feedback system in place could provide better performance and control. [Nelson Rosa]
10) The PIC will need to have 2 ports programmed to provide output alternately to magnetize and then demagnetize in every cycle, since there would be two windings in opposite directions.

8 APPENDIX

8.1 BOM

The shorter magnets we ordered are:

0.375” diameter by 0.5” length

0.25” diameter by 0.5” length

Alnicos are difficult to find for this sort of size – ordered from magnetsource.com

The longer magnets are:

0.375” diameter by 1.25” length

0.25” diameter by 1.25” length

The assembly was finally built of 0.25” by 0.5” magnets. 12 of them were stacked in 2 rows of 6 each.

Circuit Parts

33 ohm resistor

1000uF @ 160V

10,000 uF capacitor @ 35V

IXGT40N60C2 IGBT

DC Power Supply

PIC32 running on MPLAB IDE

N-Channel MOSFET with required Vgs < 3.3V

8.2 HIGH VOLTAGE, LOW-CAPACITANCE OPTION

The use of a voltage accumulator such as Linear Technologies' LT3750 [5] would allow a capacitor to be charged up to well past the voltage source. Thus, using a 12/24/48V source, we could charge the capacitor up to 300V in a matter of tens of milli-seconds- well in time to be able to switch the EPMs correctly.

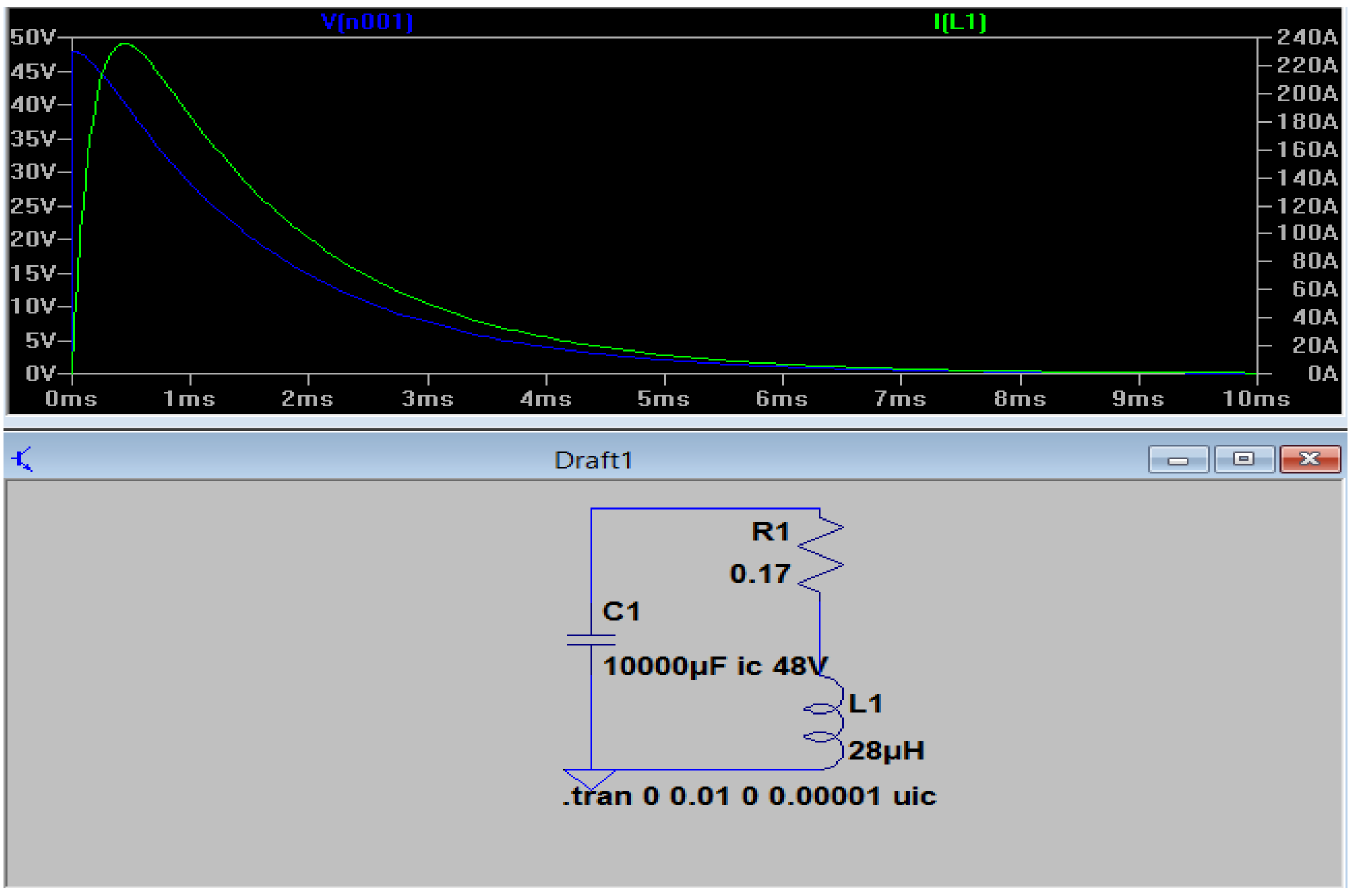


Figure 16: Simulation based on our current setup. No oscillation in the circuit due to high capacitance.

CURRENT > 150A **LASTS ABOUT 1.3MS. ENERGY REQUIRED FOR THIS IS:** 11.52J – NOT ACCEPTABLE 18

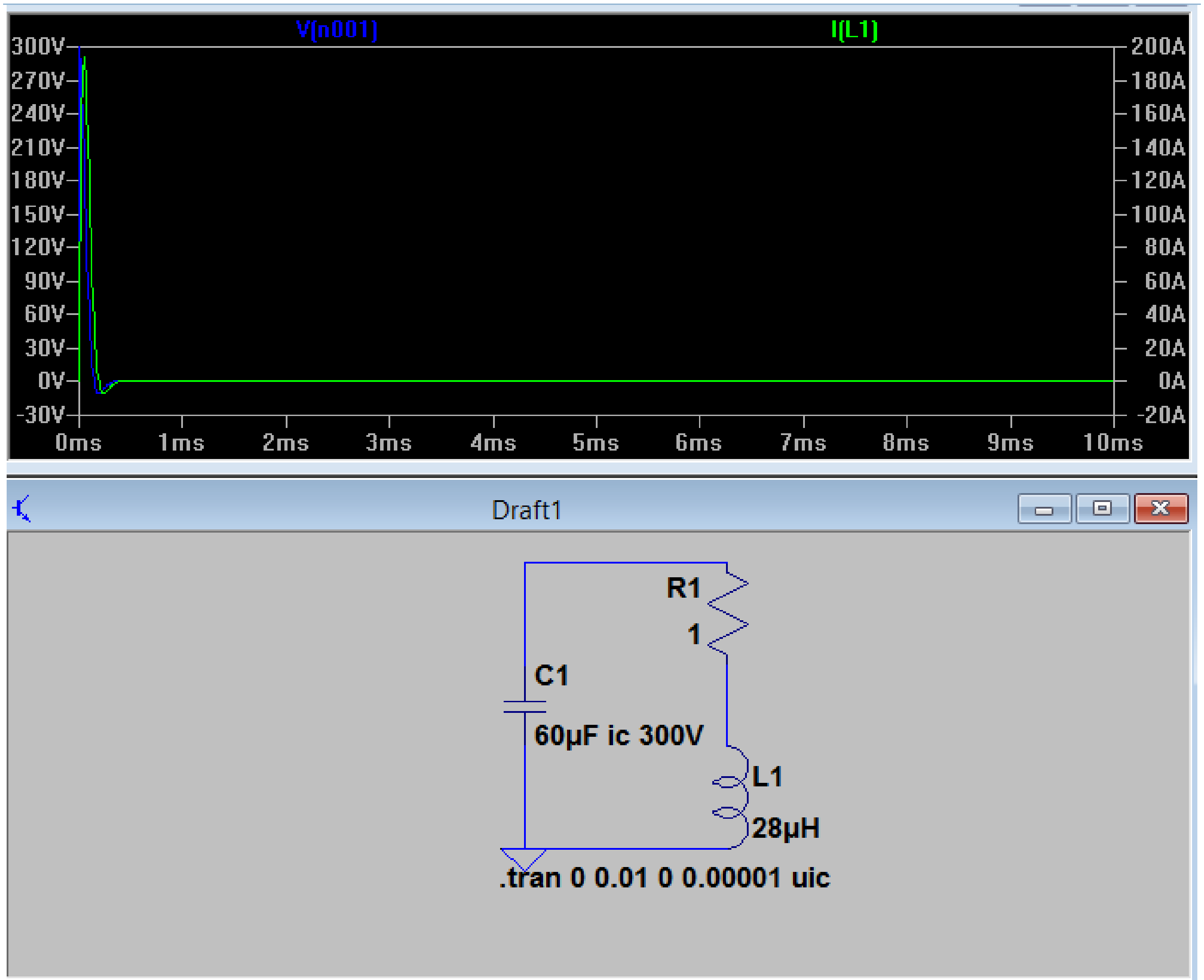


FIGURE 17: **OSCILLATION CAN BE SEEN BUT VERY SLIGHT. MUCH MORE PRONOUNCED IF RESISTANCE WAS KEPT AT 0.17 OHM. HIGH CURRENTS LAST ABOUT A THIRD OF A MILLISECOND. BUT, ENERGY USED:** 2.7J → ALMOST HALF OF THE ELECTROMAGNET WHICH IS BREAKEVEN AS A RESULT (2 SWITCHES) 19

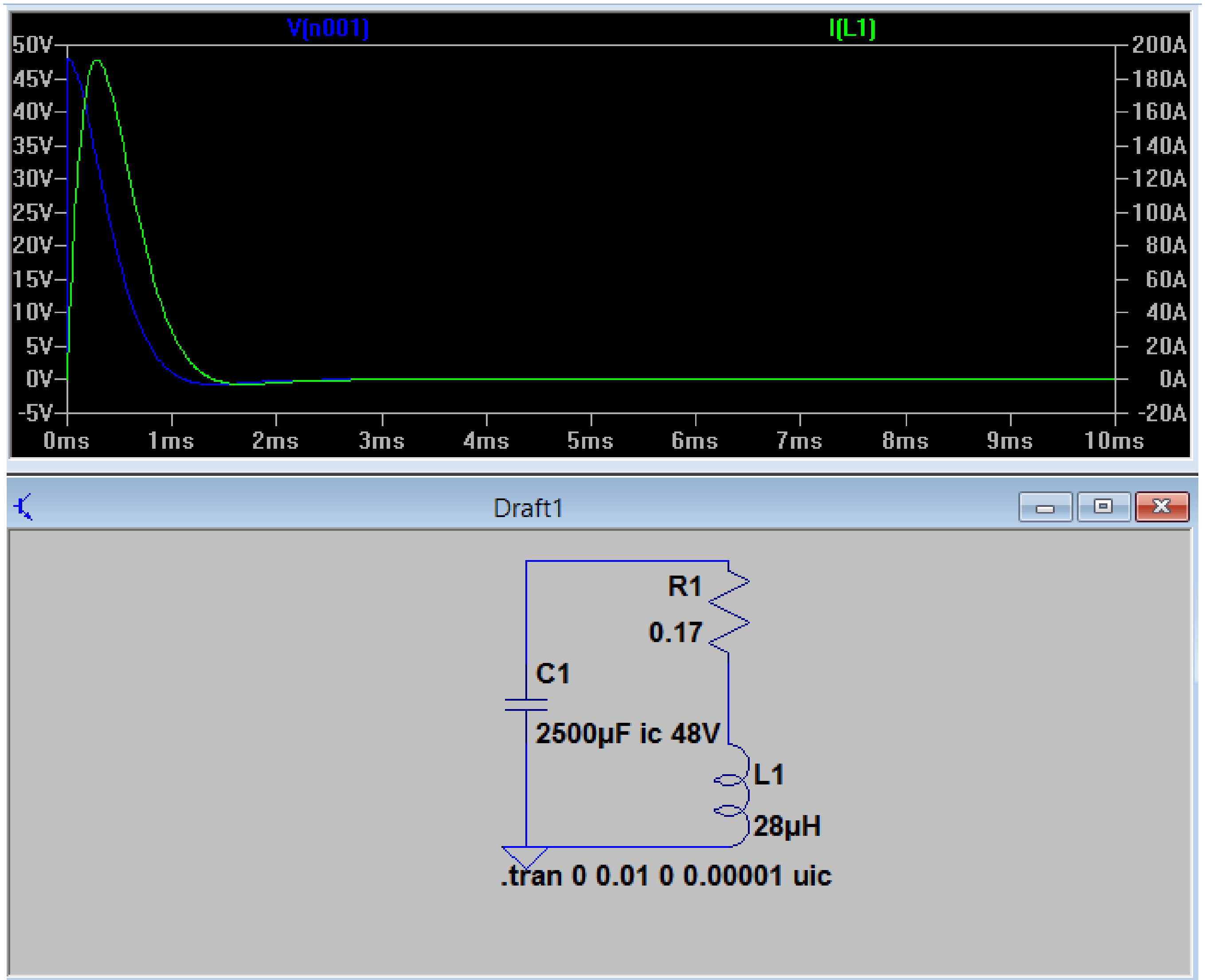


FIGURE 18: **SAME ENERGY REQUIRED IN THIS CIRCUIT AS ABOVE ~2.7J. ABOUT 1MS OF HIGH CURRENT AVAILABLE. 20**

The last case has not been tested out yet by us and will be an important determinant of the following hypothesis.

In reading the thesis, and noting some of the equations, such as the time required to reach the minimum current, it appears that the only thing that matters is hitting that minimum current value, which leads me to believe that keeping the resistance low, while applying 48V at a lower capacitance would be more beneficial than switching to 300V. Perhaps some experimentation with magnets of higher diameter is required before we can reach this conclusion as well, in order to ensure scalability of our results.

8.3 PIC32 CODE

```
#include <plib.h>

#include "NU32_2012.h"

void main()

 {

   NU32_Startup();

   // setup digital I/O for pin D0. Using Tris Registers

   TRISDbits.TRISD0 = 0;

   while (1) {

   LATDbits.LATD0 = 1;

   while(NU32USER == 0)       //while the user button is being pressed down

   {

      LATDbits.LATD0 = 0;     //set output to 0

   }

   }

}
```

8.4 VIDEOS AND PICTURES

Links to videos, pictures and latest Excel spreadsheet: https://www.dropbox.com/sh/nj5jlm1c7dy1piq/SMoZh5-w4l

9 REFERENCES

[1] A. N. Knaian, "Electropermanent magnetic conectors and actuators: Devices and their aplication in programable matter," Ph.D. dissertation, Electrical Engineering and Computer Science, Massachusetts Institute of Technology, June 2010

[2] Deyle, Travis. "Electropermanent Magnets: Programmable Magnets with Zero Static Power Consumption Enable Smallest Modular Robots Yet | Hizook." *Electropermanent Magnets: Programmable Magnets with Zero Static Power Consumption Enable Smallest Modular Robots Yet | Hizook*. Meka, Robotiq, 07 Dec. 2010. Web. 26 June 2013. <http://www.hizook.com/blog/2010/12/07/electropermanent-magnets-programmable-magnets-zero-static-power-consumption-enable-s>.

[3] Jochum, Andreas. "Parts List." *Assembly*. N.p., n.d. Web. 10 July 2013. <https://code.google.com/p/opengrab/wiki/Assembly>.

[4] "Camera Flash." *Camera Flash*. N.p., n.d. Web. 26 Aug. 2013. <http://holbert.faculty.asu.edu/ece201/cameraflash.html>.

[5] "LT3750 - Capacitor Charger Controller." - *Linear Technology*. N.p., n.d. Web. 26 Aug. 2013. <http://www.linear.com/product/LT3750>.

[6] Ward, P.; Dikai Liu, "Design of a high capacity Electro Permanent Magnetic adhesion for climbing robots," Robotics and Biomimetics (ROBIO), 2012 IEEE International Conference on , vol., no., pp.217,222, 11-14 Dec. 2012
doi: 10.1109/ROBIO.2012.6490969
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6490969&isnumber=6490927

[7] "The Gibbot." - *Northwestern Mechatronics Wiki*. N.p., n.d. Web. 26 Aug. 2013. <http://hades.mech.northwestern.edu/index.php/The_Gibbot>.

[8] "Kickstarter." *Kickstarter*. N.p., n.d. Web. 26 Aug. 2013.
http://www.kickstarter.com/projects/412473553/opengrab-open-hardware-electro-permanent-cargo-gri

[9] Blake, Carl, and Chris Bull. "IGBT or MOSFET: Choose Wisely." N.p., n.d. Web. 10 Aug. 2013. <http://www.irf.com/technical-info/whitepaper/choosewisely.pdf>.