Brushless Linear Motor

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Executive Summary

We designed and built a brushless, digitally commutating electric linear motor to replace a hydraulic or pneumatic piston with a magnetic device. Initially, we had one coil and one magnet and an intuition of how they would interact together. We had applied the scientific method to specifically describe our coils' interaction with our magnets without sophisticated physics or magnetic modeling software. We developed an experiment to measure the force verses one magnet's displacement from one coil we designed, we then developed our own modeling software using python to project the motor's future performance with two magnets and six coils. Using our tool, we could see how different coil and magnet spacing would behave and we settled on a design that produced force characteristics akin to a two phase motor.

We designed and built most of the hardware ourselves from scratch. Six identical coils of about 1000 turns were wound around PVC pipe with aid from 3D printed harness to space them appropriately. Position feedback, necessary for closed loop position control, was measured by a rotary potentiometer and gearing in a voltage divider circuit. The motor driver circuits were equipped for bidirectional command of the current in each coil individually. The motor driver board is designed to accommodate six coils, position sensing hardware, external power supply, and microcontroller connections. The microcontroller runs our C code. Our program performs mapping of incoming position signals into millimeters to determine where the magnetic rod is; then, it performs additional arithmetic mathematical transformations to use a lookup table that actively controls the output PWM's duty cycle in an effort to make the force along the motor's stroke more constant or with less ripple.

The resulting motor can produce a constant force of about 10 newtons and can be set to be stronger by allowing more force ripple. We declare that we have succeeded with the project we planned to achieve. Of course the device at hand can be refined by closing the current loop and canceling limiting and resistive magnetic effects or by further sculpting the active PWM control lookup table. We see potential for this device or restructure of its physical design to replace hydraulic and pneumatic pistons in a variety of applications; perhaps our design could even evolve into a modular linear motor system for additional application flexibility.

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1 Introduction

Motion control applications are commonplace in our technological world and they are becoming even more ubiquitous alongside our ever-increasingly automated lives. Linear actuators are a vital part of these applications and are used in applications such as robotics, prosthetics, or other mechatronic hardware. Almost any operation typically performed by hydraulics or pneumatics is an application for a linear induction motor.

The most common methods to achieve electric linear motion is with a lead screw or rack and pinion (R&P) drive; however, these all have drawbacks. The lead screw lacks speed and due to “screw whip” problems it is not recommended for long strokes. The R&P suffers in vertical applications and can have backlash issues. Both drives have a lot of mechanical components that require maintenance, experience wear and may be unsuitable in certain environments.

Linear induction motors offer a variety of advantages. They are brushless and don’t require gear systems that could be damaged in dirty environments. They have few to no mechanical parts so there is little need for maintenance and repair. They also offer high speeds and high force. The drawbacks to linear induction motor is that they require a more complex controller and more magnetic hardware.

Our goal with this project was to create a scalable linear induction motor that has little force ripple along its travel and that we could accurately control the force throughout its travel. We accomplish this using a stationary array of coils and two permanent magnets. This report details the design, construction and analysis of a scalable two phase inline coil brushless linear motor. With this design we are able to completely control the movement and force of motor and it offers a functional alternative to the more common linear drives.

2 Methodology

2.1 Motor Design Objective and Theory

Our goal was to create a scalable linear motor that we could accurately control and had little to no force ripple along its travel. We began with the understanding that by energizing a coil we can create a magnetic field inside the coil and this would exert a force on a nearby magnet. We also intuitively understood that we could expand this simple design to create an array coils at calculated spacing and move a permanent magnet and anything attached to it continuously if the coils were both commutated and energized correctly.

With the knowledge that current carrying coils interact with magnetic fields we began the process of designing our motor. We first created a one inch wide coil with approximately 1000 turns of 22 gauge magnetic wire wrapped around a one inch schedule 40 PVC pipe. We chose this pipe because a one inch cylindrical N52 Neodymium magnet would perfectly fit inside it. These magnets were the strongest we could obtain with these dimensions. By energizing the coil with 24V DC we observed that force exerted on the magnet was substantial and would suffice for our project. At this point we had already mounted the magnet onto a plastic rod that would not affect the magnetic field of our motor.

Next we understood that in order to find out the optimal spacing of our coils and the number of phases we must characterize the force versus distance of the coil we created and our magnet. We applied the scientific method to characterize our coil interacting with our magnet both because we did not wholly trust our mathematical expressions and because we did not have access to magnetic modeling software. Essentially, we discovered how our setup worked, then designed the motor instead of relying upon external references. We accomplished this be creating an experiment shown in figure 1. Our experiment measured the force by mounting our coil vertically and letting the magnetic rod rest on a weight scale with a mechanical stage underneath that we could manually lift the vertically. Next we applied a constant current to the coil and measured the force on the scale as we incrementally raised it. In order to counteract any changes in resistance in the coil due to heating up from running constant current we would turn off the power to the coil in between measurements. We characterized the force and plotted the results shown in figure 2. Note the symmetry is due to assumed commutation when the magnet was center to center with the coil, in order to achieve consistently positive or rectified force. Also, note here that we hypothesized that the number of magnets defines the number of phases the motor has and that hypothesis was proven true.

Figure 1: Picture of the experiment setup for characterizing one coil and one magnet with constant current.

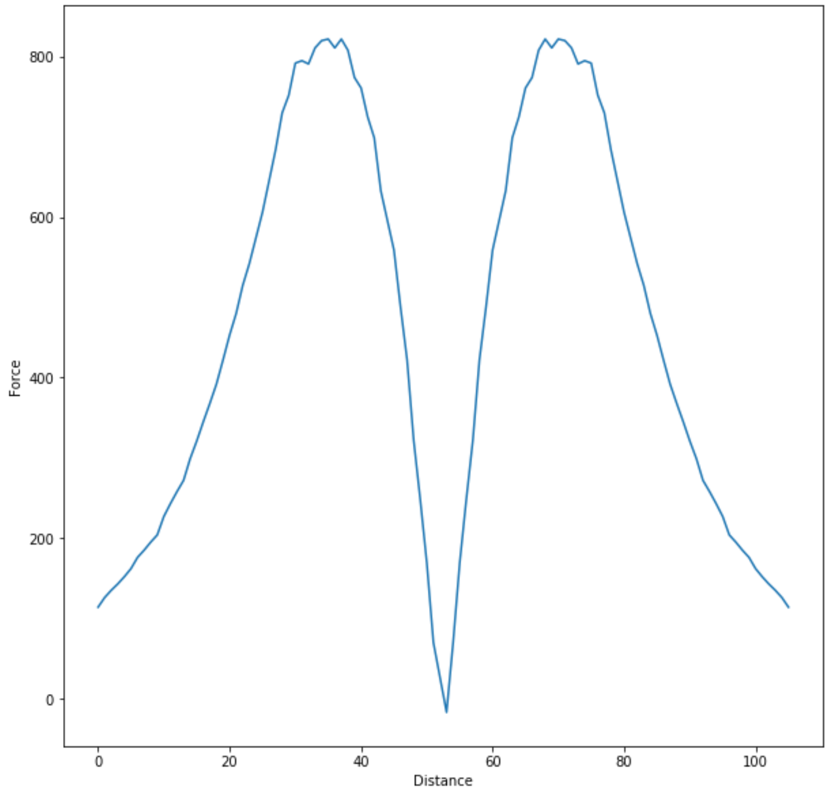

Figure 2: The force versus distance characterization of a single magnet and single coil at a constant current. Note the symmetry is due to theoretical commutation of current.

With the force versus distance data of a single coil and magnet measured we wrote a python tool that took this data and visualized the superposition of multiple coils at different spacing. The tool also lets us visualize the addition of more phases, or magnets, to our design. After trying different spacing and magnet configurations we determined that six coils with 48mm center to center spacing and two magnets with 120mm center to center spacing, or 2.5 times the coil spacing, would give us a resultant force with little ripple and a significantly long and interesting stroke. The plot of this theoretical configuration is shown in figure 3. Figure 4 shows a conceptual drawing of the motor with the determined specifications.

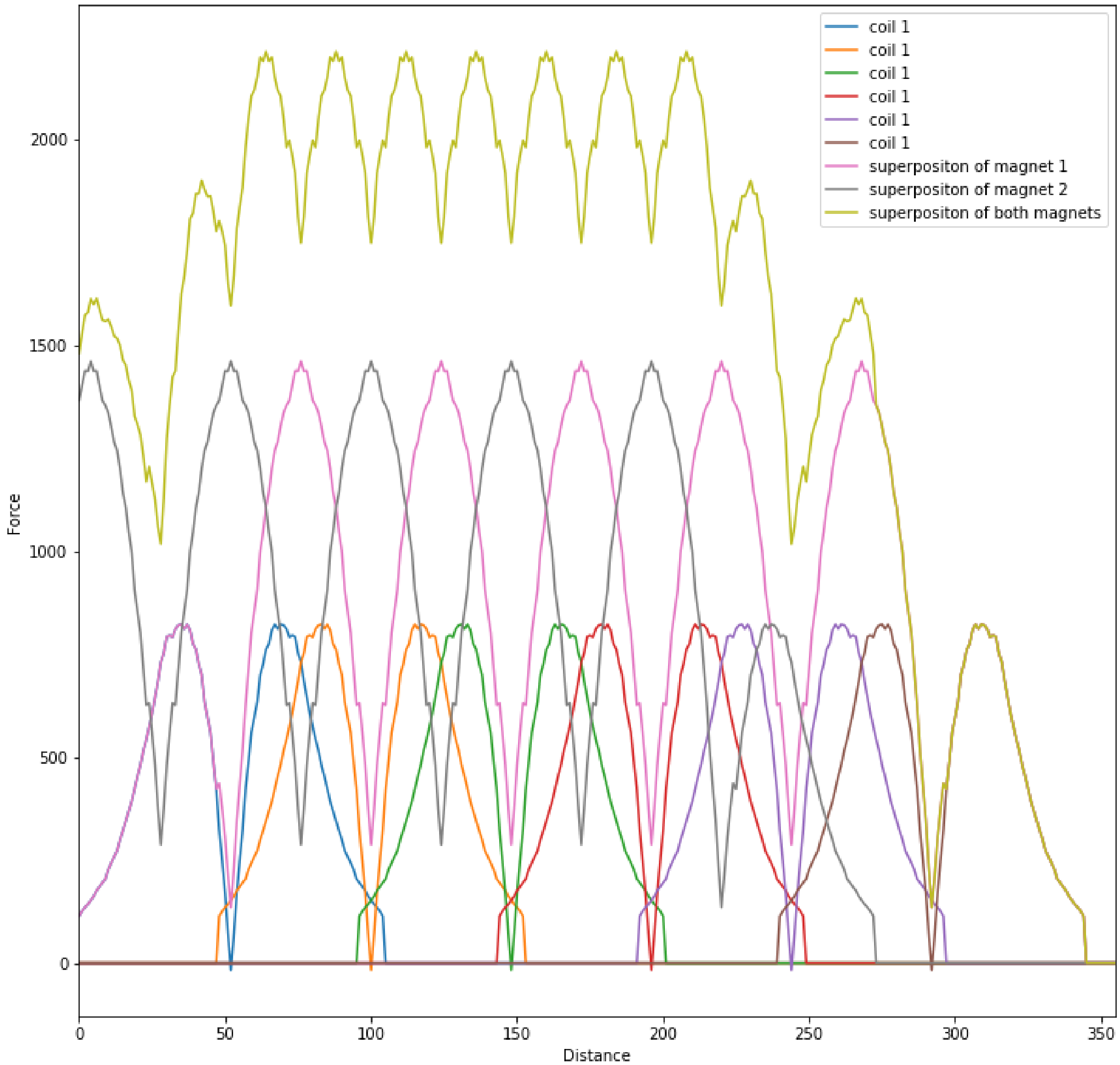

Figure 3: A plot showing the theoretical superposition of the six coils with full no PWM. Note the grey and pink curves in the middle are each superposition of a single magnet. The gold curve at the top is the superposition of both magnets.

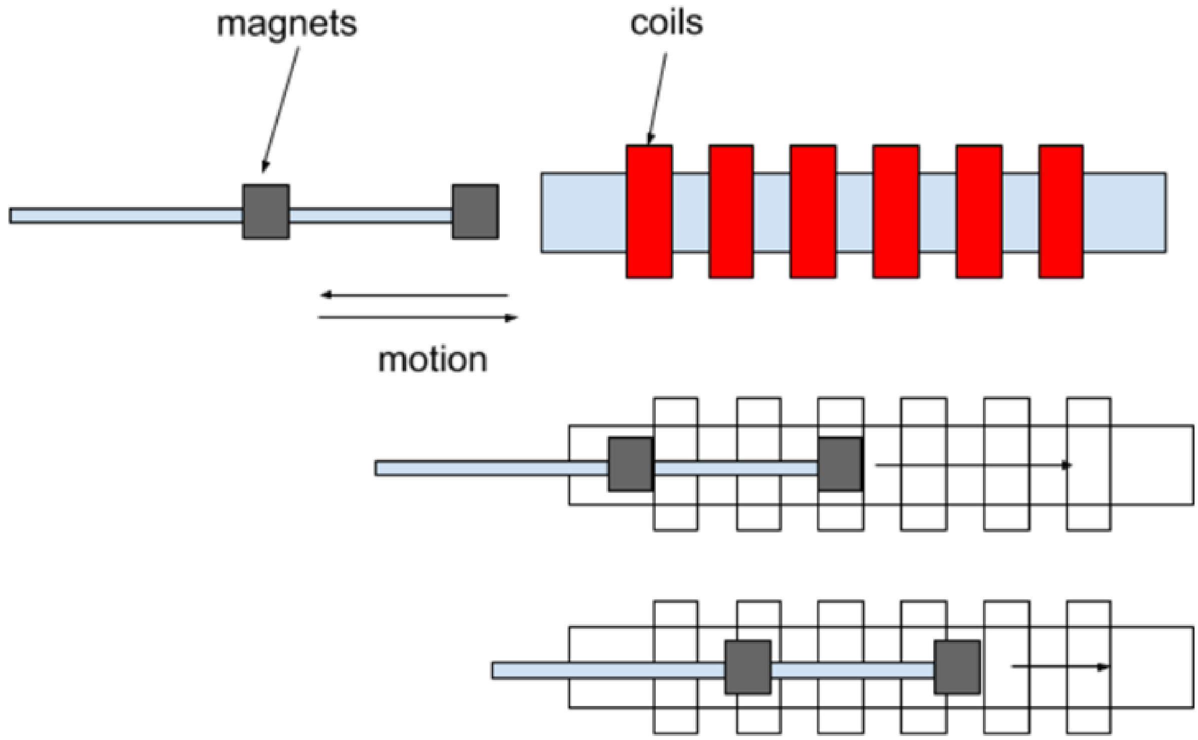

Figure 4: A conceptual drawing of our motor with six coils and two magnets.

With the physical design now established we next set out to determine the correct commutation of the coils which was now quite complicated due to the number of coils that would both be pushing and pulling both magnets. We understood and had already observed from experimentation that the commutation of the coils would have to happen exactly when the magnet was center to center with the coil or else the magnet would move in the opposite direction with significant force which was undesirable. Therefore we created a commutation table and a figure showing the commutation points that we would later embedded in software, figure 5, and table 1.

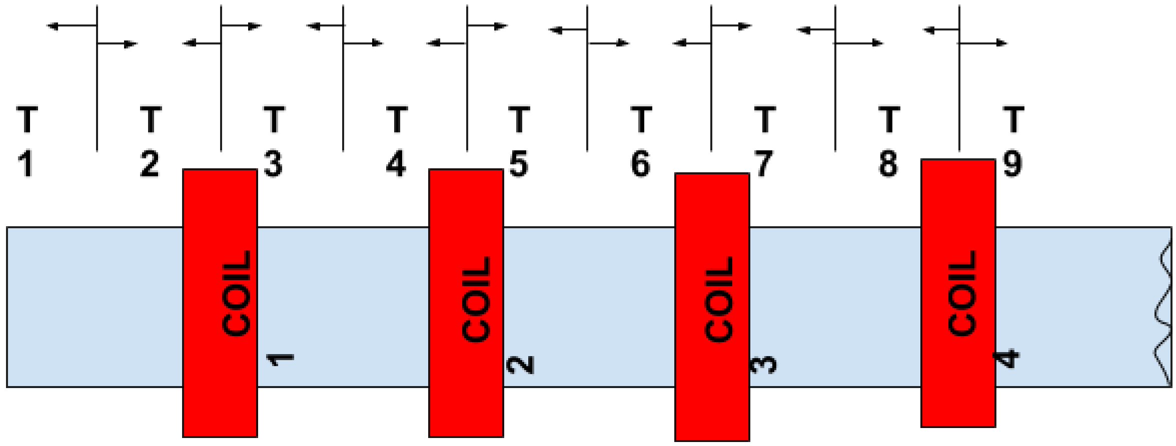

Figure 5: Figure showing commutation pints for commutation table

	COIL 1	COIL 2	COIL 3	COIL 4	COIL 5	COIL 6
T1	1	1	-1	0	0	0
T2	1	0	1	-1	0	0
T3	-1	1	1	-1	0	0
T4	-1	1	0	1	-1	0
T5	0	-1	1	1	-1	0
T6	0	-1	1	0	1	-1
T7	0	0	-1	1	1	-1
T8	0	0	-1	1	0	1
T9	0	0	0	-1	1	1

Table 1: The commutation table for opposing magnetic poles. Note the blue cell or “1” means that corresponding coil will be carrying current in one direction. A red cell or “ -1” means that corresponding coil will be carrying current in the other direction. A white cell or a “0” means coil is off.

The theoretical force profile in figure 3 was created using constant current and it predicts a significant amount of ripple. However, we understood that we could vary the current to reduce the ripple or linearize it. We determined that by taking the inverse of the measured force versus distance curve of one coil and one magnet and applied the inverse, then multiplied the former with the latter, this would have the linearization effect. We could then normalize this curve to whatever value necessary. Figure 6 shows the plots using this technique.

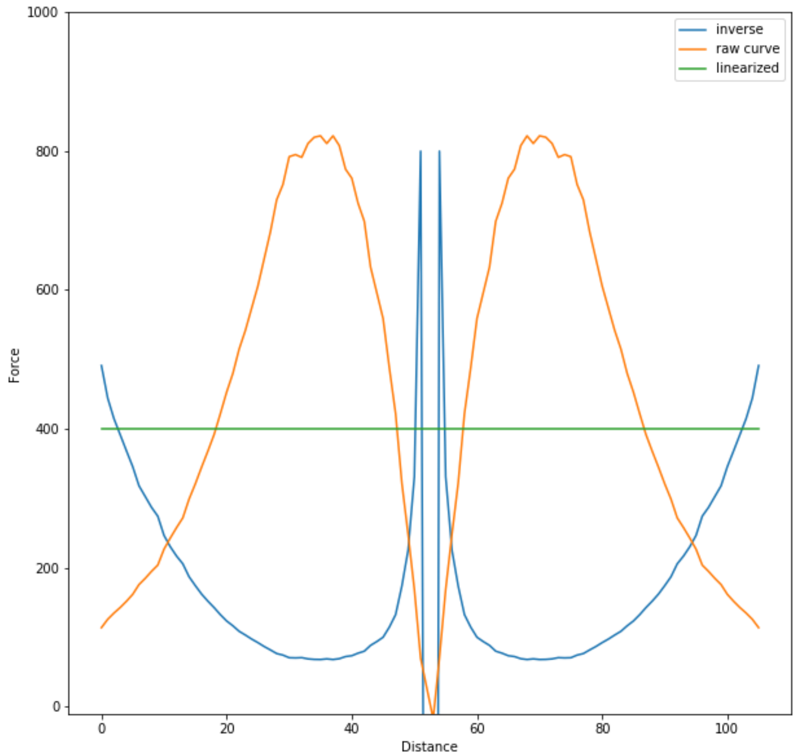

Figure 6: Plot showing the raw curve, the inverse curve and the resulting linearized curve. Note both the inverse and linearized curve are scaled in order to display on the same plot.

We also understood that there exists a tradeoff between linearization and force and that we would never be able to fully linearize or reduce the ripple. Figure 7 conveys this tradeoff; the effect of varying the current in the coils would have the effect of truncating the peaks of the force versus distance curve (blue curve) but this will also reduce the force.

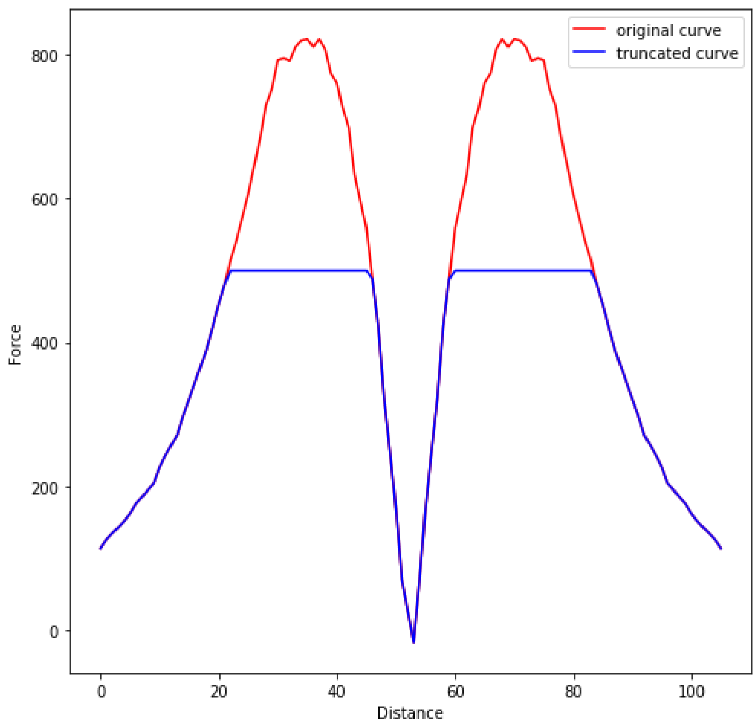

Figure 7: The theoretical trauncation of the force curve due to physical limitations.

2.2 Overall System

We constructed the motor, figure 8, after understanding what we should expect and formulating the proper spacing dimensions with help from our theoretical analysis. The overall system block diagram is shown in figure 9. It consists of the coil array with a position sensing device. This device informs the microcontroller unit (MCU) which contains the numerical mapping, logic, and look up tables needed to output the correct PWM signals to the motor driver board that control the actual coils. An external power supply applies the high power to the motor driver board. Each block is detailed in the following sections.

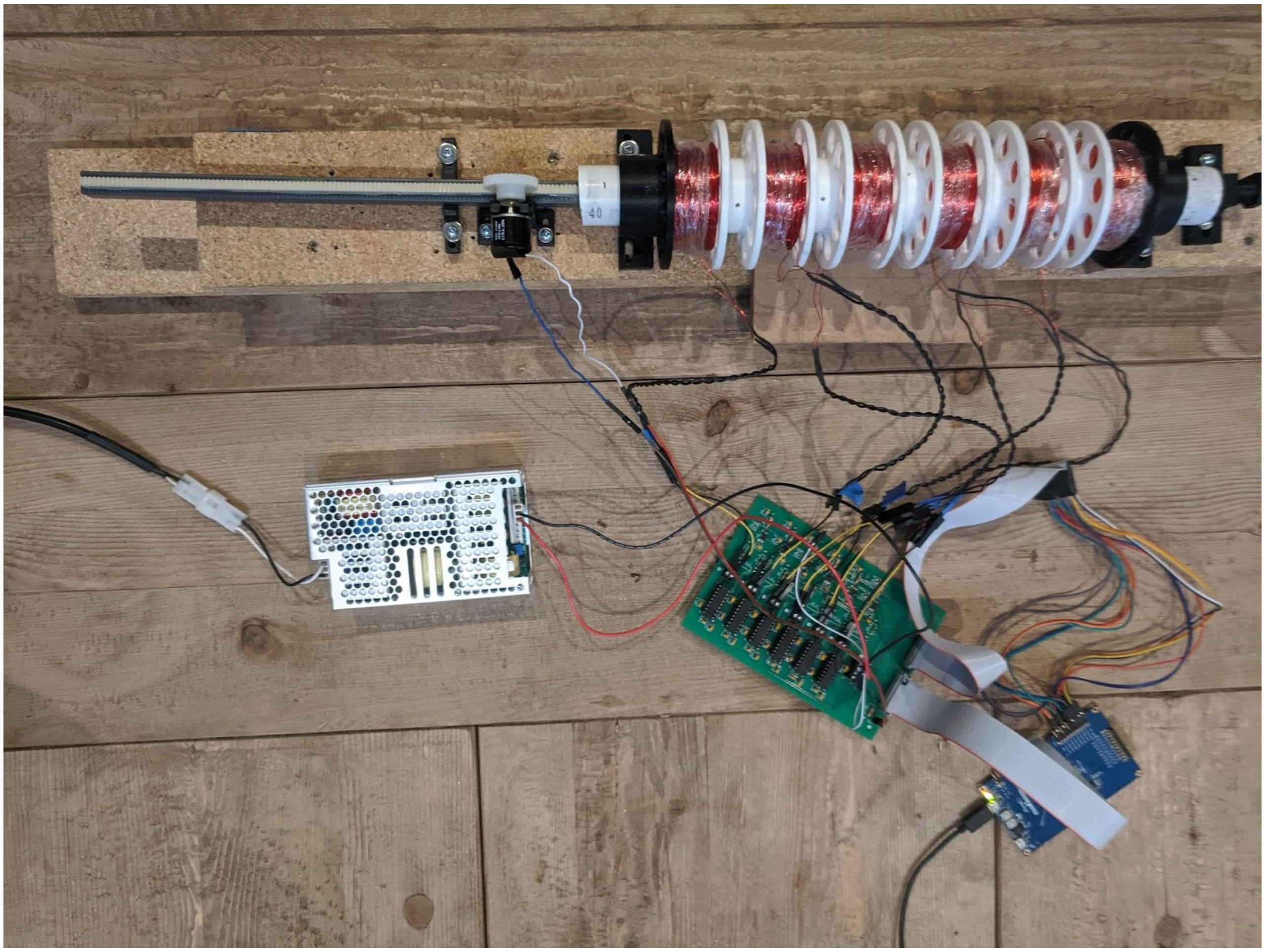

Figure 8: Picture of our constructed brushless linear motor.

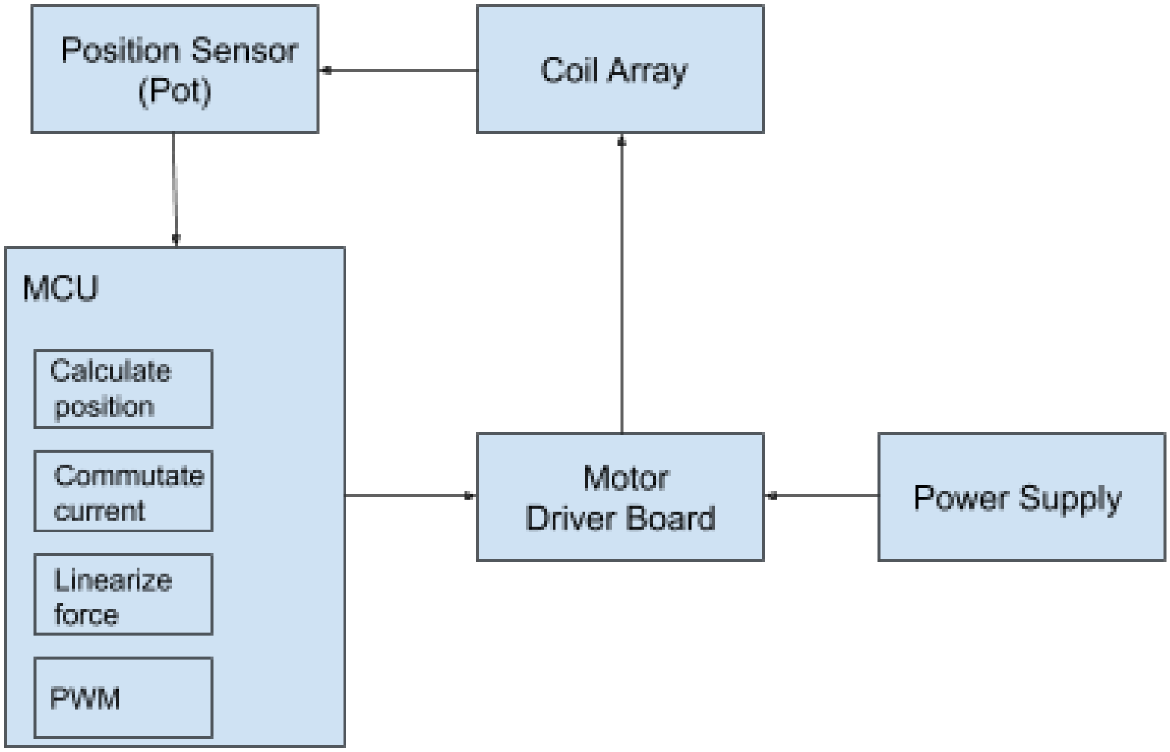

Figure 9: System block diagram

2.3 *Coil Array*

The coil array consists of six coils spaced 48 mm apart from each other in a straight line supported by a section of one inch PVC schedule 40 pipe, figure 10. Each coil is approximately 1000 turns of 22 gauge wire. To separate the coils we designed custom 3D printed ABS harnesses to contain the copper wire. Inside the coils and inside a PVC pipe there is a rod with two one-inch cylindrical N52 Neodymium magnets fastened on it, with poles opposing each other, 120 mm apart, figure 11. Our dominant design philosophy for the coils was to wind discrete coils with empty space between them; however, different approaches and overlaps can be explored to redesign the magnetic force characteristics of it. In principal, the coil array can be infinitely long to accommodate an indefinite stroke and the coils sized to fit any magnet or current flow to allow for any maximum force. Perhaps, the coil array and magnet rod could even follow a curve or be made flexible for a more unique device or be designed to be modular with replaceable and interlocking coils and rods.

Figure 10: Close up of the coil array with 3-D printed harnesses

Figure 11: The two magnets and the rod

2.4 *Position Sensor (Pot)*

The position sensor is a potentiometer (Pot) is a critically important part of our design. If this distance calculated using the Pot is incorrect our motor will not function properly. The Pot is connected to the magnet rod using a rack and pinion system as shown in figure 12. This form of measuring distance is not ideal but it was a simple approach of our project. Here we also used custom 3D printed ABS parts to support the Pot and a nylon gear and rack. The Pot itself is a 3 turn 10K Ohm. By using the Pot as part of a voltage divider we could create a variable voltage that could be read by an ADC of the microcontroller, figure 13. The choice for R1 as well as the pitch of the gear attached to Pot was chosen to optimize the resolution of the voltage divider output voltage for our particular design. The voltage dividers supply voltage came from the microcontroller itself. We used this voltage because it was determined to be stable and did not exceed the voltage the ADC was capable of reading.

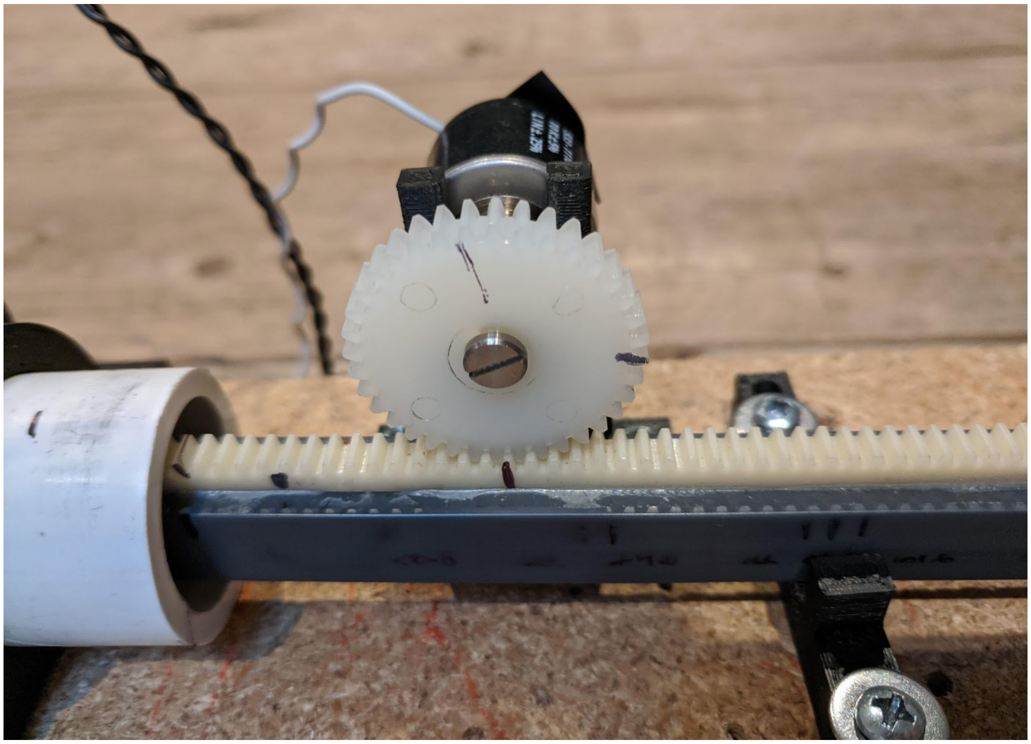

Figure 12: The rack and pinion setup of the potentiometer.

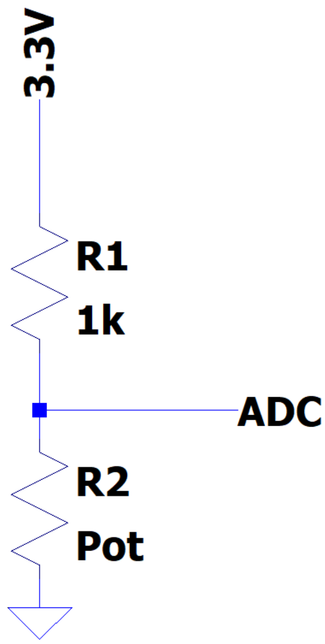

Figure 13: The Pot circuit.

2.5 Microcontroller

We used a SAMD21 microcontroller (MCU) on an Xplained Pro development board to do all of our processing. We chose this MCU because of familiarity and it had all the necessary IO, ADC and PWM functionality. Our MCU is using an onboard oscillator divided down to 1 MHz which allowed us to operate using only interrupts. Our program receives an interrupt when the ADC result connected to the Pot is ready. We are using a 16 bit ADC and are also averaging every 8 signals in order to average out any noise. We then use that result and convert it to an absolute distance using an embedded algorithm. As mentioned earlier, this step is very critical and must be done correctly. The distance tells us the exact position of our magnetic rod. With this distance we can apply the correct coil currents using the commutation table that we also embedded into the software. The calculated distance is also used to vary the duty cycle of the pulse width modulated signals (PWM) in order to linearize the force. The linearization values were also embedded in our software. The PWM signals are then sent to the motor driver board.

2.6 Motor Driver board

We created a motor driver board which houses all the electronics needed for supplying current to the coils. It includes the H-bridges and associated circuits for controlling the current, current sensing circuits and filters, and a place for the potentiometer hardware. The hierarchy of our hardware design, figure 14, allows for 6 coils; however, again there should be no limit to the number of coils we could design for. There are 6 motor driver circuits attached to the connectors for power, coil current out and return, microcontroller I/O, and a connector for our potentiometer position sensor.

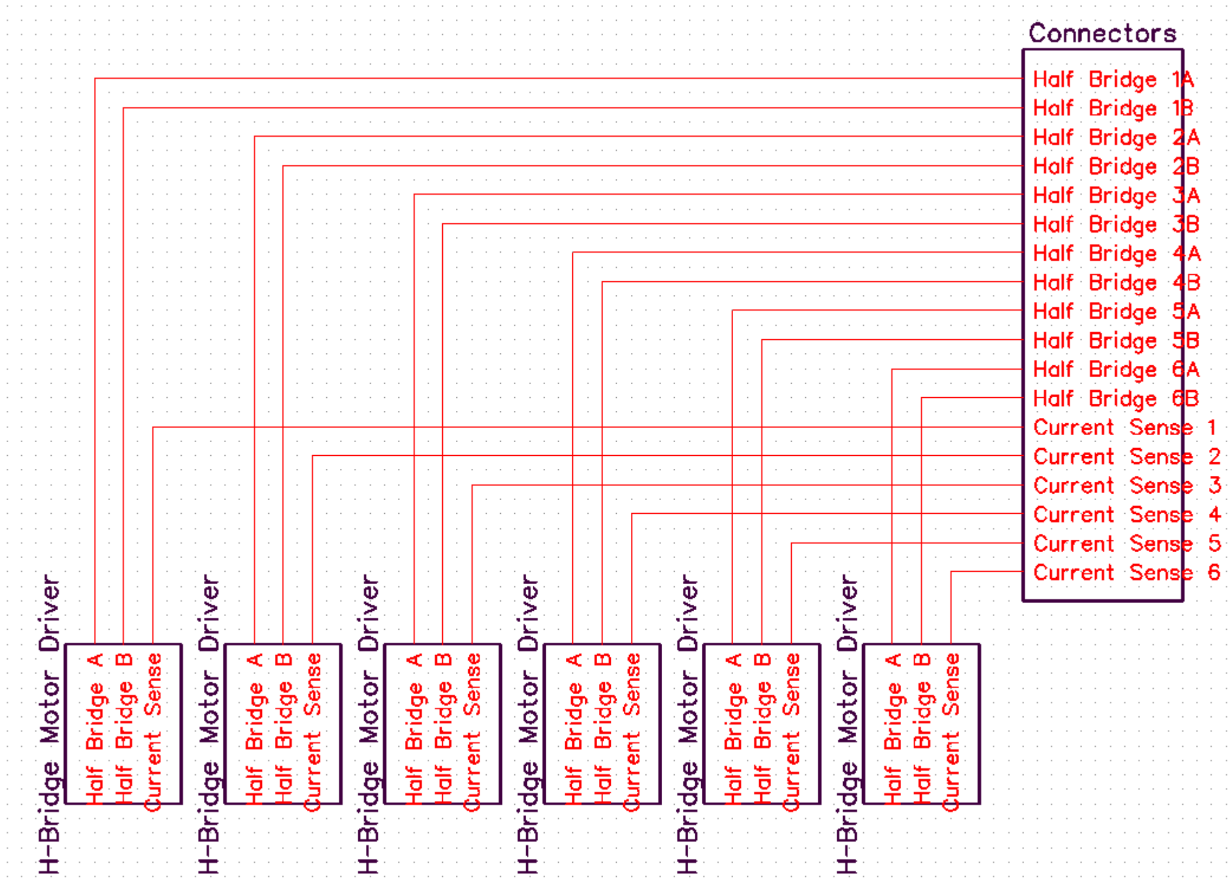

Figure 14: Block diagram of the PCB schematic

Our motor driver circuit is laid out in figure 15. To allow for bidirectional control of our coils, connected in the center of the schematic, we designed our motor driver around a STMicroelectronics L6202 H-bridge. Signals from the microcontroller to the H-bridge come from the upper left. Our circuit includes a Texas Instruments INA240A1PWR current sense IC. The current sense would allow us to the feedback loop for the current control which would handle any undesirable back EMF forces, but we are not doing that right now.

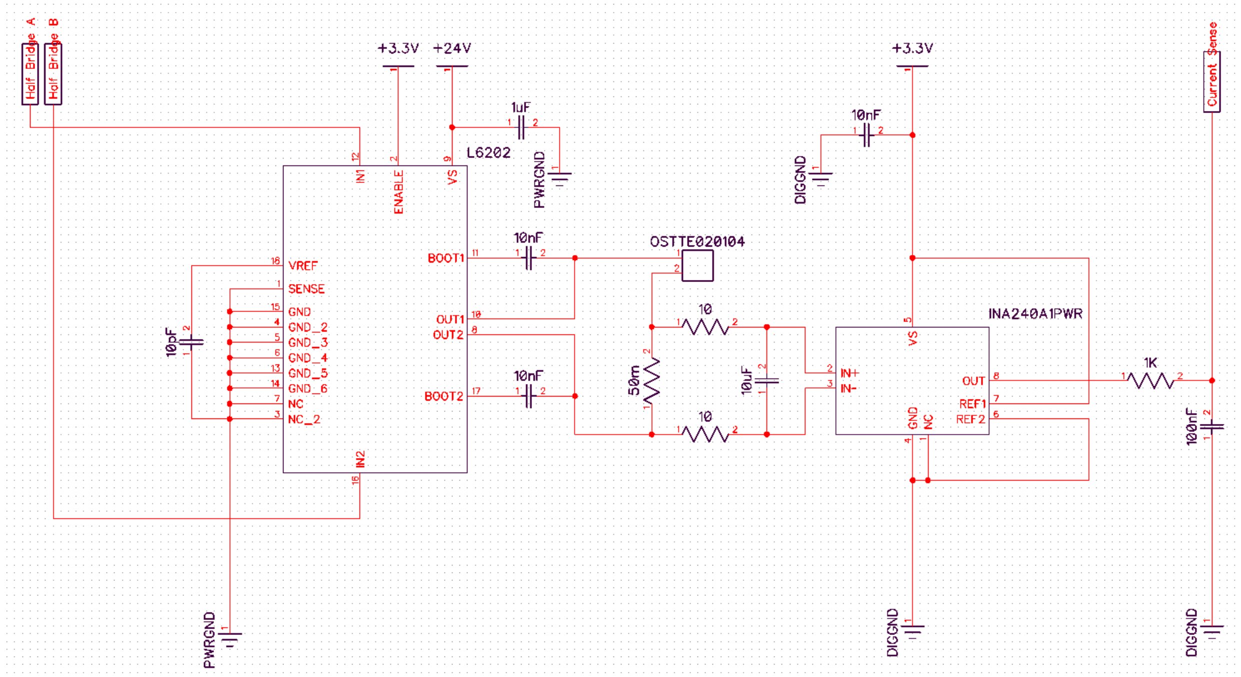

Figure 15: A single H-bridge motor driver circuit

The connector block, figure 16, includes a 4-pin power supply connection, connectors for a ribbon cable to the microcontroller, and a voltage divider circuit that connects to position sensing potentiometer. The pins of the connectors line up to the I/Os with PWM and ADC features on the microcontroller.

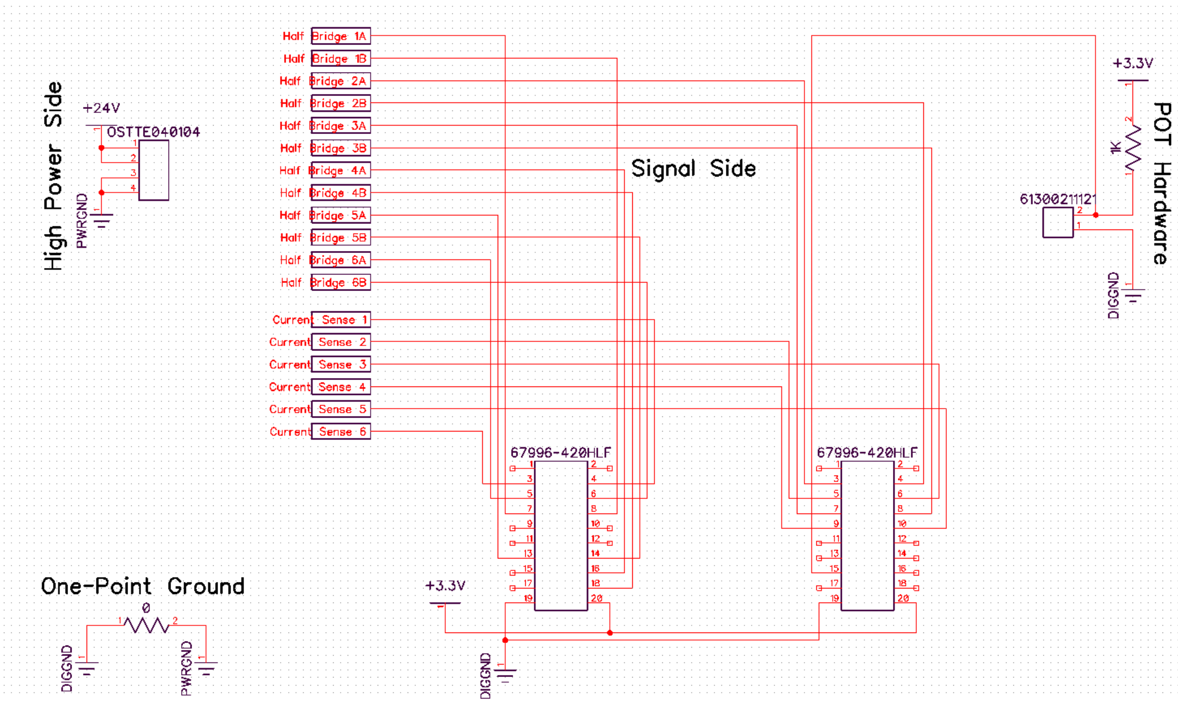

Figure 16: Connectors, power, and potentiometer hardware

Our two layer layout and final PCB are displayed in figures 17-19. The PCB layout started with a 24V or greater high power and a 3.3V digital side in mind. The high power connections, H-bridges, coil current out and return, current sensing resistors, and necessary capacitors are all on the high power side. The low power side includes the microcontroller connectors, current sense ICs, low pass filters, additional decoupling capacitors, and the potentiometer hardware.

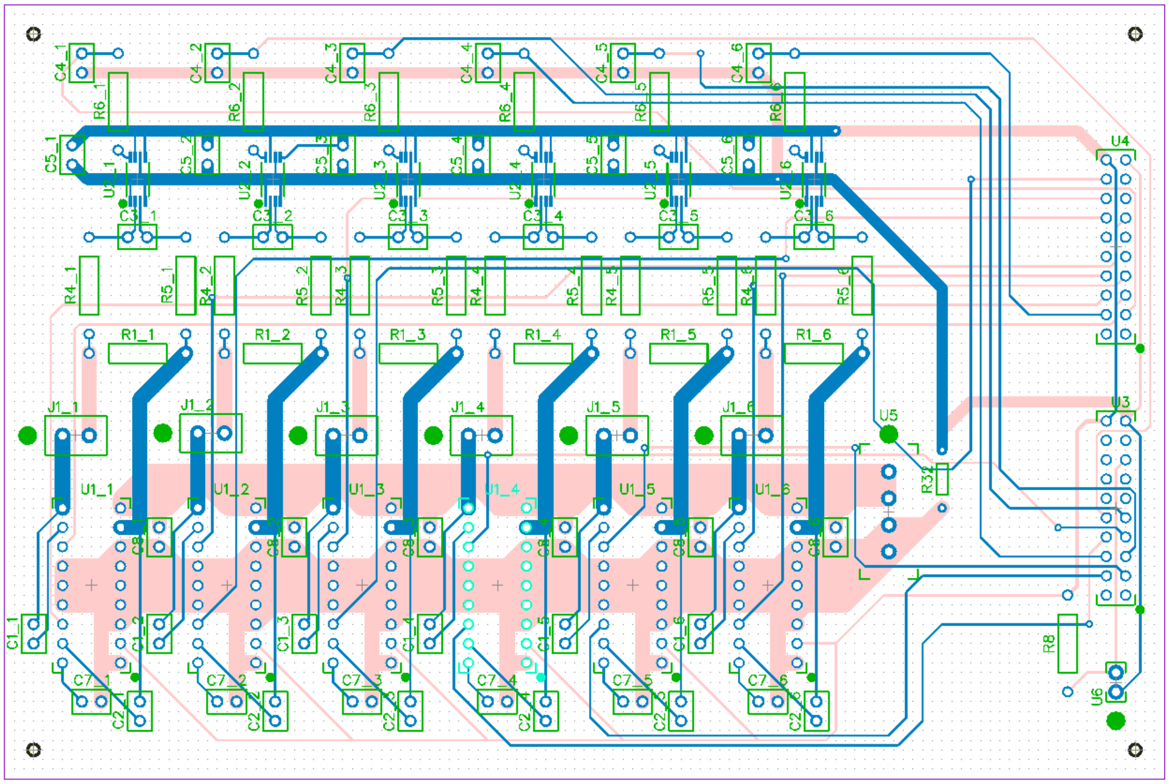

Figure 17: PCB layout top layer view

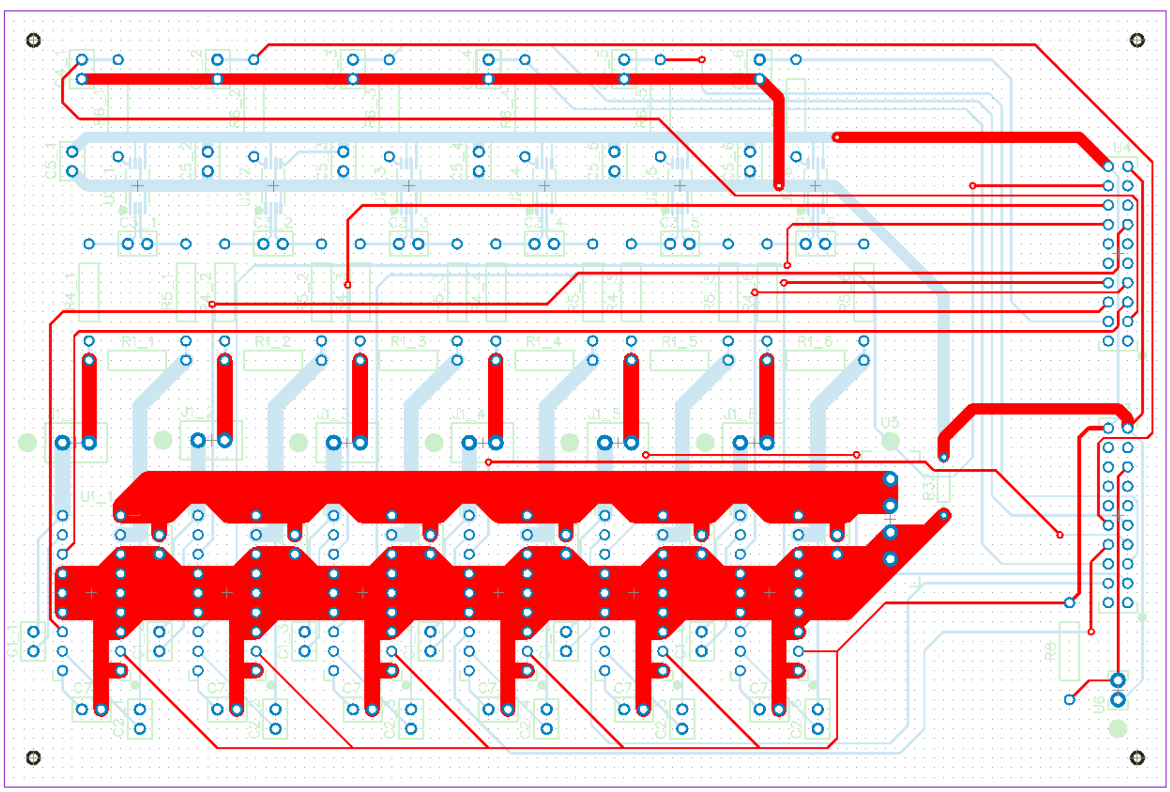

Figure 18: PCB layout bottom layer view

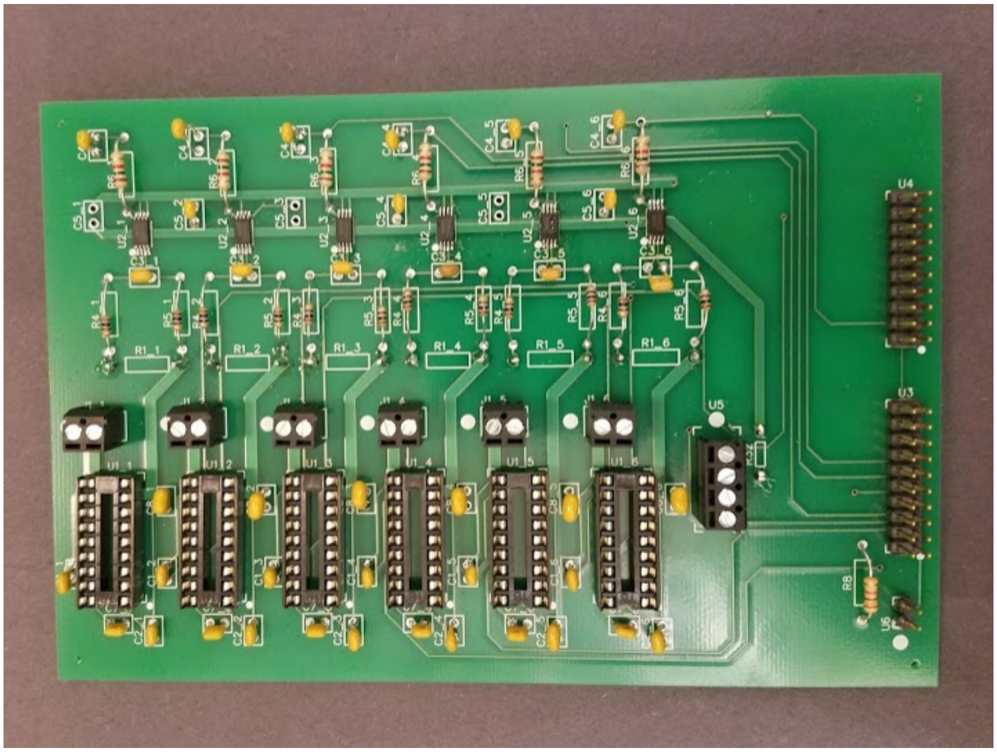

Figure 19: Final PCB

The literature used to design the motor driver circuit includes the datasheets for the STMicroelectronics L6201 [2] and the Texas Instruments INA240A1PWR [3].

2.7 Power Supply

The main power supply for the motor coils is an Integrated Power Designs' REL-110-4006. It has 4 separate voltage outputs: 24 volts, 12 volts, -12 volts, and 5 volts all limited to 2 amps. We use it for its 24 volt, 2 amp DC supply to supply the high power side of the motor driver board. We can also use the 5 volt output to power the microcontroller, instead of relying upon a laptop computer.

3. Results and Discussion

After constructing our motor per design and lots of troubleshooting, improvements and iterations of the software we were able to successfully control our motor as predicted. We observed that it was commutating correctly and had reduced ripple when we applied the linearization technique. We then setup of characterization experiment once more and measured the force versus distance again, this time using six coils, two magnets and the applied linearization. The resulting plot is shown in figures 20. The plot shows the characterization data in blue overlaid with the theoretical force profile determined earlier through analysis in gold. As can be seen the blue curve has a similar force profile as the gold curve. Also as expected the blue curve has reduced ripple compared to the gold curve which was created using constant current. The characterization results validate what we observe when running our motor.

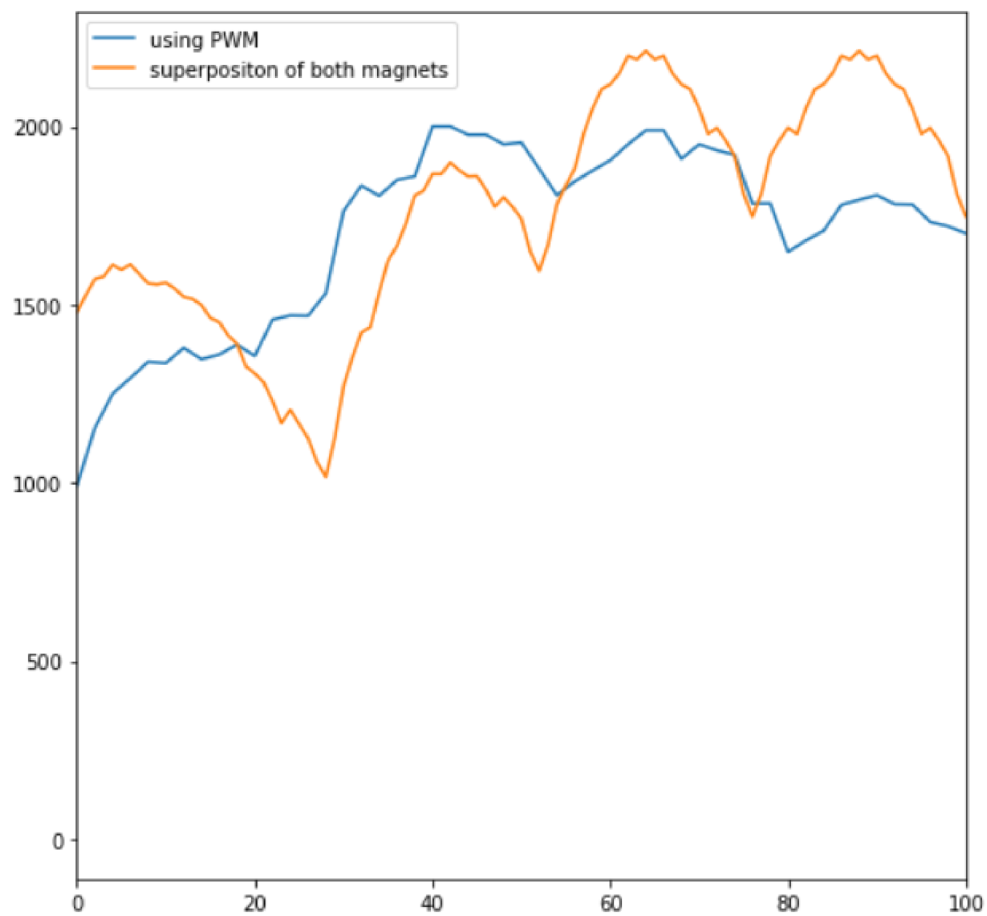

Figure 20: The force versus distance characterization of our finished linear motor overlaid with the theoretical plot for comparison.

4. Conclusions and Recommendations

We were able to achieve linear travel that had reduced ripple compared to our early models. Objectively, we succeeded by creating the linear motor we intended to. It is able to substitute hydraulic or pneumatic pistons with reduced infrastructure and additional control. In complement to that, our motor is unique compared to the dominant type of linear electric motor, the leadscrew, that holds the most market share. The drawback to our motor, compared against its leadscrew counterpart, is it requires a more complex controller. However, the advantages of our motor include a non-reliance on mechanical moving parts such as gearing and a higher maximum linear speed. Our motor design can be forced against itself or blocked without risk of damaging mechanical gears or screws.

There is still a ripple in our motor's force along its stroke and we would recommend trying different coil/magnet configurations to reduce this even further. One possible configuration could add more magnets to create a three phase motor or beyond. Yet another could be to change the length of the coils and magnets thereby reducing the ripple; although, this would require more coils to achieve the same stroke. Another method would be to overlay the coil winding perhaps sinusoidally or in some other fashion. One possible benefit of overlaid coils is the elimination of multiple magnets. Further pursuing this project, with more time, we would incorporate the current feedback that is already included in our motor driver board, could help increase the force of our motor by addressing the back EMF that naturally occur in electromagnetics. Also, we could continue sculpting the active PWM control lookup table.

5. References

[1] Microchip, “SAM D21 Family” Microcontroller datasheet.

[2] STMicroelectronics, “DMOS FULL BRIDGE DRIVER” L6201 datasheet.

[3] Texas Instruments, “INA240 High- and Low-Side, Bidirectional, Zero-Drift, Current-Sense Amplifier With Enhanced PWM Rejection” INA240A1PWR datasheet, July 2016 [revised FEB. 2018].

6. Appendix

Software program listing

1. Atmel Studio
2. Jupyter notebook (Python 3)
3. DipTrace
4. Microsoft Excel