The RPMaster

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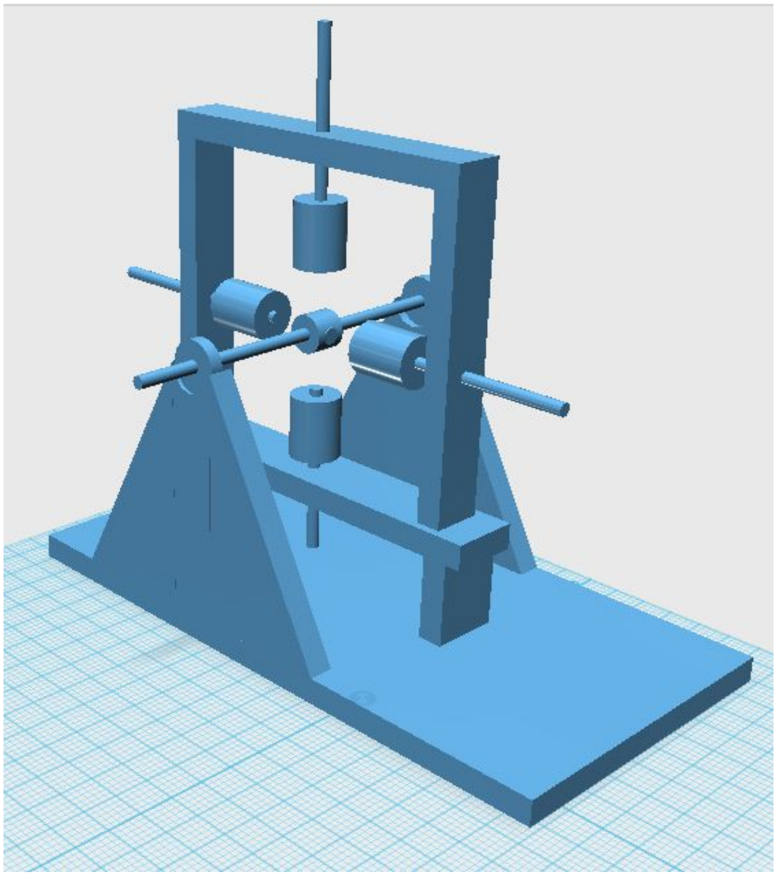

I. Abstract

The purpose of this project was to construct a fully functioning electric motor. We used a multitude of different parts to build our motor, including wood, iron bolts, electronics and 3D printed pieces. Ultimately, we created a brushless, two phase electric motor with a maximum speed of 1000 RPM, a maximum running torque of 0.0013 N/m, and a maximum efficiency of 0.26%. Throughout the project, we faced many obstacles, each of which ultimately taught us a lot about how to best construct a successful electric motor.

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II. Motivation and History:

Electric motors are important, especially from an environmental perspective. As nonrenewable sources diminish, people turn towards renewable energy sources such as electricity generated by solar panels or wind turbines to fuel their daily lives. Since motors are vital to everyday activities (cars, water pumps, fans, etc.), replacing petroleum fueled motors with electric motors has the potential to make a huge difference. Chrysler and GE in the 1970s developed the first fully electric car, their Protoype EV [1]. Concepts from that first prototype have carried into current electric vehicle designs, such as regenerative braking and the battery configuration [1]. Now, many other companies (i.e. Nissan, Tesla, Toyota, etc) have followed suit, creating electric cars of their own, and changing the automotive industry for the better. As climate change has worsened, electric cars have become more and more popular, with the general population shifting towards alternate and renewable energy sources.

Our motor was nowhere near as complex as those used in electric cars, however electric cars served as the inspiration for our two-phase brushless motor - essentially a much simpler, lower-power version of the car's motor. A brushless motor is a motor in which the permanent magnets rotate while the electromagnets remain stationary. We decided to build a brushless motor because they are not only more efficient than their brushed counterparts, but are also thought to rotate more quickly which was our main priority. Brushless motors are also less susceptible to wear and tear in strenuous applications, though this was of less importance to the specific scenario, given that our motor is not meant for intense work [2].

What made brushless motors even more interesting to us, is that high power versions are actually used in most large engineering projects such as electric vehicles and aircrafts; as aspiring engineers, this made learning how brushless motors work all the more important to us. By creating a brushless motor, we also gained the opportunity to learn about and utilize electronics.

While brushed motors have been used commercially since 1886, brushless motors have been around for much less time, only becoming commercially viable and prominent after 1962 [3]. Before 1962, engineers were faced with the problem that their brushed motors quickly wore out in physically strenuous applications. In 1962, T.G. Wilson and P.H. Trickey developed the first brushless DC motor [3]. They implemented a solid state device (a device built from solid materials - typically crystalline semiconducting materials, rather than vacuums or gas-discharge tubes), to reverse current flow when a small external voltage is applied by a DC power source. They determined that the three key design choices that affect a brushless DC motor's performance are field position detection (determining where the magnetic field was during the motor's operation), switch selection (selecting which devices will be used to switch current), and the switching arrangement itself (how the switch is implemented into the machine).. Unfortunately, while the the motor obviously didn't wear, it also didn't have much power. Changes in the 1980's, however, enabled brushless DC motors to evolve. First, more powerful permanent magnets were produced due to better manufacturing processes. That, combined with high power, high voltage transistors, made DC motors more practical, enabling them to generate as much power as the old brush DC motors. At the end of the '80's Robert E. Lordo came out with the first large high-powered and low voltage brushless motor [4] that is still used in today's major engineering creations (aircrafts, electric vehicles, etc) [3]. His design included multiple interconnected stator and rotor modules, with the stator module sections axially aligned and interconnected. Each of the individual stator modules were wound with multiple parallel winding sections, similar to our electromagnets [5]. Lordo used strong permanent magnets, placed directly under each winding section (marked by the number 28 in Figure 1) and high voltage transistors, to design his high horsepower motor [6].

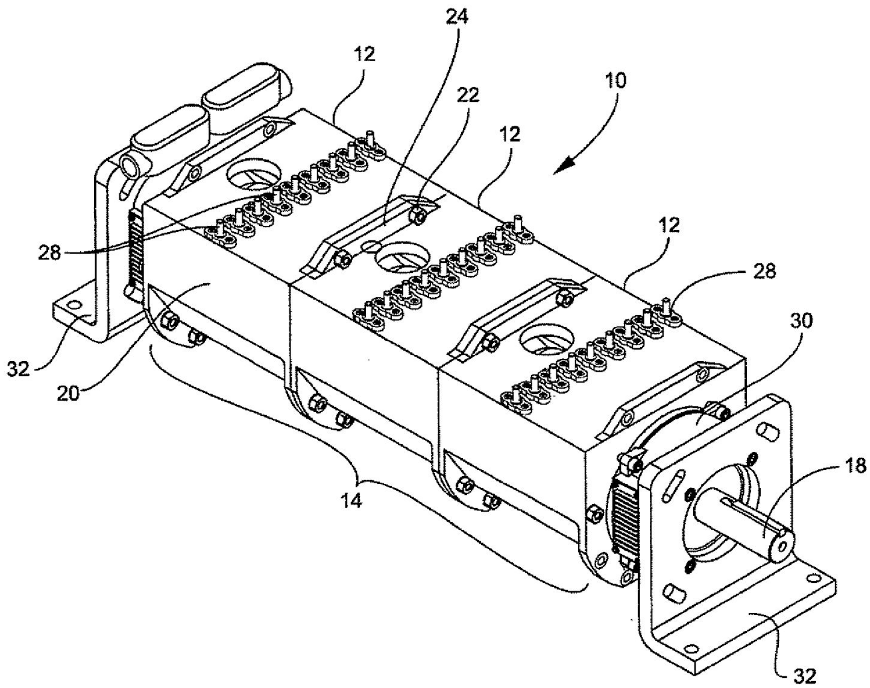

Figure 1: A diagram of Lordo's high-power motor design.

III. Theory of Operation

Circuit components: the Hall Chip

A hall chip is a small electrical probe that prevents current from flowing in the presence of a magnetic field. It has a power-in pin, a pin connected to ground, and a power-out pin. This electronic device is a vital part of the circuit that enables us to switch on and off our electromagnets based on the position of the permanent magnets.

Circuit components: the NPN Transistor

Transistors, similar to hall chips in their physical makeup (i.e. 3 pins), act as "faucets." When voltage is applied to the base (the middle pin), the transistor essentially opens like a faucet, allowing current to flow from power-input (the first pin) to the power-output (the last pin). We used a Darlington transistor, which consists of two separate transistors with a shared collector source. The two transistors are wired in series (see Figure 2) to doubly amplify the current that is sent to the relay coil. For simplicity, we will refer to the Darlington transistor as a single entity in the rest of this paper.

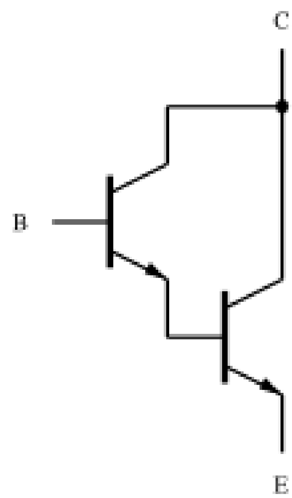

Figure 2*: The circuit diagram of a Darlington Transistor.*

Circuit components: the Relay

The relay is an electronic device that allows us to switch current between our LED's and electromagnets. When current flows through the coil in the relay, the magnetic field generated from the current in the coil exerts a force that moves the iron switch inside the relay from its resting position (closing the electromagnet circuit) to its alternate position (closing the LED circuit). The relay is an amplifier in the sense that a small current in the relay coil is used to control the higher current LED/electromagnet circuits.

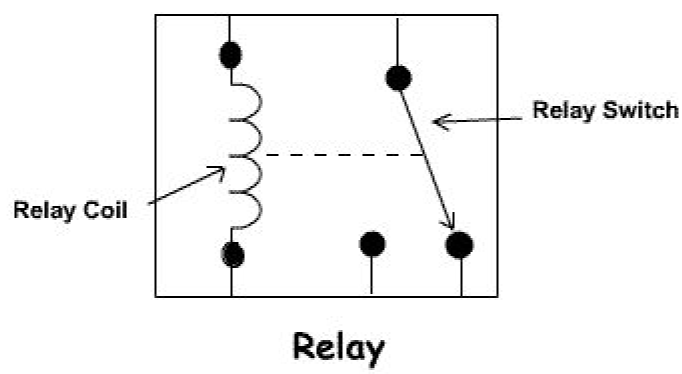

Figure 3: The circuit diagram of a simple relay.

How the circuit works put together

When a hall chip senses no magnetic field, it opens the voltage output pin's connection to ground, no longer allowing the current to take the path of least resistance (straight to ground), and forcing it to go to the base of the transistor. Current at the base of the transistor essentially opens a "faucet"(inside the transistor), which allows current to flow from power through the transistor and out to the coil in the relay. When the current goes through the relay coil, the switch within the relay redirects the current flow from the electromagnet's circuit to that of the LED. When the hall chip is in the presence of a magnetic field, no voltage is applied to the transistor so not current goes through the coil of the relay. Since the switch remains in its home position, it powers the electromagnet circuit. The electromagnet thus creates a magnetic field that attracts (exerts a force on) the large permanent magnets on our rotor. The magnetic forces on the rotor, give it torque, causing it to spin. When the small trigger magnets rotate out of range of the hall chip, the hall chip closes, directing the current to ground, which turns of the transistor and switches the relay back to the LED circuit, thus turning the electromagnet off.

IV. Design

Many aspects of our motor's design were chosen to minimize energy wastage. We chose to separate our rotor from the electromagnet holder in the hopes of minimizing the wasted kinetic energy caused by wobbling (by reducing the mass subject to wobbling). If they were attached, any time the rotor shook, it would move the entire chassis, hindering the performance of our motor by reducing the energy put into spinning our rotor. In reality, this idea proved more than useful. Though we were unable to measure if our design reduced wobble, the separation of parts made making adjustments to our motor easy, which proved advantageous given the number of changes we had to make to get our motor functioning.

If the axle itself isn't perfectly straight, it will oscillate unevenly, increasing wobble and making it harder to rotate. Also, with a bent axle, energy is lost to fighting gravity in each rotation. With this in mind, we chose a steel bolt rather than a wooden dowel as our axle, because it was the sturdiest, straightest, and most rigid material we had access to. We decided not to print our entire rotor in the 3D printer because we wanted to keep the rotor as light as possible to maximize our angular velocity.

To prevent the hall chips from being affected by the magnetic fields created by the electromagnets, we decided to place them at one end of the axle, far away from the electromagnets at the middle of the axle**.** At the end of the axle, we have two trigger permanent magnets placed in the same orientation as the main permanent magnets on our rotor (See Figure 4). Two hall chips (one connected to the top and bottom electromagnets, and the other connected to the right and left electromagnets) were placed around the trigger magnets with wires and popsicle sticks that made adjustments effortless. The hall chips are positioned so that, when triggered, the permanent magnets are 45 degrees away from the electromagnets they are approaching. Thus, for the duration the electromagnet is turned on by the hall chip, it exerts only a pulling force on the permanent magnets, quickly turning off before the permanent magnets reach the point where they are in line with the electromagnets. This prevents the electromagnets from ever exerting a backwards-pulling force on the rotor.

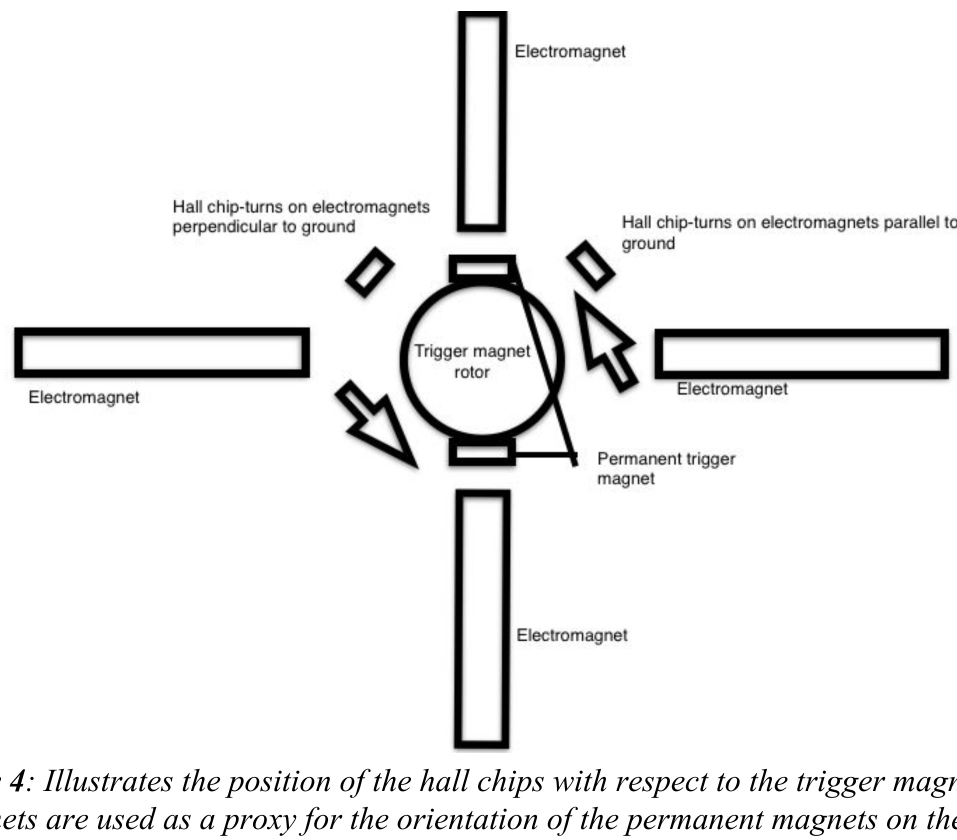

Figure 4*: Illustrates the position of the hall chips with respect to the trigger magnets (the trigger magnets are used as a proxy for the orientation of the permanent magnets on the main rotor).*

CAD Diagrams:

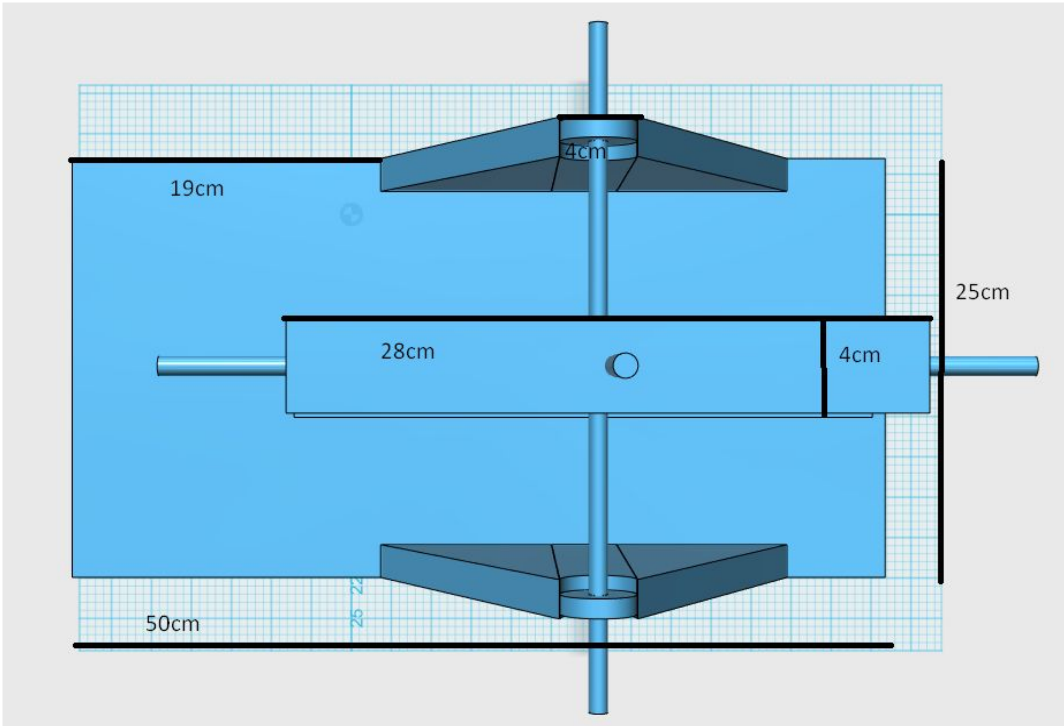

Figure 5: *A top-down view of our final motor design. We chose a large and sturdy piece of wood for our base, and triangular rotor supports (since triangles are the most stable shape). The core of the motor is shifted to the left, to give our circuit breadboard space on the right of the base.*

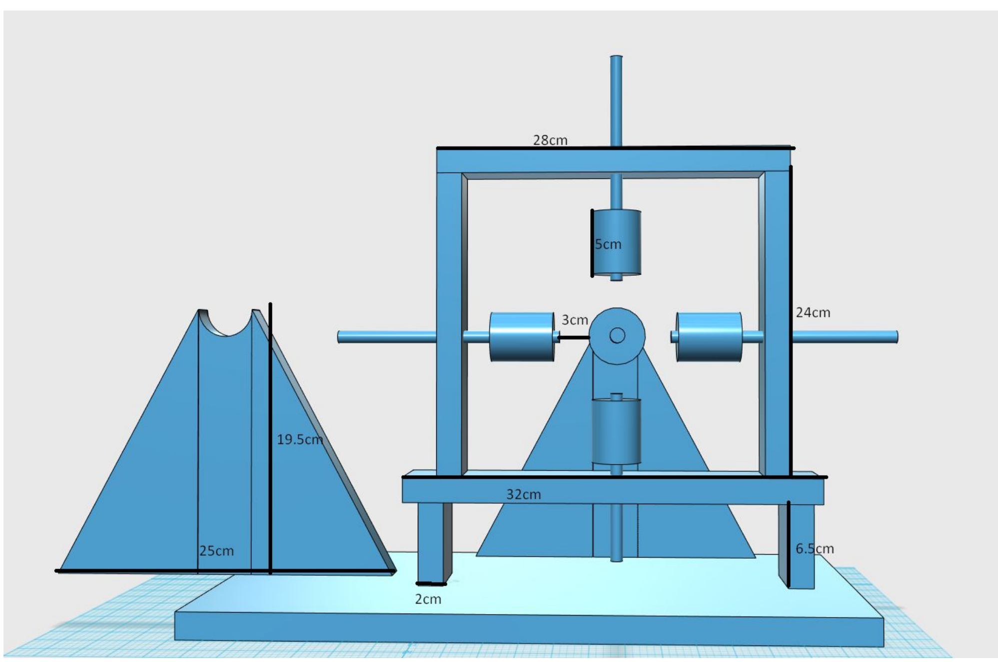

Figure 6: *A side-view of our motor. Note: the electromagnet stand is not fastened to the base; this enabled us to adjust positioning more easily. Since our electromagnets were coiled on bolts, we can easily screw them in or out of the stand (thereby adjusting them closer or farther to the*

rotor).

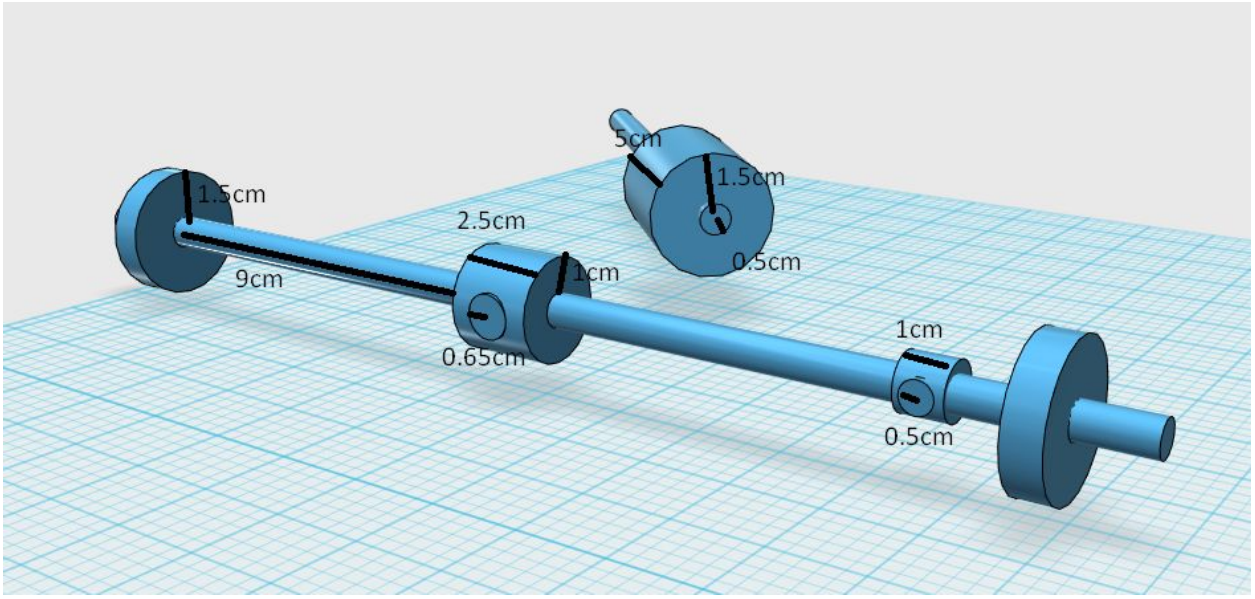

Figure 7: *Illustrates the dimensions of our rotor (front) and electromagnets (back). While we had originally planned to use long thin permanent magnets on the rotor (Appendix 12), we opted for short and wide permanent magnets because they were easier to work with and enabled us to move the electromagnets closer to the rotor. We kept the rotor small to minimize weight and maximize our rotational velocity.*

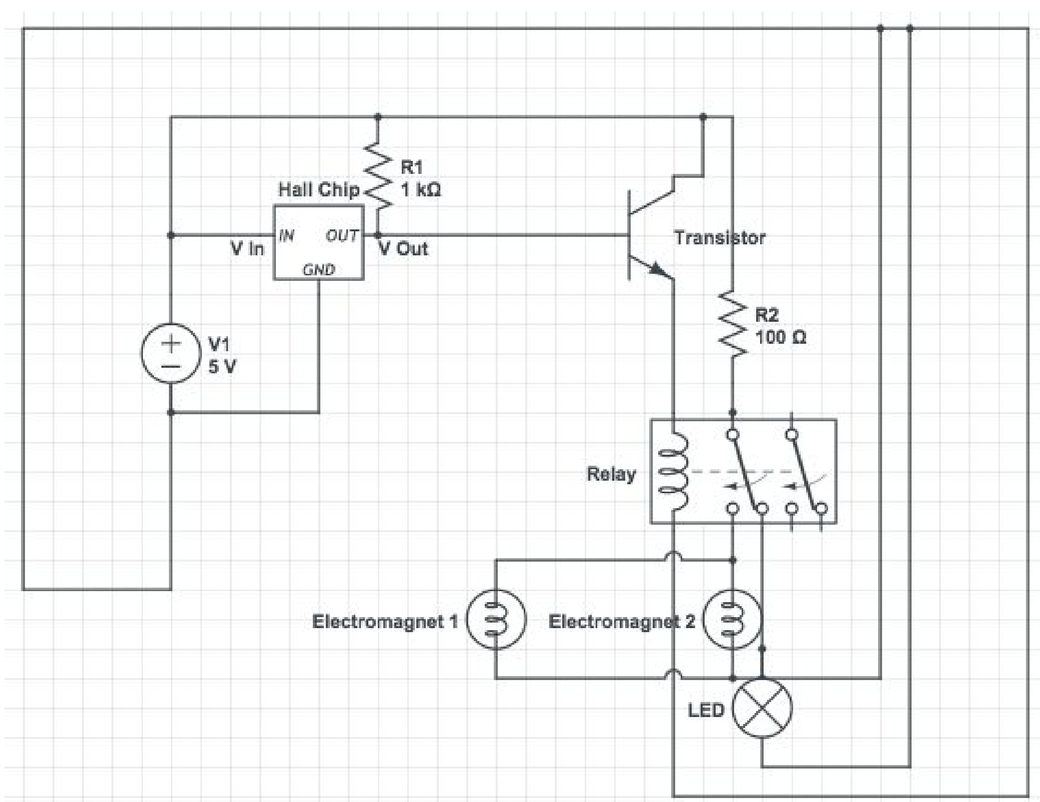

Figure 8: *The circuit diagram. Our motor made use of two circuits identical to this diagram.*

Photographs

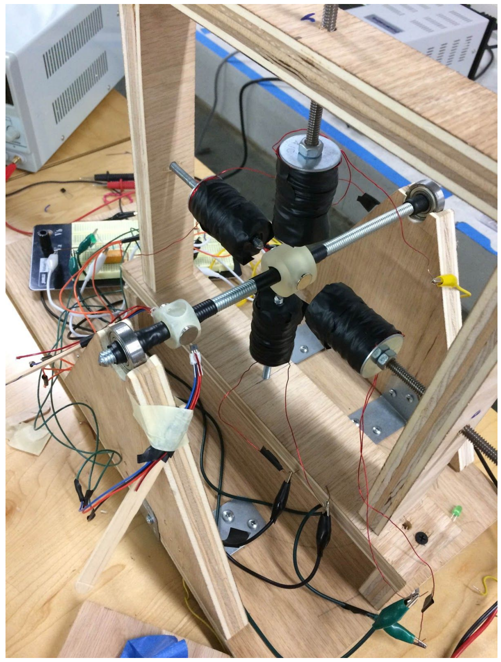

Figure 9: *Photograph of the motor in its final state.*

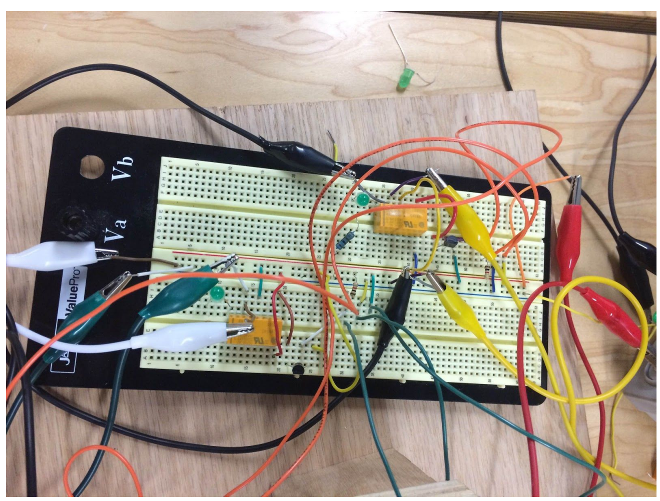

Figure 10: *Depicts the final breadboard. The two circuits operate individually, however they have the same power source. Each electromagnet has color coordinated wires and alligator clips to simplify any circuit adjustments. The LEDs in the circuits helped us isolate errors and malfunctions within our circuits (i.e short circuits or the relay popping out of the breadboard).*

V. Results

Overall Performance

	Maximum RPM (rotations/ min)	Maximum Running Torque (N/m)	Power Input (W)	Power Output (W)	Efficiency (%)
The RPMaster	1000.2 rpm (at 26 volts)	0.001303 N/m (at 16 volts pulling a 33 g mass)	25.32 Watts (at 12 volts)	0.065 Watts (at 12 volts)	0.256% (at 12 volts)

Table 1: *Illustrates the key specs of our motor*

Calculation Explanations

To determine the rotational velocity, we used a photogate (a laser emitter and a photoresistor) attached to an oscilloscope that measured when the laser's path was broken by the tape we attached to our rotor. A photoresistor's resistance varies with respect to the light it absorbs. In the circuit, the oscilloscope is connected to a resistor in series with the photoresistor. Essentially, when light is blocked from the photoresistor, it's resistance increases, and since the total voltage stays the same, the voltage drop on the other resistor decreases, which is illustrated by a trough in the oscilloscope reading (see Figure 11). In this case, the speed of our motor is 16.67 Hz. To calculate the RPM, we multiplied the frequency (rotations/second) by 60 (seconds/min) to get (by dimensional analysis) rotations/minute.

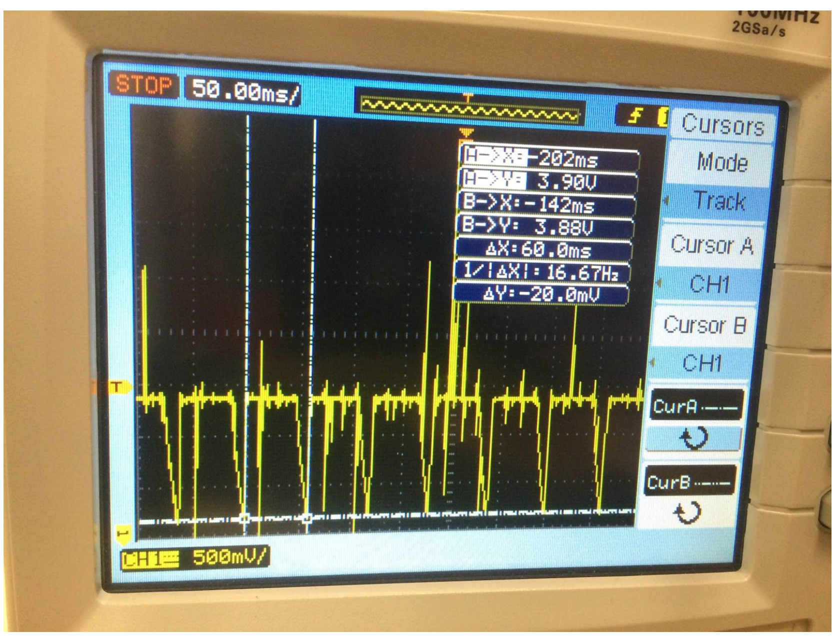

Figure 11: *The oscilloscope screen illustrating when the laser's stream of light is interrupted by*

the tape on our axle.

We found the running torque of our motor at different voltages by fastening one end of a string to a weight (in this case 33 grams), and the other end to our axle. We attached a weight to the end of a string while the other end of the string was taped to the motor's axle. To reduce friction, the string ran through a pulley attached to the side of the table. With a motion sensor plugged into a Labquest device, we recorded the distance the weight moved up as a function of time while our motor reeled it in. With this data, we analyzed the velocity vs time graph, and determined the acceleration for that specific run (the slope of the velocity v. time graph). To determine the total upward acceleration caused by our motor, we added 9.81 (the acceleration of gravity - see Figure 12). Using the total acceleration, we calculated the total force our rotor exerted on the mass (F = m*a, where a is the total acceleration (net acceleration acceleration of gravity)), and multiplied that by the radius of our axle to determine torque (Torque = F*distance).

A source of error during the measurement of acceleration is the piece of cardboard attached to the weight. We attached the cardboard to the weight to increase the accuracy of the motion detector (by enlarging the area that can be detected). The air resistance caused by the cardboard however, was not taken into account for during our calculations. Since the air resistance slowed down the acceleration of the weight, our calculated force exerted by the motor on the weight is lower than the reality, though the amount by which is it lower is unknown. Thus, the actual torque from our motor is higher than our calculation suggests.

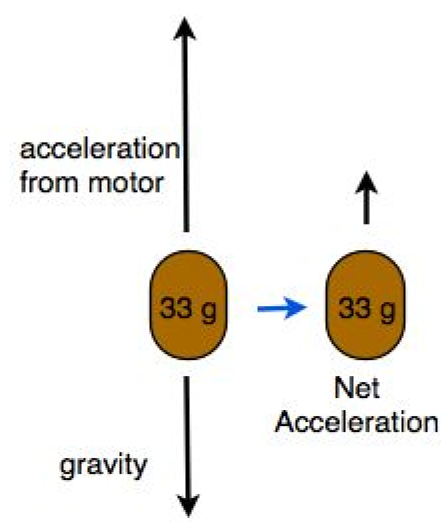

Figure 12*: The left diagram breaks up the mass' acceleration components. The right diagram illustrates the net acceleration (what we calculated with the motion sensor).*

To determine the power output of our motor, we made use of the relationship Power = torque*angular velocity. The calculation was essentially, Power (J/s) = running torque (N*m)*2Pi (radians/rot)*RPM(rot/min)/60(sec/min). We determined the power output of our motor, at 12 volts, pulling up a 33g mass with 476.2 RPM, to be 0.065 Watts.

Power input was determined by the equation: P=IV. We found the average current for a given voltage and multiplied the two to get the power input. At 12 volts, the power input was 25.32 Watts. From here, calculating the efficiency was easy: we just divided the power output by the power input and multiplied by 100. Our result was 0.25% efficiency. While this low number seems rather inefficient, this is actually a reasonable efficiency for a motor.

RPM v. Voltage

We determined that the input voltage of our motor and its resulting revolutions per minute are proportional. We measured the RPM at different voltages (see above for calculation explanation, and below for results), and found that for every volt increase, the RPM went up by approximately 35. This makes sense, because as the voltage increases, the current increases, resulting in a stronger force pulling the rotor, thus making it spin faster.

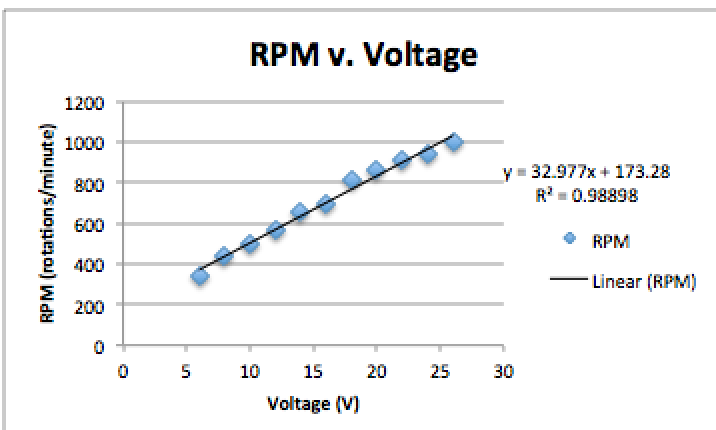

Figure 13: *Illustrates the relationship between voltage and our motor's RPM*

Voltage (v)	Hertz (Hz)	RPM (rpm)
6	5.747	344.82
8	7.246	434.76

10	8.333	499.98
12	9.434	566.04
14	10.87	652.2
16	11.63	697.8
18	13.51	810.6
20	14.29	857.4
22	15.15	909
24	15.62	937.2
26	16.67	1000.2

Table 2: *The data points used to make Figure 13*

Running Torque v. Voltage

We found that the input voltage of our motor and its running torque are also directly related. After calculating the running torque at various voltage inputs, we determined that for every volt added, our running torque increased by 0.000001 N*m. This make sense given that Torque = Distance to the rotation axis (a constant) * Force , and the force is dependent on the voltage (a higher voltage results in a higher angular acceleration and F=ma).

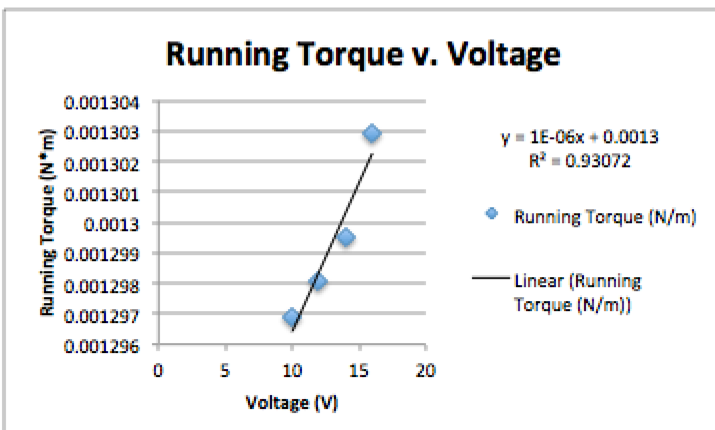

Figure 14: *Illustrates the relationship between running Torque and voltage*

Voltage (v)	Measured Acceleration (m/s/s)	Total Acceleration (m/s/s)	Running Torque (N/m)
10	0.015	9.825	0.001297
12	0.02368	9.834	0.001298
14	0.03476	9.845	0.001300
16	0.06062	9.871	0.001303

Table 3: *The data points used to make Figure 14*

VI. Conclusion

Though we ran into several problems along the way, we eventually managed to build a functional two-phase brushless motor with a max speed of 1000 RPM (at 26 volts). We had a 0.25% efficiency, and a maximum running torque of 0.001303 N*m (at 16 volts) Unfortunately, our motor had no start up torque, and required a spin to get started and overcome its resting equilibrium position. This is likely due to the large attraction between our permanent magnets and the iron core of our electromagnets.

There are multiple sources of error in taking measurements. To start, our calculations did not account for air resistance or friction, both of which have a significant impact in the real world. Not only that, but our RPM measurements with the oscilloscope had the potential for error given that our frequency was determined by hand adjusting the rather than using a computer to find the exact time between troughs.

Our design underwent several adjustments throughout the building process. Though our design plans changed quite a bit, we learned a lot about designing a motor from our original mistakes. One part of our design that worked well was compartmentalizing our motor design by separating the axle and electromagnet structures. Though we do not know if it successfully reduced our motor's wobble, it absolutely made making adjustments relatively facile; we were able to easily pull the rotor on and off the motor and adjust the electromagnets' distance to the rotor. It also enabled us to modify the electromagnets themselves (by unscrewing them from the holder), which proved immensely helpful when we needed to cut off the excess iron (by removing the nut and washer at the end of the electromagnet) to reduce the permanent magnets' attraction to the iron core of the electromagnets.

One original design flaw, was trying to get the most powerful permanent magnets. While in theory, that would increase the force with which our rotor moved towards the electromagnets (thus, causing our motor to spin faster), in reality, the powerful magnets prevented our electric motor from moving in the first place; essentially the magnetic attraction between the large permanent magnets and the iron core of our electromagnets was so strong, turning on and off the electromagnets had little effect. The electromagnetic pull wasn't *nearly* strong enough to break the permanent attraction. To address this, we modified both our electromagnets (by removing all excess iron) as well as our rotor (by using smaller weaker permanent magnets). These changes, eventually led to our motor successfully functioning. In future projects, we could further address this problem by choosing a rod made with minimal amounts of iron for our electromagnets core.

Another mistake was making the entire motor too large. If we scaled everything down, it would have been easier to work with and would have had less structural flaws. Also, we tried to do too much at the beginning, and didn't get anything working on its own before combining it with other parts. Looking back, we see that we may have started off with too complex a design, and should have begun with a simpler goal. Instead of starting with a four phase motor, and then bringing it down to two, we should have started with a single phase motor that worked and then added complexity.

If we were to remake our motor, we would do several things differently. First, we would make our electromagnets more goal-specific. While our current ones work, they are excessively long which increases only the resistance, reducing the current and magnetic force they exert on our rotor (since F=BIL). Our new electromagnets would be much shorter and wider, to maximize the force exerted on our rotor, thus increasing our motor's speed. In addition, if we had more time, we would make our motor do push/pull instead of only pull. We could do this by making use of the relay and attaching wires in place of the LED to our electromagnets in the opposite orientation (so as to reverse current flow). This would likely result in our motor having a start-up torque.

Electric motors are vital to everyday life. Whether it is to drive an electric car, to pump water through a household, or to make a smoothie (with an automatic blender), motors are key. Understanding how they work is important because as they continue to increase in popularity, their reliability and functionality will be crucial to the success of their implementation.

VII. Acknowledgements

We'd like to thank Dr. Dann for his support throughout this endeavor. In addition, Jeffrey Barratt was always a helpful source of information and encouragement.

VIII. Bibliography

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IX. Appendices

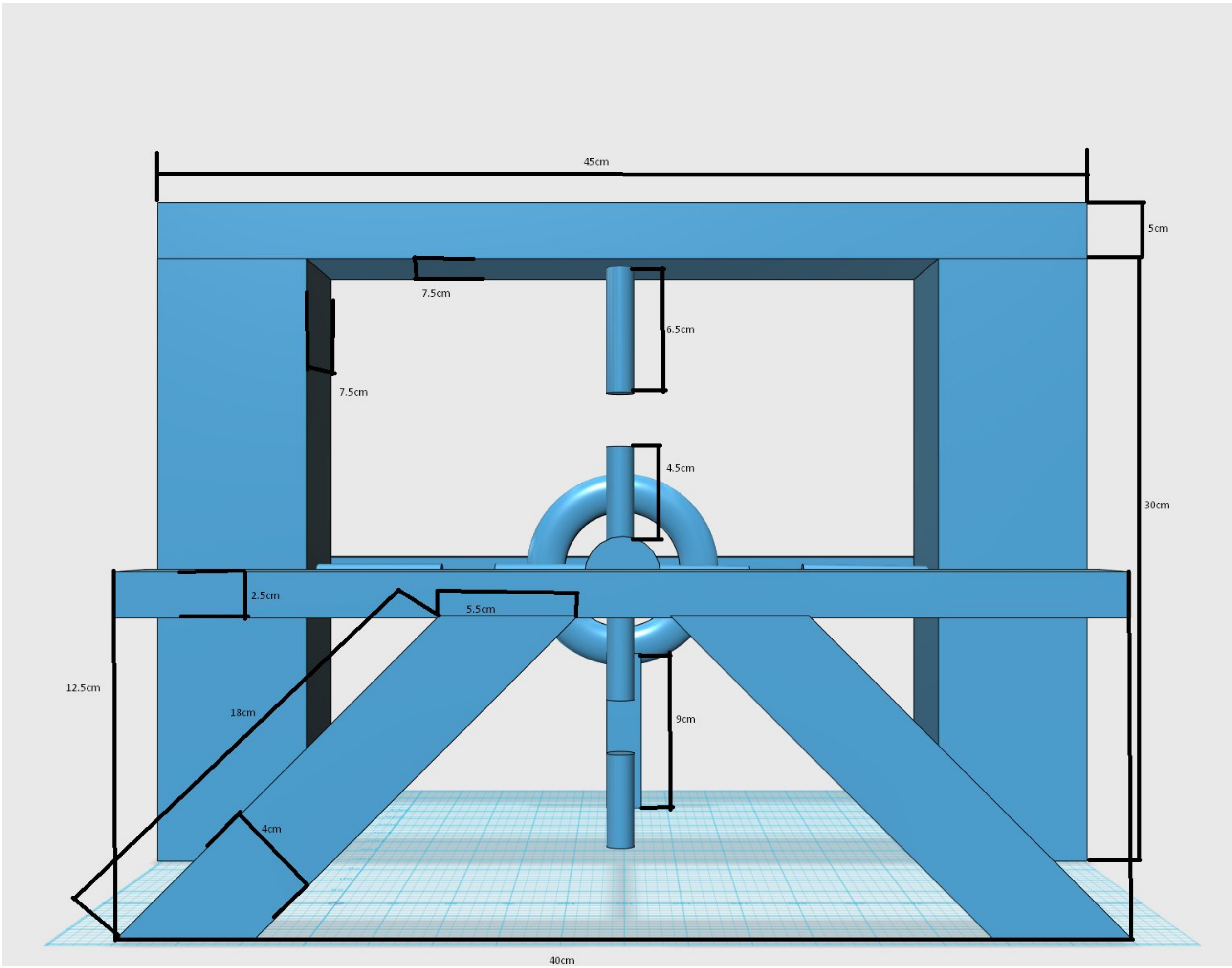
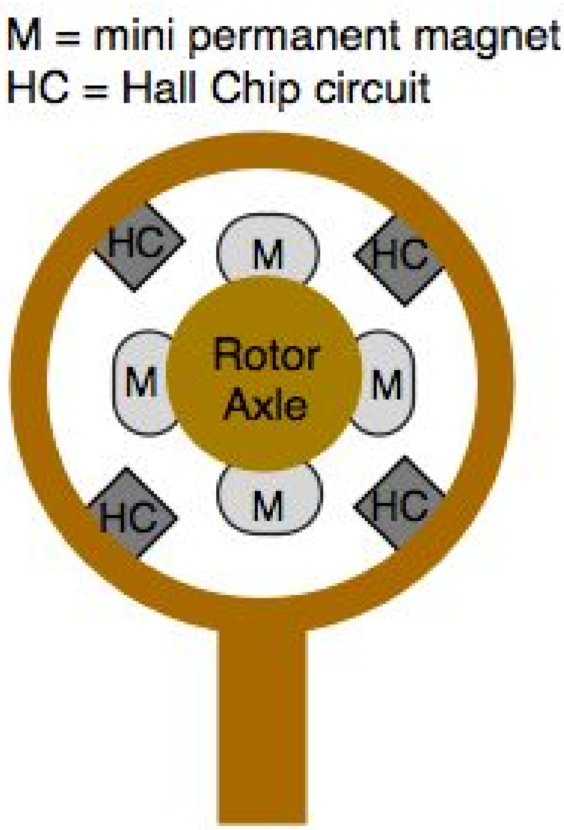


Figure 15: *Above is our initial plan for our electric motor. Some of the dimensions above are larger than the dimensions of our final design because of part-availability limitations. We had initially planned to use a hall chip stand (as pictured, details below), but didn't end up integrating it because of the complications it added, like slowing down our hall chip adjustment.*



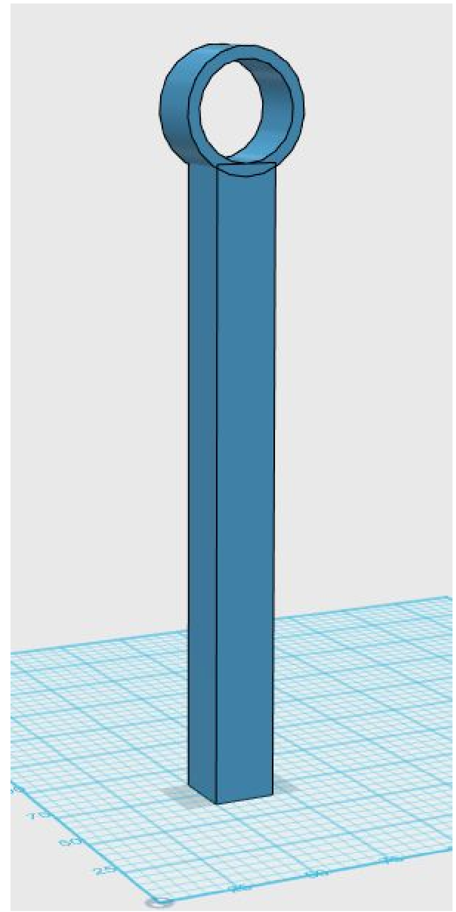


Figure 16 (left): *This is a diagram of how we initially planned to lay the hall chips out. Because we ended up triggering pairs of electromagnets (top and bottom or left and right) instead of individual electromagnets, we only used two hall chips instead of four.*

Figure 17 (right): *This is a design of our simple hall chip stand. We used the Makerbot to 3D print this part, but did not use it because it proved difficult to integrate.*