The Hover Table: A Responsive Table for the Future

Ryan King-Shepard and Diana Lamaute | 6.111 Final Report | Fall 2015

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1. Overview

In the movie “Back to the Future II”, plucky protagonist Marty McFly travels to the year 2015 and finds that the world has undergone a futuristic revolution. During his adventure, he utilizes a hoverboard that allows him to soar gently and gracefully above the ground as he zips past people and obstacles alike to escape foe after foe. This moment was the inspiration of our project.

Our project’s aim was to create a self-correcting hover to challenge the static design of tables today and give consumers a taste of the future Mr. McFly traveled to. We wanted to design and create a table that could adjust to the user’s needs. The implementation of the electromagnetic table would utilize proportion-integral-derivative control to allow and maintain customizable heights and tilt configurations. A magnetic base designed to maintain stable magnetic forces being fed pulse-width-modulation current to reduce power consumption..

In short, the electromagnetic system will allow users to control magnetic forces to orient the furniture of the future into any position that fits their needs; be it a set of mirrors for lighting control, a room design to add some feng shui, or merely a stand design to hold a morning coffee.

2. High-Level Design

2.a Terms

There are some key terms to keep track of in this final report:

ADC: an analog to digital signal converter

PID: Proportional-integral-derivative control; a type of controller that utilizes the sum of the error signal’s integral, derivative, and base form in order to improve system performance and stability.

PWM: Pulse-width modulation wave; a wave form that provides an average DC value via an oscillating square wave where the longer the wave is high during its period, the higher the average value.

2N3904: An NPN transistor that has a wide-array of applications; for the purposes of this document, it will act like switch turning on and off current

1N969B: A zener diode; a component used to prevent current from flowing in a single direction. Like the 2N3904, a zener diode has a vast number of applications, but for the purpose of this document, it is like a current gate; allow current to flow one way, but not the other.

IR (Distance) Sensor: a sensor which uses the reflection of infrared light it emits against a surface to determine distance to that surface

Base: The part of the table that rests on the ground with the magnets and sensors.

Tabletop: A square plastic tile with four permanent magnets attached to the corners

2.b Project Overview

Figure 1 below presents the high-level design of the project.

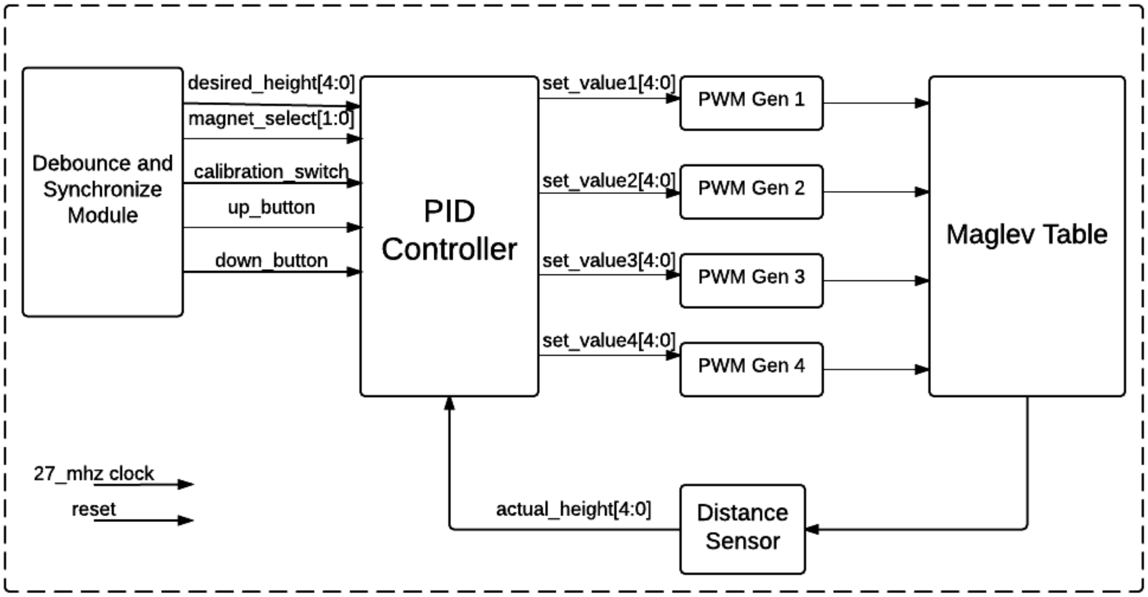

Figure 1: Overall Schematic of Electromagnet table

To summarize, the PID controller takes in a 5-bit desired height from the user to produce an error between the actual and coveted height. The error signal is processed through the controller to generate four set value outputs to their own PWM generator. The PID controller also takes in 2-bit magnet selection in order to customize the magnetic force on each individual magnet in calibration mode. The calibration switch input is used to switch the controller to calibration state if high or feedback state when low and the up and down button are used to adjust the selected set value outputs, which in turn controls the magnetic force output for that magnet. The 4 PWM generators then provide current to the 4 electromagnets on the base of the maglev table to produce force to the table top. The distance sensor then measures a new height for the table and feeds it into the controller, starting the process over again.

2.c Decisions and Motivation

To truly achieve completion of a marketable hover table, the full construction of the table should include both height and tilt control. The primary goal of the project was to have controllable height with tilt being an intermediate goal. Other stretch goals included creating a display on the monitor to project what the current height and tilt of the table were and to have the user be able to calibrate the table using hand motion directed at a camera.

Unfortunately the intimidate goal could not be completed due to design changes. The first stretch goals progress was lost during a horrid computer crash and the second stretch could not be completed due to timing constraints.

The decision to use electromagnets attached to the base was based on allowing both a floating surface and fast control with pulse width modulation, which cannot be done with solely permanent magnets. This pairs nicely with the neodymium permanent magnets for the tabletop, since relative to their size they produce a very strong magnetic field. Thus, the only controlling necessary takes place from the table’s base.

3. Module Implementation

3.a Magnetic Table (Plant) – Diana Lamaute

This is the physical component of the hover table. The sub-components include the magnets and sensors.

3.a.I Magnets

There are four electromagnets at the base of the table, which is a square with side length 4.5 inches. Each electromagnet is wound to 4000 turns around a ¾ inch diameter cylindrical ferrite core, and has a diameter of 2 inches—one can see the magnetic wire used in Figure 4. They are spaced equally apart to create as even of a field as possible. This arrangement is shown in Figure 2. To control each magnet, one sends pulse-width modulated (PWM) signals to each magnet, raising or lowering the duty cycle to raise or lower the tabletop, respectively. We switched from commercial to handmade electromagnets because commercial ones are optimally designed to lift, and therefore have both poles on the same side. Thus, I created these to have the north and south poles on opposite sides in order to let a permanent magnet repel.

In Figure 4, the square floating on top is the tabletop (Fig. 3), which has one small permanent neodymium magnet at each corner. The tabletop consists of a thin but sturdy plastic square with side length 3.25 inches, with a neodymium permanent magnet, .5 inches in diameter, at each corner. This slightly exceeds the distance to reach the exact center of each electromagnet, thus resulting in a force that pulls the tabletop in all four directions equally and results in stability. However, since I was unable to machine this piece of plastic since it is so thin, and because I do not have robotic precision, the placement of the magnets was such that it was harder to reach the steady state. Thus, I made sure to place the tabletop while holding a board (not pictured) on one of its sides to keep it from turning.

In order to test the magnets, first each individual one made was tested with a .5A current through it, using a single neodymium magnet to verify that it was repelled. Then, after having assembled the table's top and base, the top was held over the base and the current was gradually increased until the table hovered. This yielded the current needed to support the weight of the tabletop.


Figure 2: Table base

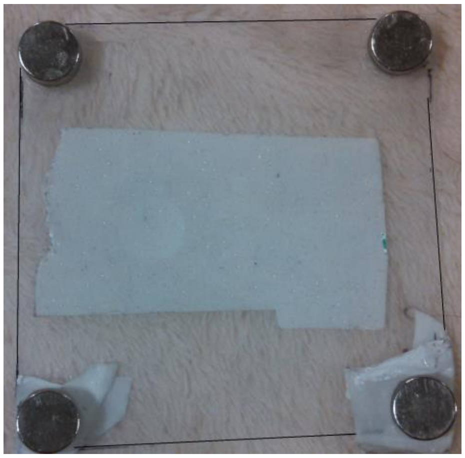
Figure 3: Tabletop

3.1.2 Sensors

The main sensor, to keep track of the tabletop's height, is the IR sensor. This, as is visible in Figure 2, is placed at the center of the base and regularly takes measurements of how high the tabletop is relative to the base. This is sent to the controller to adjust the electromagnets as needed. In order to do this, the analog signal produced by the IR sensor needs to go through an ADC to send it to the FPGA for controls.

The IR sensor was tested by reading its outputs while holding a board over it and checking that the distances corresponded to the voltages the sensor was outputting. The specifications sheet for the IR sensor states that it is responsive in a range from 4 to 30 cm and has a graph of distance versus voltage. Therefore, if the tested response corresponds well to this graph, we know it is working properly.

Figure 4: Finished table setup, from the side.

3.b Proportional-Integral-Derivative(PID) Controller [Ryan]

The PID Controller is a finite state machine responsible for setting the different current levels in response to the distance beam and accelerometer readings. The inputs are the global clock, the desired height set by the user, the magnet selection bits, the calibration switch, the up and down buttons, the actual height from the distance sensor, and the tilt data from the accelerometer, while the outputs are 4 set values of voltage level for the PWM generator module. The controller has two main states of operation: calibration and feedback. During calibration, users can set the magnetic force of each magnet manually by directly influencing the corresponding set value output, while in feedback, the controller sets the magnetic forces in order to maintain the desired height set switches 4 through 0.

Originally, the feedback state was designed based on the Laplace interpretation of PID control show in Figure 5 with e(t) representing the error between desired values and measured values, y(t) representing the controlled variable, the current level, and E(s) and Y(s) the corresponding Laplace transforms.

$$y(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + \ K_d \frac{d}{dt} e(t)$$

$$Y(s) = \left(K_p + \ K_i \frac{1}{s} + \ K_d s\right) E(s)$$

Figure 5: equations representing PID control with the top shown in the time domain and the bottom shown in the frequency via Laplace.

This is where the proportional term, integral term, and derivative term is multiplied by the error in order to produce the controlled value; in this case the current level. The general methodology is to find the three gains, Kp, Ki, and Kd, that will maximize stability and performance of the system.

The problem with this interpretation was transitioning it to the digital realm. Multiplication is easy in the digital realm, making the proportional term easy to translate, but integration and derivation are generally functions performed using analog circuits. In order to build a proper controller, the functions would have to be simulated on the digital platform. The derivative function of the error could be done by comparing the current value of the clock cycle with the previous one in order to find the rate of change. However, this makes the controller sensitive to noise as any blip among the sensor readings would cause a dramatic shift in system behavior. Integration could be simulated with a buffer that would hold the 5 or 10 latest error values and then sum them for the integral component. This unfortunately led to integral wind-up, where the integral-error term dominates the system and leads to behavior over-compensating for stability. This might cause the table to jump to maximum height or have growing oscillations around a certain height until bounding from maximum to minimum.

The final design of the feedback state used the z-transform of the PID system, which is very compatible with the digital realm. Figure 6 shows the z-transform of a PID system.

$$Y(z) = \left[K_p + \ \frac{K_i}{1 - z^{-1}} + \ K_d(1 - z^{-1})\right] E(z)$$

Figure 6: z-transform version of PID Controller

If the equation is manipulated and transformed into a difference equation, as shown in Figure 7, the digital implementation only needs the current error, the past two clock cycle errors, and the previous cycles set value.

$$Y(z) = z^{-1}Y(z) + \left\{(K_p + K_i + K_d) + \left(-K_p + 2K_d\right)z^{-1} + K_d z^{-2}\right\}E(z)$$

$$y[n] = y[n-1] + \left(K_p + K_i + K_d\right)e[n] + \left(-K_p + 2K_d\right)e[n-1] + K_d e[n-2]$$

Figure 7: Rearranged form of PID z-transform and its representation as a difference equation

The final design aspect of the feedback state was determining the gains, Kp, Ki, and Kd, of the feedback system. One of the biggest challenges for the controller was the constant change of the table design. As the table changed, finding an accurate plant to model it for control analysis became more and more troubling. Thus, the Ziegler-Nichols Frequency Domain method was used to approximate proper gains for the system. The ZNFD method is done by setting the integral gain Ki and derivative gain Kd to 0, while increasing the proportional gain Kp until the output oscillates. This meant to increase Kp until the table oscillated around a desired height. Once the oscillating gain was found, the period of the oscillations was measured. The ZNFD approximation then sets Kp to .6 the value of the oscillating gain, sets Ki to half of the period and Kd to an eighth of the period. For the table, this resulted in a Kp of 6, a Ki of 4, and a Kd of 1.

The calibration state allows the user to directly change the amount of magnetic force each electromagnet outputs. First the user sets the switch 7 to on, indicating that that the controller should switch states. Second they use switches 6 and 5 as the magnet selection bits in order to choose which magnet out of the 4 they wish to manipulate. Once a magnet is selected, the up and down buttons can be used to either increase or decrease the force that magnet applies. Once the user likes the configuration of the table, they can switch back to feedback state with the configuration intact and approaching the desired height set by switches 4 through 0.

3.c Pulse Width Modulation(PWM) Generator [Ryan]

The PWM Generator takes in a 5-bit set value and output a voltage PWM wave that is 3.3V when high and 0 volts when low. This PWM wave is feed into a 2N3904 transistor that acts as a switch, thus creating a current PWM modulation wave to the electromagnet. Each electromagnet has their own PWM Generator in order to allow custom configurations of the table. Figure 8 shows a complete diagram of the process.

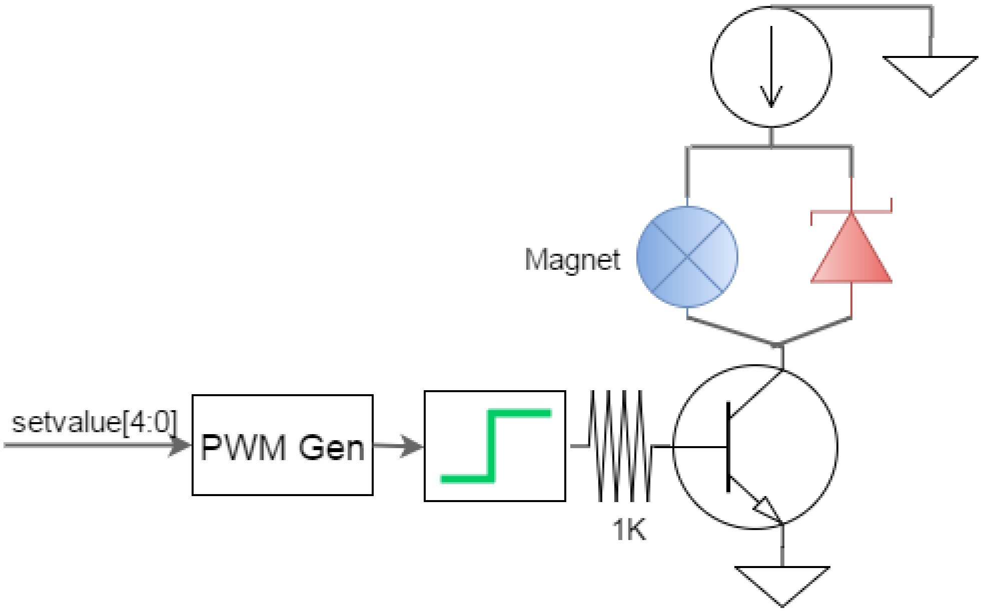

Figure 8: PWM Generator Module for one magnet

Out of all of the modules, the PWM Generator changed the most frequent. While the table design was being updated and modified, several different magnets were considered, each one taking in a different kind of input and thus needed a different Digital Analog Converter (DAC), current amplifier, or PWM generator to connect it to the controller. The final magnets chosen were hand-spun electromagnet with ferrite cores that required DC Current. A PWM wave would reduce the power and thus the heat built up by the electromagnets over operation time. The module is split into two major components; the digital converter that transforms a 5-bit set value into a 1 Hz voltage wave and the circuit that utilizes the wave in order to modify the current.

The converter takes the 5-bit set value and generates a 1 Hz wave by basically figuring out how many clock cycles to keep the wave high and making the remainder of the wave cycles low. This is done by implementing a 32-bit counter that counts to twenty-seven million, the number of clock cycles in a 1 Hz wave using the 27 MHz clock. A placeholder known as up_count is used to hold the number of clock cycles the wave is high and is calculated using the following equation. “MAX” refers to the twenty-seven million, the limit of the counter.

$$up_{count} = \sum_{0}^{4} setvalue[i] \frac{MAX}{2^{5-i}}$$

Figure 9: Equation to number of high-voltage clock cycles

When set value is composed of only 1's, up_count in theory should be equal to "MAX" in order to have a full one hundred percent duty cycle. Instead up_count is approximately "MAX" allowing for a small dip in the PWM wave. This was designed this way so that the system would never have a constant value at the maximum amount of current drawn and burn through the transistors.

Once the voltage wave is produced by the PWM Generator, it is sent to the current-controlling circuit. The circuit is composed of the electromagnet in parallel with a 1N969B zener diode while both components are connected in series to a 2N3904 NPN transistor. The transistor acts as a switch; when the voltage is high, it acts like a short and allows current to flow through. When the voltage is low, it acts like an open circuit and prevents current from flowing. However, during the low periods, voltage made build up on the collector end of the transistor. This voltage can cause damage over time, so the zener diode is used to offset the voltage. The 1K resistor attached to the base is to prevent drawing current from the FPGA.

4. Test Suites, Redesigns, and Future Additions

4.a Table

The first goal would to make the tabletop stronger and more stable. The primary change would be to replace the metal screws holding the electromagnets on the table with plastic ones, which would not interfere with the field as much. They were not a huge problem in the hovering, however if one of the tabletop's neodymium magnets got too close to the screws, it would attract rather than repel because the screw was not magnetized in any particular direction. In addition, more precision in the shape of the tabletop and placement of the magnets can result in easier stabilization of the tabletop when placing it. Therefore, it might be useful to look into strengthening the electromagnets by supplying a greater current and perhaps adding more turns. Meanwhile, researching other materials for the tabletop which are sturdier, easier to machine, and light would help impact the versatility of this table.

Another functionality for which we originally planned as our first-level stretch goal was tilt adjustment. This would require attaching the two-axis accelerometer to the tabletop. One concern might be that this adds weight, so it would definitely be important to implement the table adjustments mentioned previously first.

4.b PID Controller

The PID Controller was tested in Model Sim under different sensor reading to simulate 4 different conditions; holding the table at a position, returning to a desired position, calibrating to a certain configuration, and holding that configuration while approaching a desired height. Under the current design scheme, it completes each of these tasks in simulation.

The main issue with the controller was the time it took to find a functional digital controller. While an initial controller was built ahead of schedule, the time it took to test and fix it took much longer than planned. Instead of trying to simulate the analog components of control into a digital circuit, finding a PID model which already fit into the digital realm would have been time and cost-effective.

The controller is also prepared for tilt input, but due to timing constraints, an accelerometer was not attached and the tilt correcting control was not used. Unlike the previous design, where the tilt would receive its own PWM controller for both the X and Y axis, the new design would merely give them a hybrid-Proportional controller. The hybrid-P controller would have a small proportional gain that would incorporate only the current tilt error and combine the output with set value of the height controller. This was chosen because the tilt in simulation was incredibly sensitive and would wobble back and fro constantly. By integrating the tilt controller output into the overall output, the table corrected itself naturally and remained flat enough, even with the loss of exact precision.

As for future additions to the controller, the tilt control is definitely an addition that would be easy to come to fruition. Another future improvement would be to take up the mantle of the stretch goal and have the controller able to calibrate the table based on hand movement. The final suggestion is to add the functionality where the controller will output magnetic force functions that would cause table to spin or dance in the room, giving it the ability to be a more versatile furniture piece.

4.c PWM Generator:

The PWM Generator was tested in Model Sim and LTSpice. Besides the constant design change, the most difficult part of this module was the large amount of current flowing through the components. The operating current of the table is 1.0 Amp with 0.5 Amps at minimum and finding a circuit that would draw that would causing a short was difficult.

The initial design caused for small-signal current amplifier that would govern the current of a larger power source. However heat and power soon became an issue and the design was modified to use PWM wave to reduce these. This meant the amplifier could no longer be used due to the slow switch off time. At one point, current was no longer an issue since the magnets took a voltage PWM wave. This design would not last long since the magnet running off the voltage PWM wave were too weak to lift any substantial weight. An attempt was made with a circular magnetic ring and bismuth crystals, but both proved to be too heavy and too ineffective.

When the final design of the hand-spun magnet was finalize, the first attempt for the PWM Generator was careful placement of small resistors. Figure 10 shows the design of the rough draft.

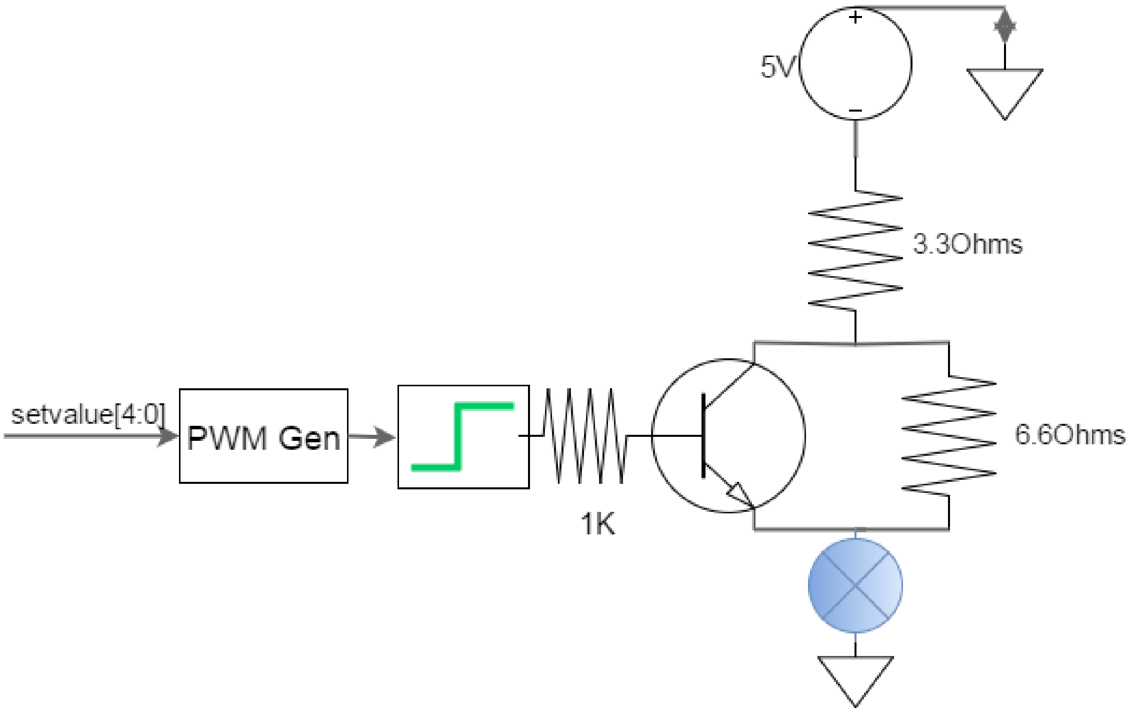

Figure 10: First PWM Generator model with resistors

As feared, the resistors were too small and a constant current flowed through the circuit, ignoring the PWM control signal. The final circuit was designed shortly after, but many transistors died in the process of a stable configuration that could balance the current around the operating point.

In hindsight, there are two main corrections I would make to the PWM generator. Firstly, I would replace all of the zener diodes with schottky diodes who are known for fast-switching time in order to improve the PWM performance. Secondly, the 2N3904s would be replaced with power mosfets more equipped to handle bigger DC current and add further protection to the FPGA.

5. Conclusion

The hover table will bring furniture into the future and give consumers a taste of future Mr.McFly visited. It will have a range of applications, from simply making furniture adjust for different purposes, to increasing accessibility by creating a more responsive table.

In reflection, it was an exciting project for the team, as neither of us have had extensive experience with magnets. The project gave the team a newfound skillset in working with an analog based plant and crafting a digital controller. This venture was definitely an exciting learning experience, and the fact that we were able to create a tabletop float with electromagnets and generate an adjustable PWM wave with an FPGA demonstrates a success that many doubted we could achieve. This project demonstrated that a more robust self-correcting hover table certainly is possible with further work building off of that which we have created.

6. Appendix

Part Name	Number Required	Price
Neodymium Magnets	4	$8
IR sensor	1	-
Ferrite Cores	4	$11.93
Analog ADC	1	$13.25
Magnetic Wire	-	-
2N3904	4	-
1N969B	4	-