The Effect of an Electromagnetic Levitation Stabilization Apparatus on the Stability of a Model Statue

4 January 2016

Abstract
This project aims to make an electromagnetic levitation apparatus that automatically stabilizes to combat opposing forces. The system includes 4 electromagnets on the corners of the structure. A gyrometer is constantly taking measurements and will detect if the levitating platform starts to tilt. If this happens, the system will send 12 volts through specific electromagnets causing the statue to levitate a few inches off of the structure. Using Maxwell Tensile Strength calculations to find the magnetic flux, the apparatus can theoretically lift 11 kilograms 1 inch into the air. Depending on the tilt of the statue as measured by the gyrometer, the electromagnets will compensate by sending added voltage in the opposite direction. This is done by 4 transistors and pulse width modulation control using an Arduino. Pulse width modulation is a type of digital signal that helps to vary voltage to the electromagnets. Therefore, the statue will stay flat regardless of any movement. The experiment was conducted to see if there would be a statistically greater angle at which a block on a platform falls over with the apparatus compared to the angle without it. The research hypothesis states that the model statue with the apparatus would fall over at significantly greater angle than the model statue without the apparatus. The null hypothesis states that there will be no significant difference. The results show an increase in angle at which the model statue falls over. Therefore, there is an increase in stability with the electromagnetic device. Without the apparatus, the model statue fell over at a mean angle of 14.286°. With the apparatus, it fell over at an average angle of 24.741°, a 73% increase in stability. The p-value calculated with a one-tailed independent t-test is $1.371*10^{-23}$ which is less than the alpha value, 0.05. Thus, the null hypothesis is rejected and the research hypothesis is supported. Therefore, the data supports that the apparatus is successful in stabilization of the platform.

Introduction
Rationale:
The David by Michelangelo is an iconic sculpture of the male nude by Michelangelo. Despite being one of the most important symbols of the Renaissance, many don't know that it is in danger of falling over. The center of gravity of the statue is different than the center of gravity of the base. Thus, there is tension on the sculpture's ankles, and hairline fractures have formed (Anderson). Over time, the state of the statue has reached such a poor condition, that if the statue were to be tilted 15 degrees in an earthquake, its ankles would fail (Corti et. al). Current stabilization techniques are similar to the ones used in buildings in San Francisco to prevent damage from earthquakes and cost upwards of $265,000 (Anderson). Electromagnetic stabilization would be a cost-effective solution that would involve the base detecting an earthquake with a gyroscope/accelerometer that reads the X, Y, and Z rotational values and the surface responding with movement in roll, pitch, and yaw (Invensense). The levitating square-shaped surface would consist of a magnet at each corner and the aforementioned

gyroscope. These values would be transmitted to an Arduino microcontroller chip (Diodes Incorporated, ON Semiconductor). Pulse Width Modulation uses a digital signal to control the current supplied to the 4 electromagnets in the base. Also, with four electromagnets and a 12 volt power supply, the structure can theoretically lift an 11 kg surface (Schmipf, Vogel). This structure can be scaled up to the much larger Statue of David with more voltage and electromagnets. The experiment will see if this stabilization system can successfully stabilize a model statue.

Assumptions:

- The acclerometer is an accurate measurement of tilt
- Tilting the apparatus and measuring the angle at which the model statue falls over is an accurate measure of stability
- The tilting will be consistent
- The Lego blocks are an accurate representation of the Statue of David because they both fall over at approximately 15 degrees of tilt

Objective: The apparatus will determine if an electromagnetic levitation apparatus can improve the stability of a statue as measured by the angle at which the model statue falls over and a possible explanation for why.

Expectations: The model statue that uses the apparatus will fall at a significantly greater angle than the model statue that doesn't use the apparatus. Thus, the apparatus will increase stability.

Hypotheses

Alternate Hypothesis (H_1): *With the levitation apparatus, the statue will tip over at a significantly greater angle than the statue without the apparatus*

Null Hypothesis (H_0): There will not be a significant difference in the angles that the statue tips over with the levitation apparatus and without the apparatus.

Methodology

Materials/Equipment/Facilities

Name of Material	Source	Cost
2 6in x 6in x 0.75 Wood	High Technology High School Tech Lab	$0.00
2 6in x 8.5 in x 0.75 Wood	High Technology High School Tech Lab	$0.00
2 8in x 6in x 0.75 Wood	High Technology High School Tech Lab	$0.00
4 ⅝-11 x 6 Galvanized Iron Bolts	Student Researcher (http://www.homedepot.com/p/Everbilt-5-8-in-x-6-in-Galvanized-Carriage-Bolt-10-Pack-803670/204281337)	$15.04
8 ½-11 x 1 Screws	Student Researcher	Previously Purchased
Colorful Disc Magnets (4-Pack)	Student Researcher (http://www.homedepot.com/p/MASTER-MAGNETICS-Assorted-Color-Disc-Magnet-4-Pack-96834/205203695)	$3.58
Remington Industries 24SNSP 24 AWG Magnet Wire, Enameled Copper Wire, 1.0 lb., 0.0221" Diameter, 803' Length, Red	Student Researcher (https://www.amazon.com/gp/product/B007OYG9HS/ref=oh_aui_detailpage_o05_s00?ie=UTF8&psc=1)	$16.40
Makerfire® Arduino GY-521 MPU-6050 Module 3 Axial Gyroscope Accelerometer Stance Tilt	Student Researcher (https://www.amazon.com/gp/product/B00NH8Z6BU/ref=oh_aui_detailpage_o01_s00?ie=UTF8&psc=1)	$7.99
Arduino Uno REV3 Board	Student Researcher (https://store-usa.arduino.cc/products/a000066)	$24.99
N-Channel MOSFET 60V 30A x4	Student Researcher (https://www.sparkfun.com/products/10213)	$3.80
6A05 Silicon Rectifier Diode	Student Researcher	$6.13

	(https://www.amazon.com/uxcell-1000V-Silicon-Rectifier-Diodes/dp/B0087ZT9T8/ref=sr_1_fkmr0_1?ie=UTF8&qid=1480117926&sr=8-1-fkmr0&keywords=6a05+diode+50v)	
RadioShack UL Hookup Wire 18AWG	Student Researcher (https://www.radioshack.com/products/ul-hookup-wire-18awg)	$9.99
LK-Spring Double Side Prototype PCB Universal Printed Circuit Board with 5 Sizes,20PCS	Student Researcher (https://www.radioshack.com/collections/breadboards-ic-sockets/products/radioshack-grid-style-pc-board-with-2200-holes)	$11.50
5/8 in. Galvanized Coarse Threaded Hex Nut	Studetnt Researcher (http://www.homedepot.com/p/Everbilt-5-8-in-Galvanized-Coarse-Threaded-Hex-Nut-804086/204647895?MERCH=REC-_-SearchPLPHorizontal1_rr-_-NA-_-204647895-_-N)	$1.80
Dual Row 6 Position Terminal Strips	Student Researcher (https://www.radioshack.com/products/radioshack-6-position-dual-row-barrier-strips)	$2.99
Heat Sink Transistor Mounts x4	Student Researcher (https://www.radioshack.com/products/to-220-mounting-hardware)	$7.96
RadioShack TO-220/TO-202 Heat Sink x4	Student Researcher (https://www.radioshack.com/products/to-220-to-202-heat-sink)	$9.96
Grand General 55230 Black 16-Gauge Primary Wire	Student Researcher (https://www.amazon.com/gp/product/B00INVEQB2/ref=oh_aui_detailpage_o03_s00?ie=UTF8&psc=1	$6.45
eTopxizu 12v 30a Dc Universal Regulated Switching Power Supply 360w	Student Researcher (https://www.amazon.com/gp/product/B00D7CWSCG/ref=oh_aui_detailpage_o03_s00?ie=UTF8&psc=1)	$17.96
PIXNOR 1/4W Resistor Kit 56 Values x 20pcs =1120pcs (1ohm-10Mohm) Metal Film Resistors Assortment	Student Researcher (https://www.amazon.com/gp/product/B00SD6F6FC/ref=oh_aui_detailpage_o05_s01?ie=UTF8&psc=1)	$10.99
SunFounder DC 9V/650mA Power Plug Adapter for Arduino UNO R3 Mega 2560 1280 (3 Feet)	Student Researcher (https://www.amazon.com/gp/product/B00F4UURCM/ref=oh_aui_detailpage_o00_s00?ie=UTF8&psc=1)	$5.99
4 2 x 4 Lego Blocks	Student Researcher	Previously Purchased

	(https://www.amazon.com/LEGO-Parts-Pieces-Yellow-Bright/dp/B015RSIMJU/ref=sr_1_1?ie=UTF8&qid=1481236034&sr=8-1&keywords=2+x+4+lego)	
StarTech PC Mounting Computer Screws M3 x 1/4-Inches Long Standoff - 50 Pack SCREWM3	Student Researcher (https://www.amazon.com/gp/product/B00032Q1J4/ref=oh_aui_detailpage_o06_s00?ie=UTF8&psc=1)	Previously Purchased

<u>Name of Equipment</u>	<u>Source</u>	<u>Cost</u>
Band Saw	High Technology High School Tech Lab	Borrowed
Drill Press	High Technology High School Tech Lab	Borrowed
12 in Ruler	Student Researcher	Previously Purchased
Hand Drill	High Technology High School	Borrowed
Hand Sander	Student Researcher	Previously Purchased
5/8 in Bit, ½ in Bit and ¾ in Bit	Student Researcher	Previously Purchased
Phillips and Slotted Screwdriver	Student Researcher	Previously Purchased
Printer	Student Researcher	Previously Purchased
Autodesk Inventor 2016	Student Researcher	Previously Installed
Etekcity MSR-R500 Digital Multimeter, Volt Amp Ohm Meter with Diode and Continuity Test, Red	Student Researcher	Previously Purchased
Scotch Tape	Student Researcher	Previously Purchased
Gorilla Glue	Student Researcher	Previously Purchased
Laptop with Arduino Software	Student Researcher	Previously Purchased
Sandpaper	High Technology High School Tech Lab	Borrowed
Electric Tape	Student Researcher	Previously Purchased
Heat Sink Silicone-Based Compound	Student Researcher (https://www.radioshack.com/products/caig-laboratories-heat-sink-silicone-grease)	$2.99
Dual Row 6 Position Terminal Strips	Student Researcher (https://www.radioshack.com/products/radioshack-6-position-dual-row-barrier-strips)	$2.99

DMiotech 0.8mm 100G Lead Free Rosin Core 1.8% Soldering Solder Wire Roll Reel	Student Researcher (https://www.amazon.com/gp/product/B015DM18KU/ref=oh_aui_detailpage_o05_s00?ie=UTF8&psc=1)	$9.21
Vastar 60W 110V Adjustable Temperature Black Welding Soldering Iron with 5pcs Different Tips, Desoldering Pump, Stand, Anti-static Tweezers and additional Solder Tube for Variously Repaired Usage	Student Researcher (https://www.amazon.com/gp/product/B01547OES2/ref=oh_aui_detailpage_o05_s00?ie=UTF8&psc=1)	$14.99
SE MZ109 Soldering Station with Helping Hand, 2-1/2" Dia. Lens	Student Researcher (https://www.amazon.com/gp/product/B0007MF0W4/ref=oh_aui_detailpage_o05_s02?ie=UTF8&psc=1)	$5.49
Thermaltronics TMT-TC-2 Lead Free Tip Tinner (20g) in 0.8oz Container	Student Researcher (https://www.amazon.com/gp/product/B00NS4J6BY/ref=oh_aui_detailpage_o03_s01?ie=UTF8&psc=1)	$7.95
Hakko 599B-02 Solder Tip Cleaning Wire and Holder	Student Researcher (https://www.amazon.com/gp/product/B00FZPGDLA/ref=oh_aui_detailpage_o03_s01?ie=UTF8&psc=1)	$9.14
T Square	High Technology Tech Lab	Borrowed
Wire Stripper	Student Researcher	Previously Purchased
Surge Protector	Student Researcher	Previously Purchased
110v power source/wall outlet	Student Researcher	Previously Obtained
Vice Grip	High Technology Tech Lab	Borrowed
USB 2.0 Arduino Cable	Student Researcher (https://www.amazon.com/AmazonBasics-USB-2-0-Cable-Male/dp/B00NH11KIK/ref=sr_1_3?ie=UTF8&qid=1481235738&sr=8-3&keywords=usb+2.0+cable)	Previously Purchased

Needed Area	Name of Facility/Availability
Basement	Student Researcher’s House
Tech Lab	High Technology High School Tech Lab

Total Price: $213.43

Experimental Design Diagram:

Title	The Effect of an Electromagnetic Levitation Apparatus on Stability of Model Statue
Hypothesis	**Alternate/Research** *With the levitation apparatus, the statue will tip over at a significantly greater angle than the statue without the apparatus.* **Null** There will not be a significant difference in the angles that the statue tips over with the levitation apparatus and without the apparatus.
Independent Variable	Whether the levitation apparatus is used.

Levels	Without Levitation Apparatus	With Levitation Apparatus
# trials:	12	12
Control?	control	

repeated trials-12+12=24

Dependent Variable	Angle at which the model statue tips over
Operational Definition of Dependent Variable	Angle in degrees at which the model statue tips over as shown by the gyrometer/accelerometer
Constants	Model Statue (4 2x4 Lego Blocks: see Materials List) Angle increments when testing (1 degree) Construction of wooden structure (See Figure 5) Circuitry and Coding (see Figures 8 and 9 and code below) Gyrometer/Accelerometer (MPU-6050) Environment (Basement) Experimental Method (see Methodology)

Experimental Setup, Graphics, Illustrations

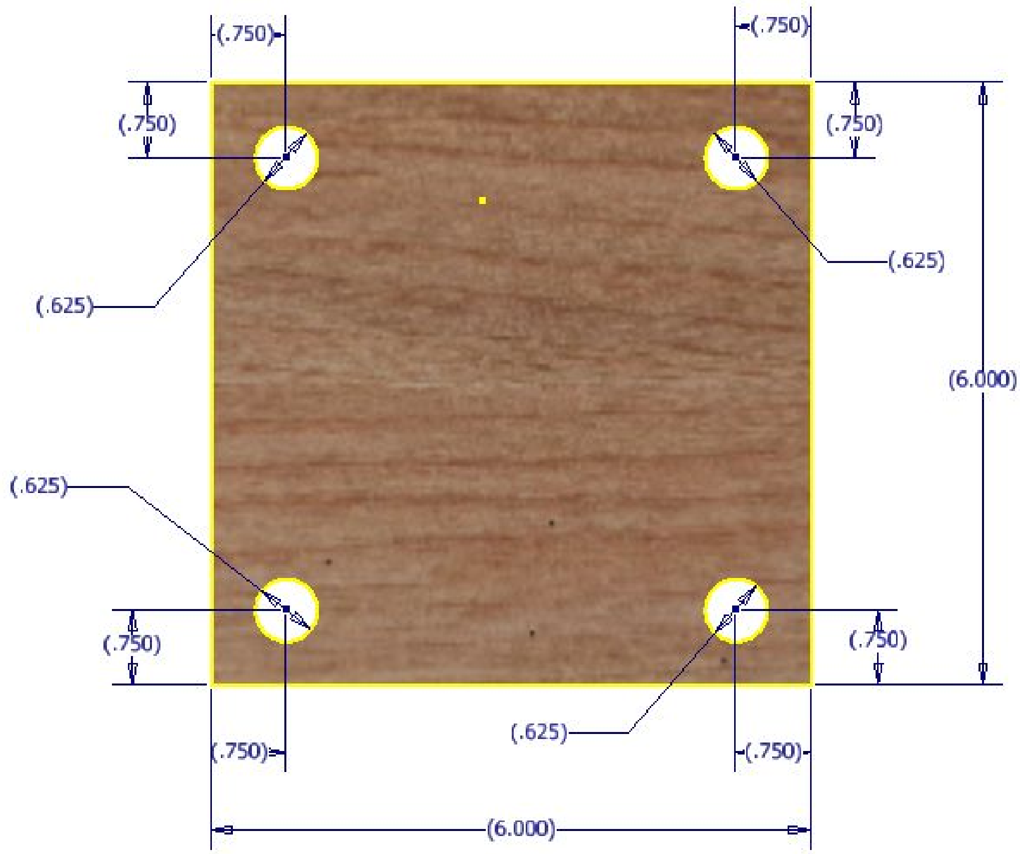

Figure 1: Computer Model of Dimensions of Base and Holes of Apparatus

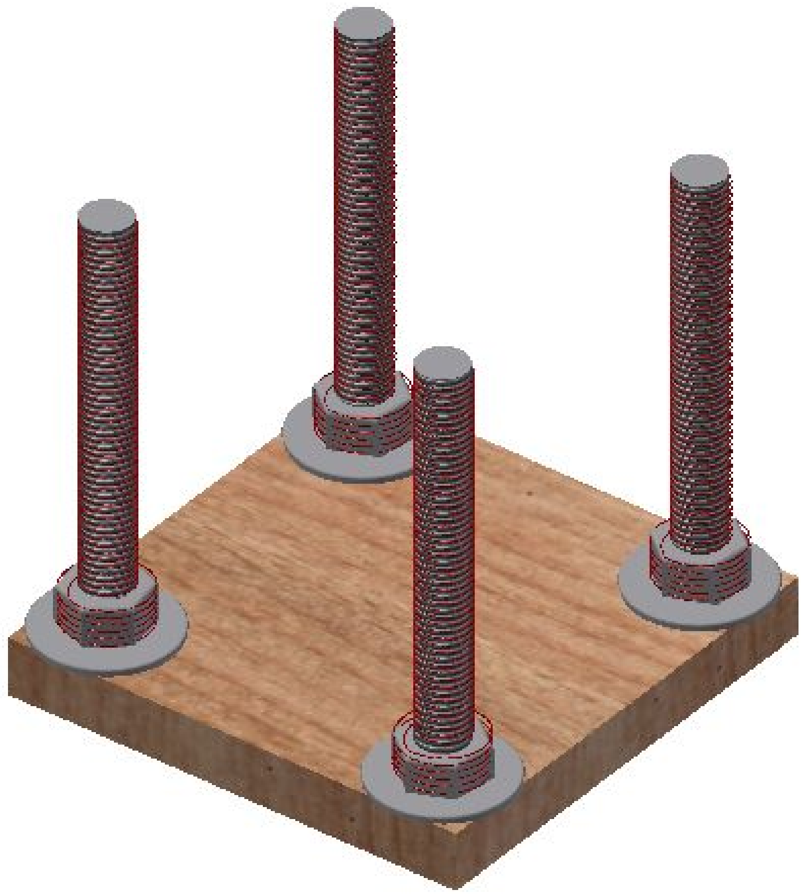

Figure 2: Computer Model of Base Assembled with Bolts and Solenoids

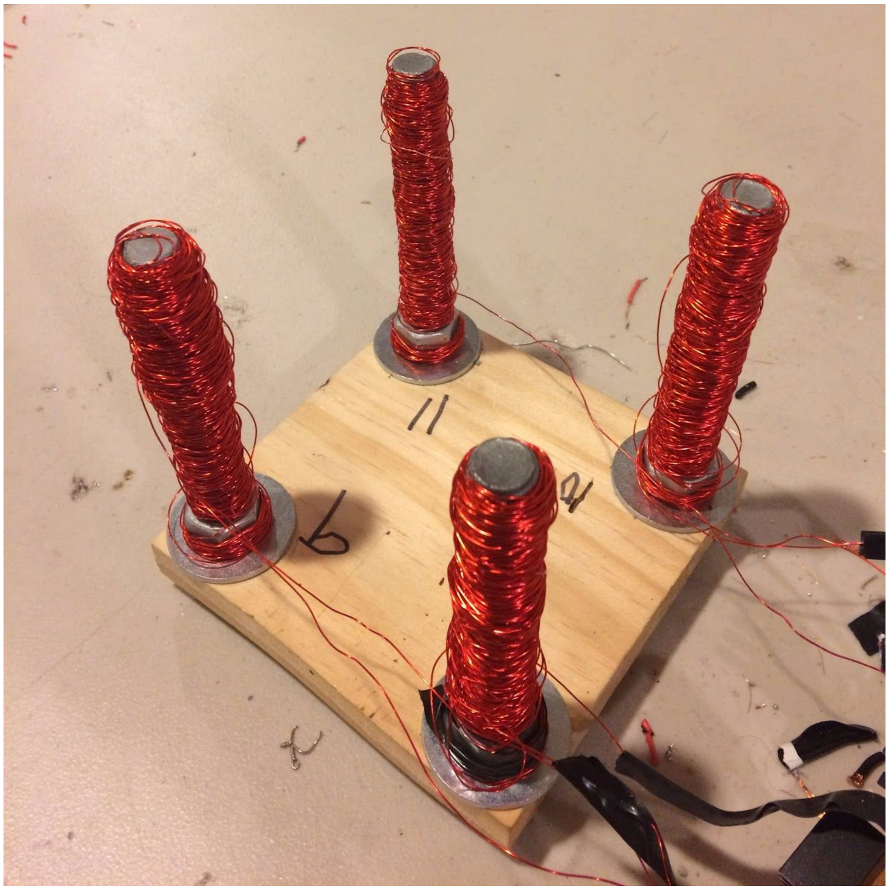

Figure 3: Image of the Base Assembled with Bolts and Solenoids

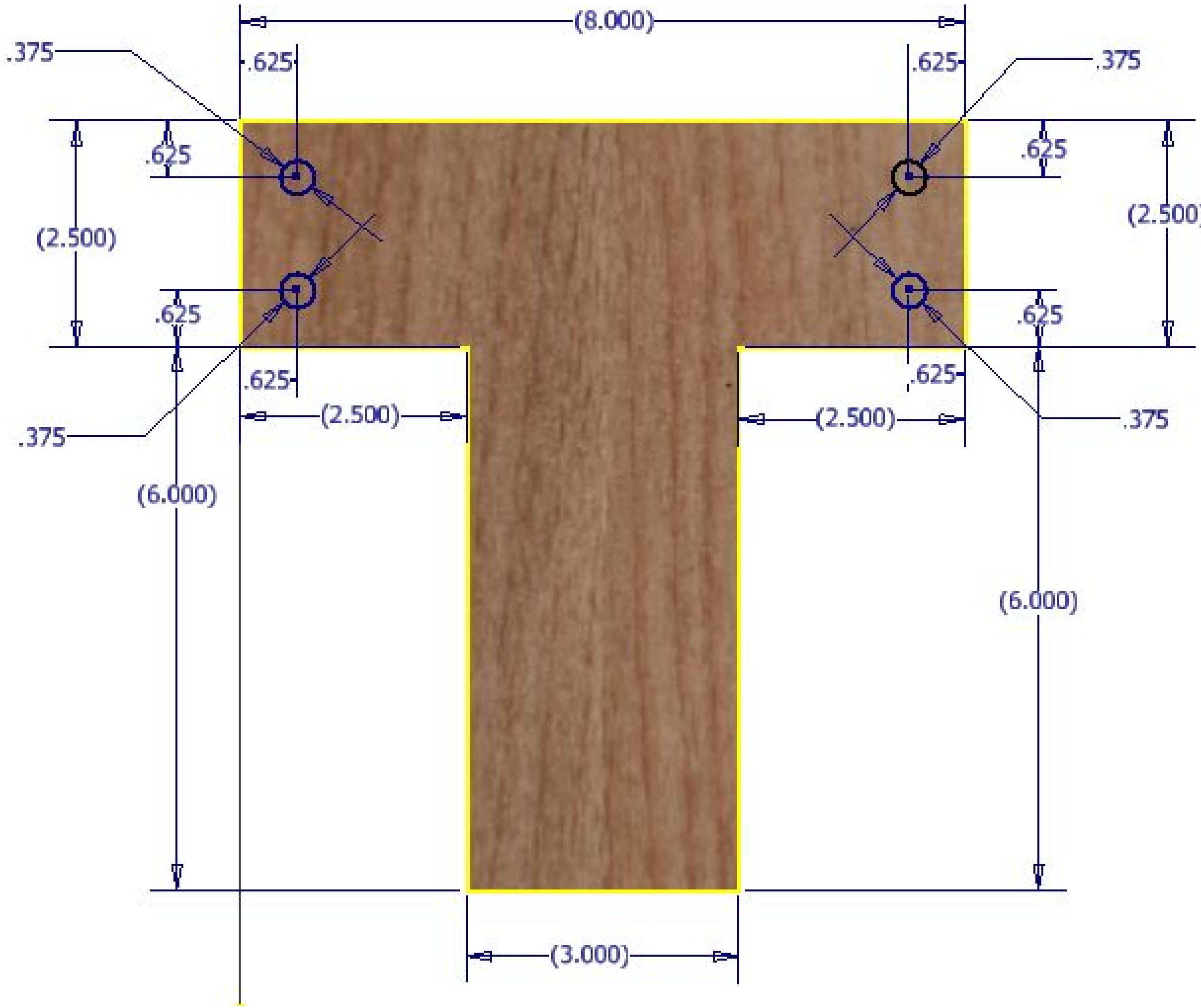

Figure 4: Computer Model of Dimensions for Wide "T" Wall and Placement of Screws

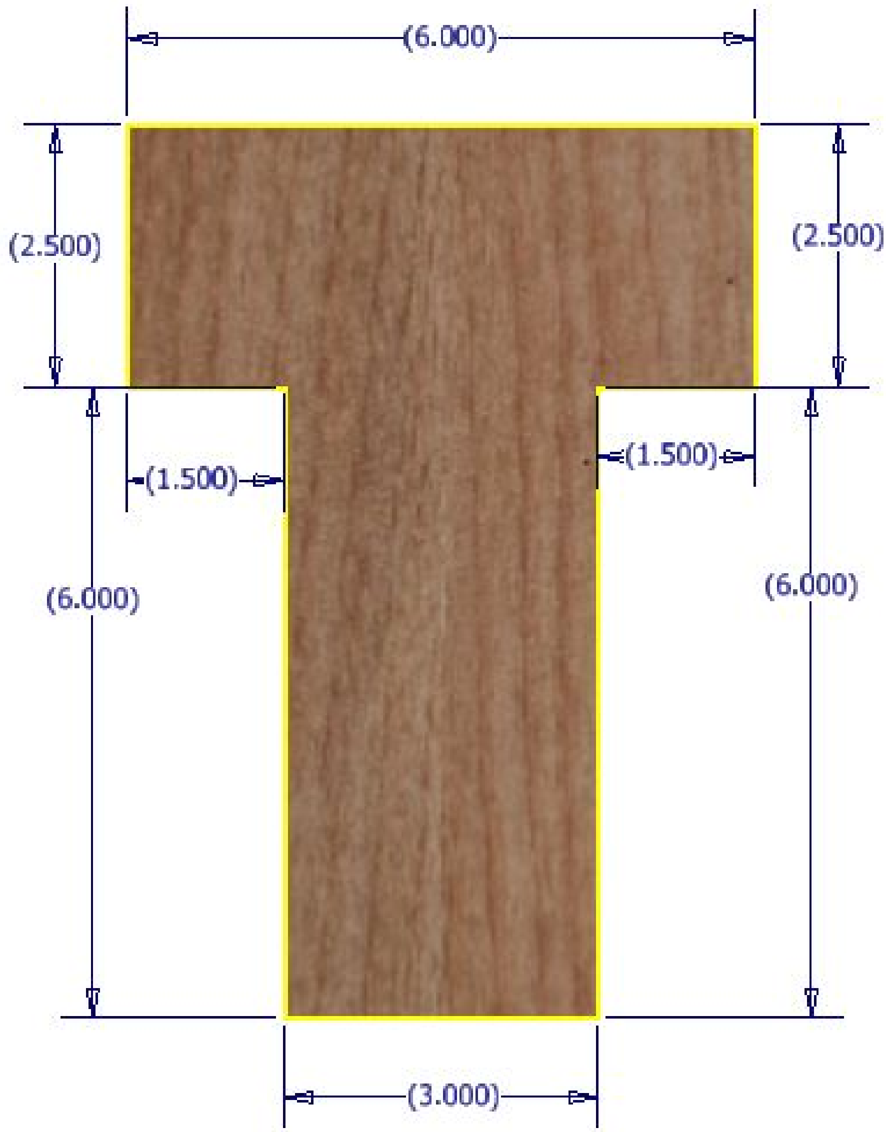

Figure 5: Computer Model of Dimensions for Narrow “T” Wall

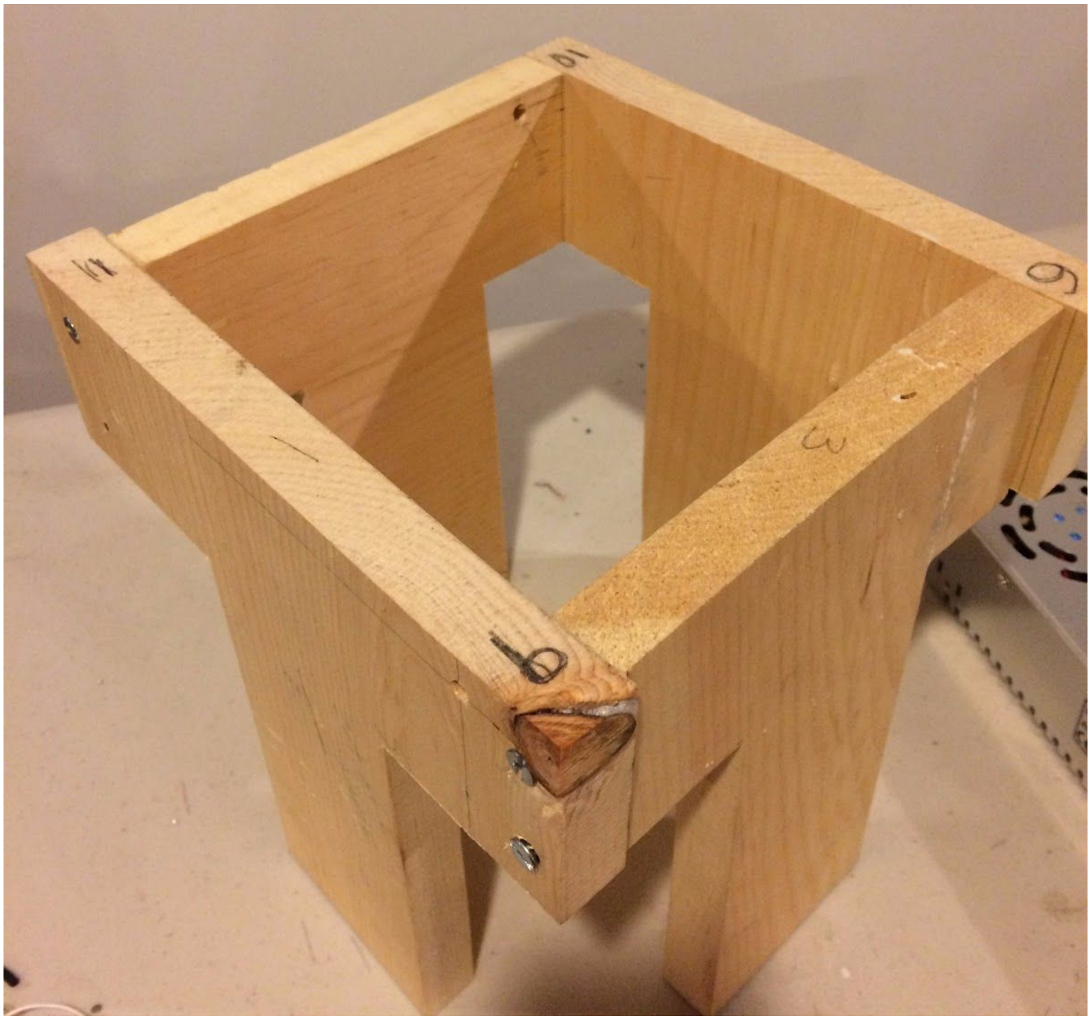

Figure 6: Image of Assembled Walls

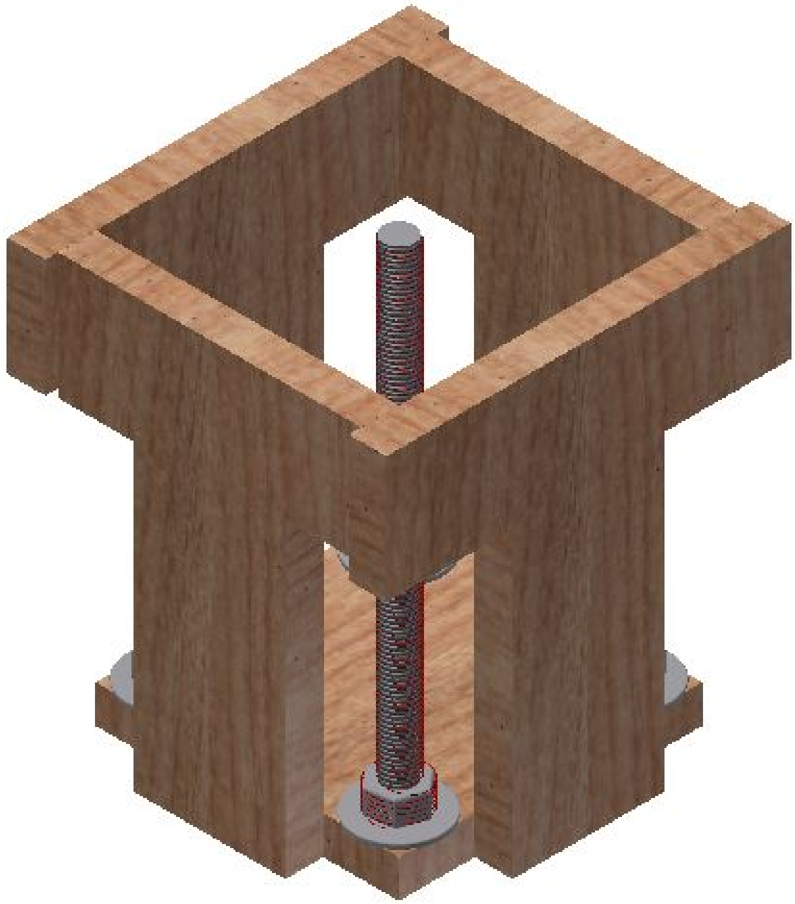

Figure 7: Computer Model of Complete Base with Walls

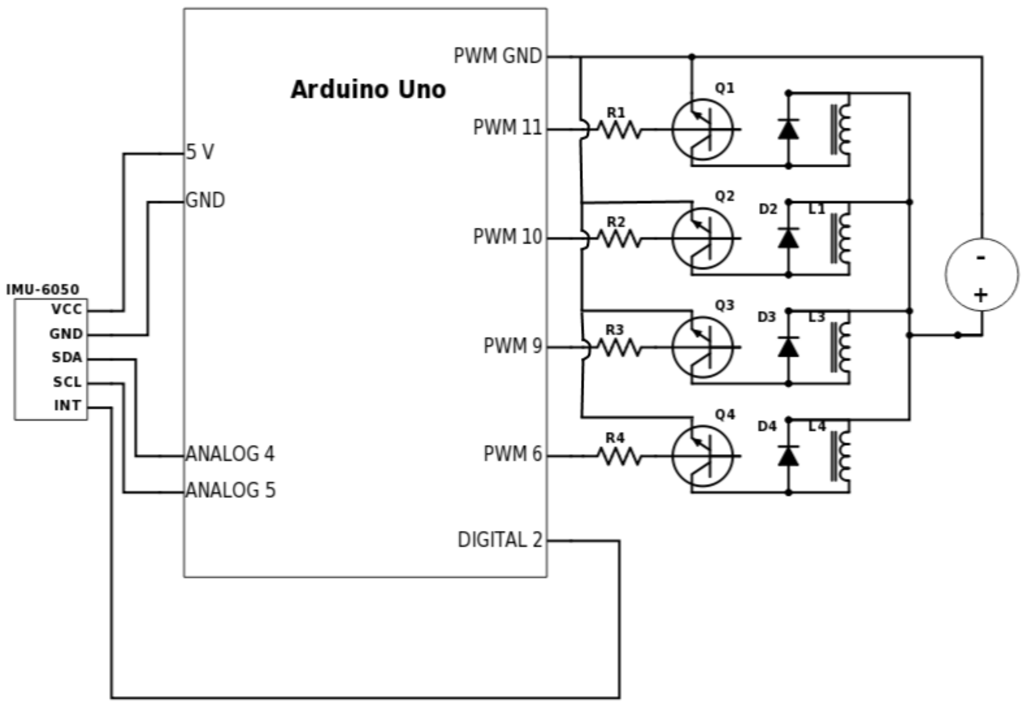

Figure 8: Schematic of Wiring

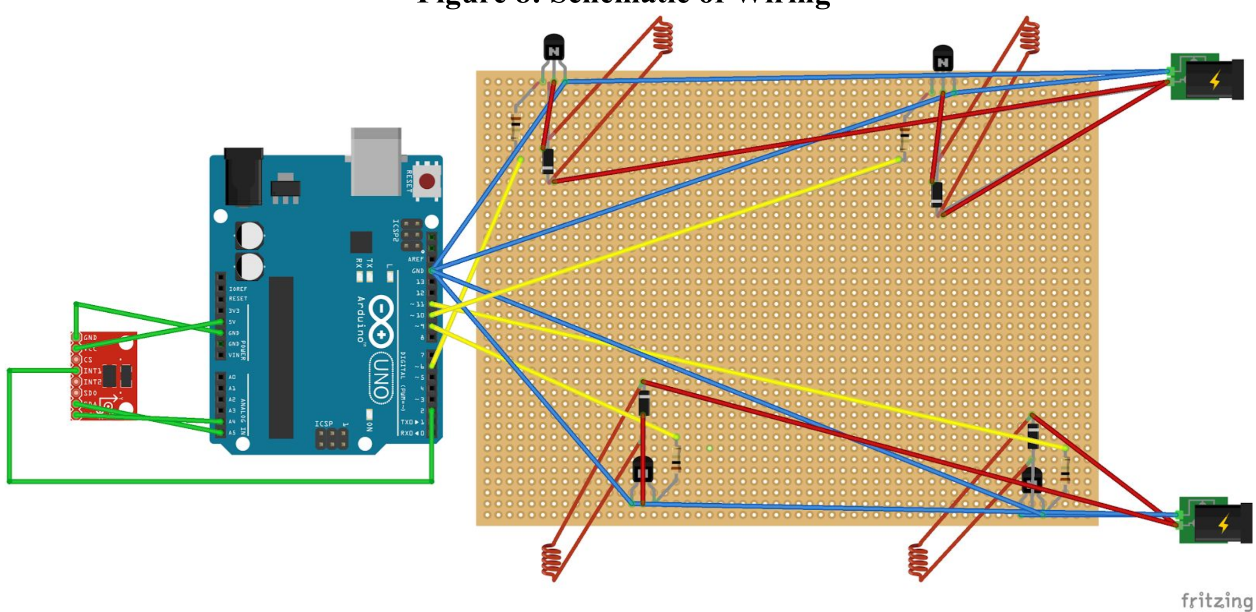

Figure 9: Circuit Diagram Drawn Using Fritzing

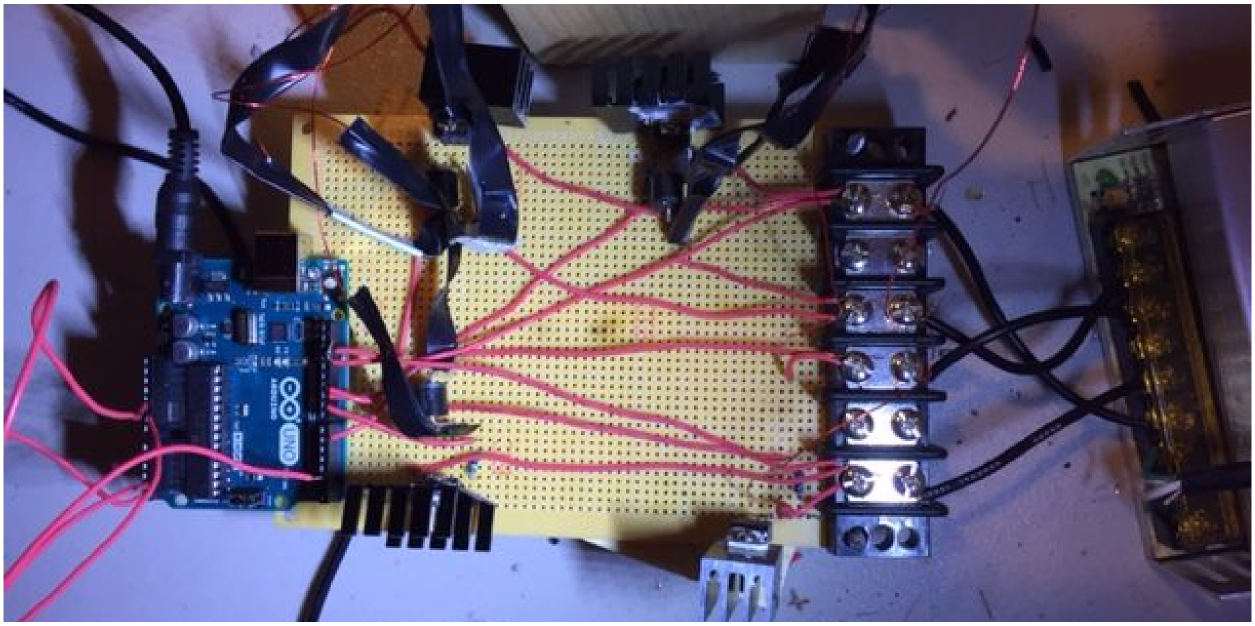

Figure 10: Image of the Circuitry

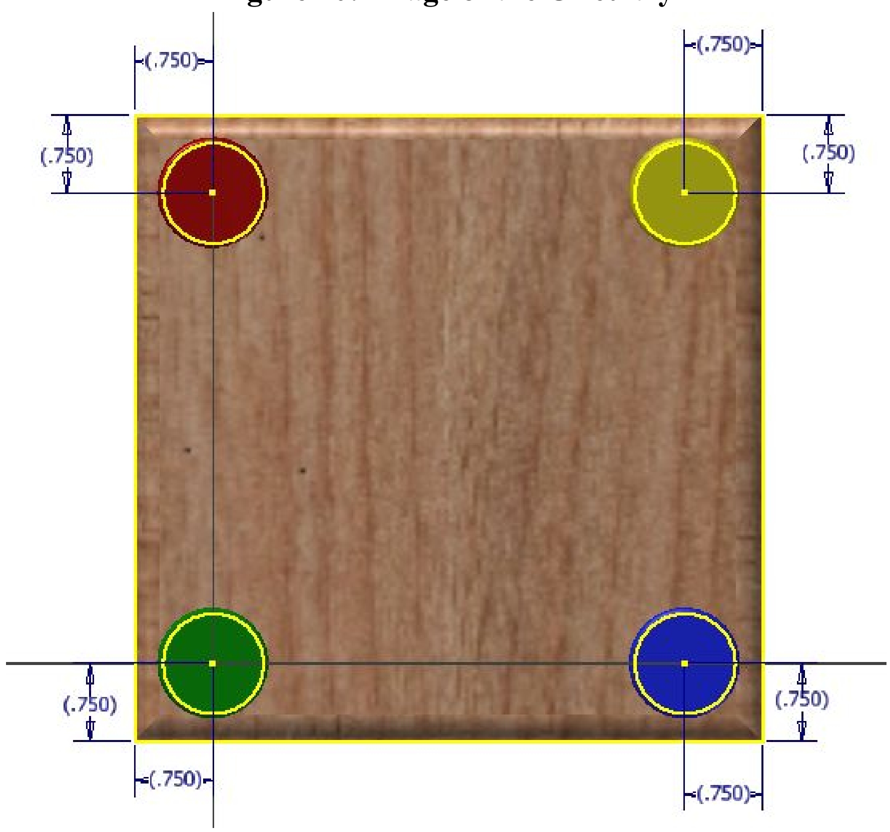

Figure 11: Comuter Model of Dimensions of Levitating Surface with Magnets

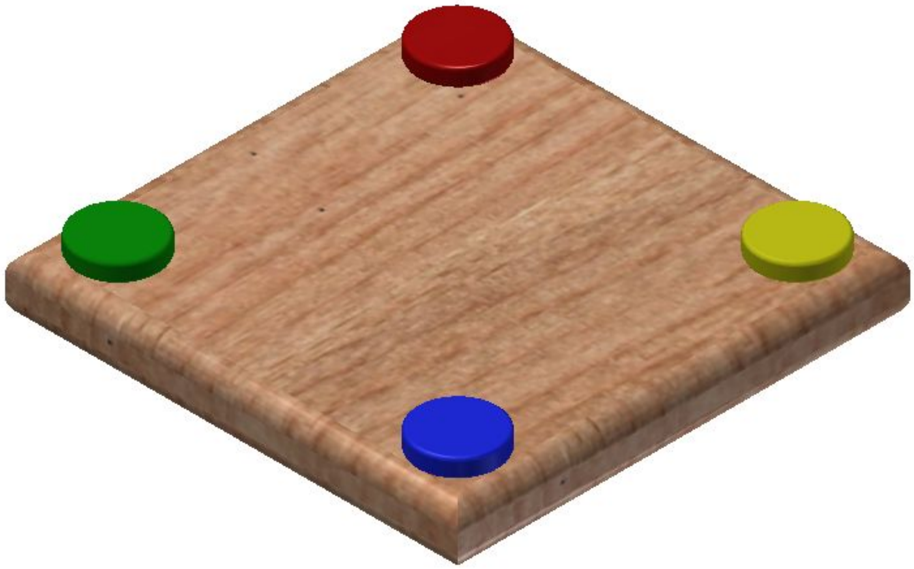

Figure 12: Computer Model of Levitating Surface

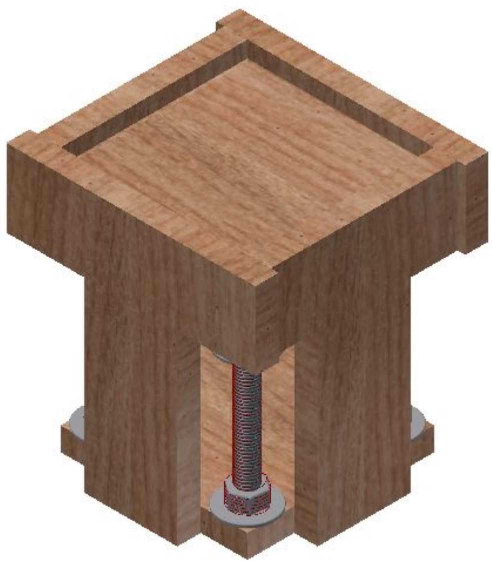

Figure 13: Computer Model of Finished Structure

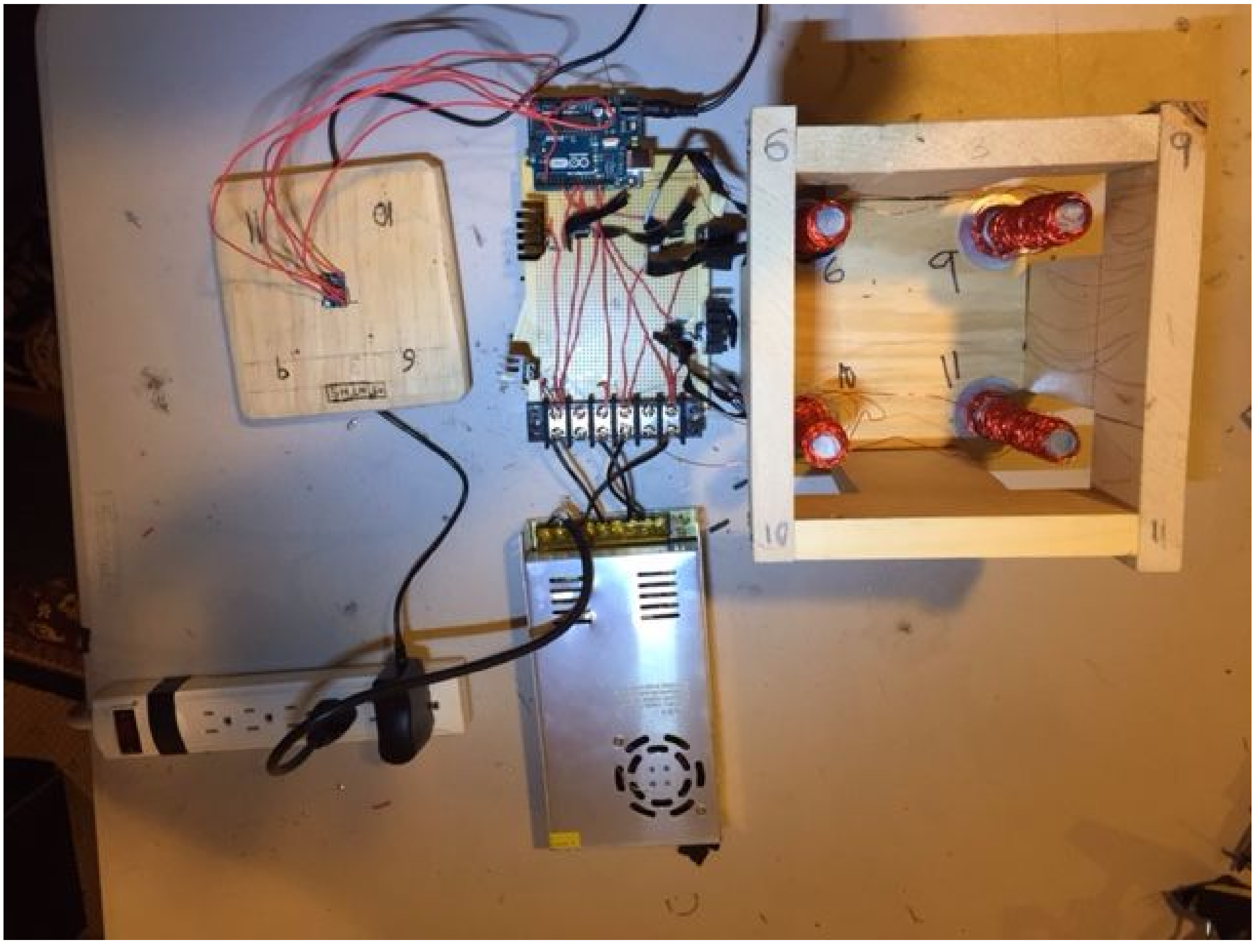

Figure 14: Image of Completed Apparatus

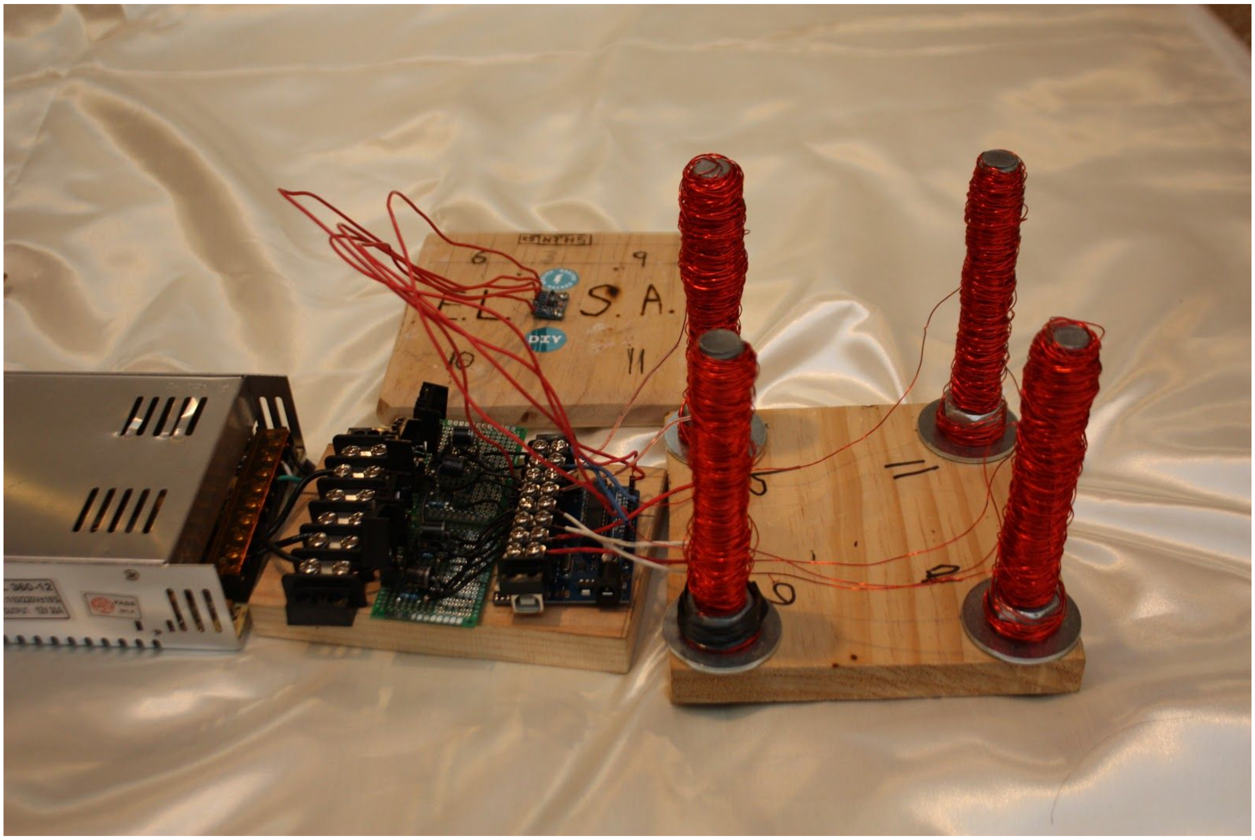

Figure 15: Final Product Side View

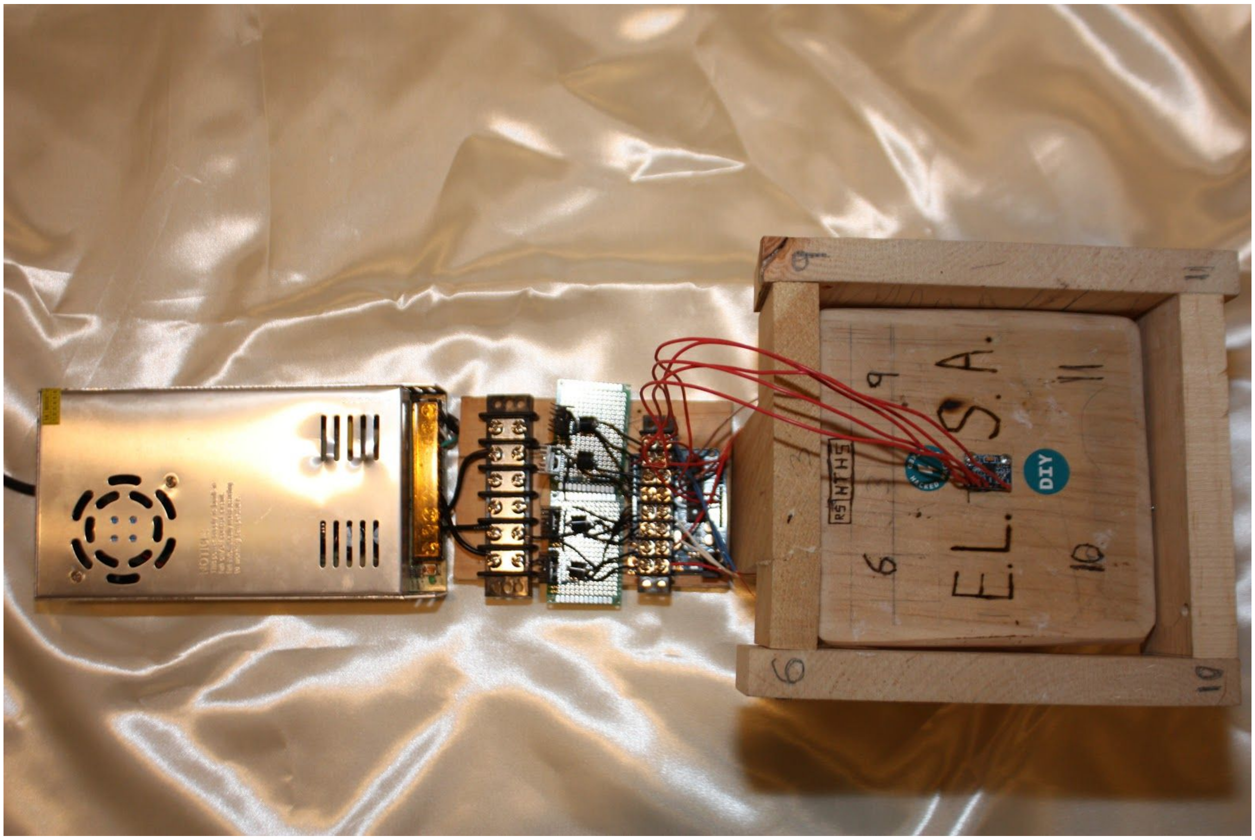

Figure 16: Final Product Top View

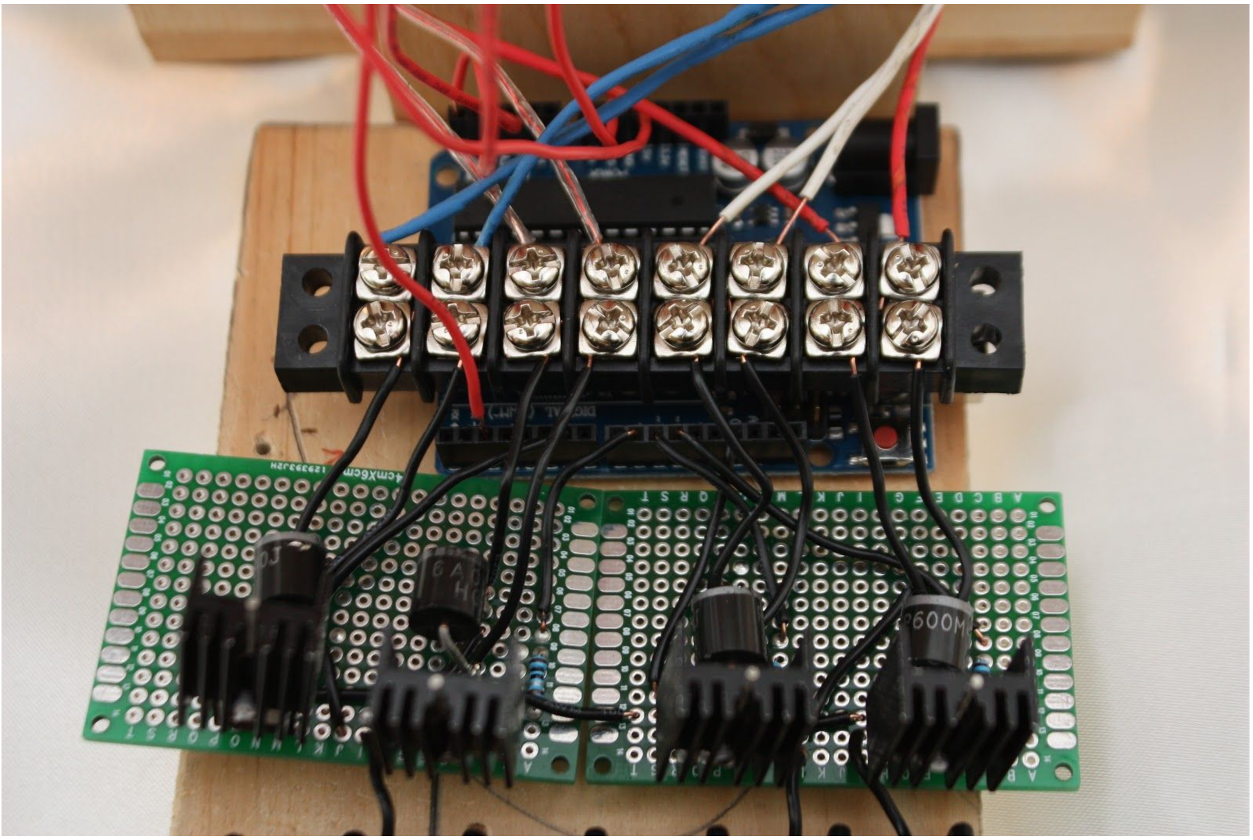

Figure 17: Final Product's Circuit

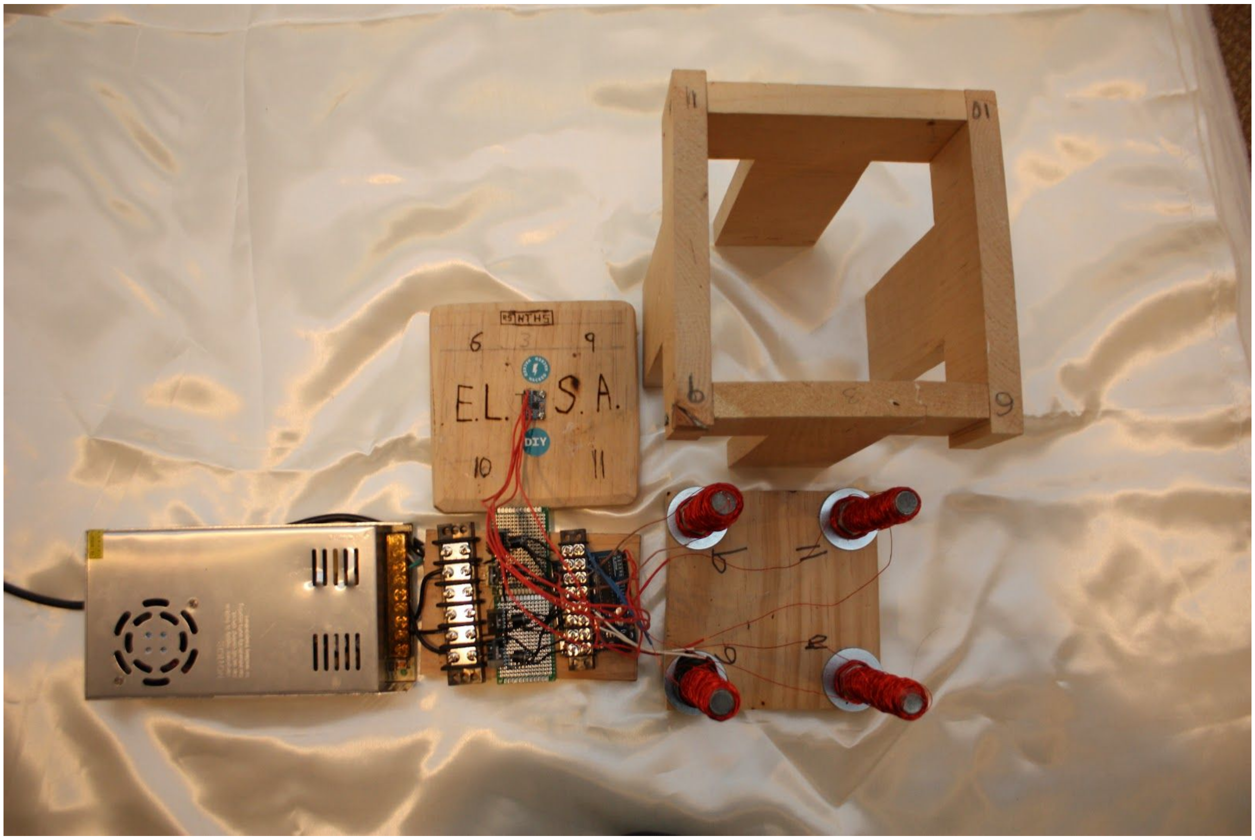

Figure 18: Final Product Top View Deconstructed

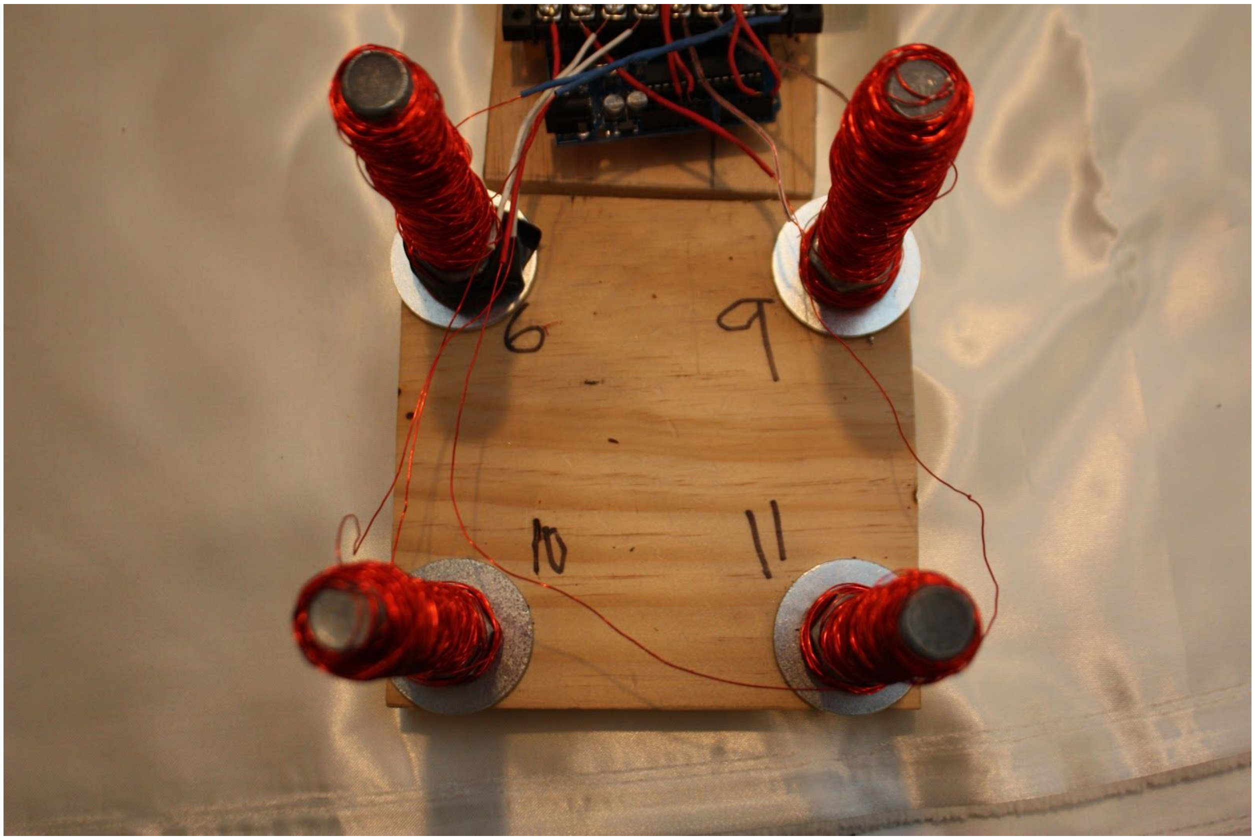

Figure 19: Final Product Electromagnets

Methodology: Procedure

Construction of Base

1. Go to an open area, put on safety goggles, and long pants. Tie back any long hair
2. Obtain the 6 in x 6 in wooden block and the ⅝ in drill bit.
3. Mark off parallel lines 0.75 in from each edge of the block (see Figure 1)
4. The intersections of the 4 lines should make four crosses. Drill 4 holes at these intersections using the ⅝ in drill bit and the drill press. (see Figure 1)
5. Obtain the four 6 in bolts. Thread the four bolts through the holes.
6. Thread the four washers through the bolts.
7. Twist the ⅝ in nut on the narrow end of the bolt until the nut is flush with the washer. (See Figure 2)

Construction of Electromagnet

1. Obtain the copper wire.
2. Using electric tape, tape the copper wire to the edge of the base leaving 12 inches of wire (use a ruler) for circuitry.
3. Start wrapping the wire around one of the nuts of the base. Complete 50 revolutions.
4. Start wrapping the wire while following the threads of the corresponding bolt.
5. When you hit the top of the bolt, temporarily electric tape the wire to the top of the bolt.
6. Bring the wire to the top of the nut.
7. Complete 1 revolution following the threads of the bolt.
8. Remove the electric tape.
9. Repeat steps 4-8 10 times.
10. Leave 12 inches of wire (use a ruler) and cut the wire using wire cutters.
11. Using sand paper, sand off the edges of both sides of the wire until the silver interior of the wire shows.
12. Repeat steps 2-11 on the other three bolts.

Construction of the Walls

Note: When using a band saw or drill press, make sure to wear safety goggles, clear the area, and be extremely careful.

1. Obtain a 8 in x 8.5 in x 0.75 in block of wood.
2. Mark 2 lines 2.5 in from the two longer edges with a t-square.
3. Mark a line 2.5 inches from the top of the wood.
4. This should divide the wood into six regions. Using a band saw, cut out the bottom left and bottom right portion to make a “T” shape. (See Figure 4)
5. Mark lines 0.625 inches from each of the longer edges.
6. Mark lines 0.625 inches and 1.375 inches from the top. This will create 4 intersections (see Figure 4)
7. Repeat steps 1-6 on another piece of wood
8. Obtain a 6 in x 8.5 in x 0.75 in block of wood.
9. Mark 2 lines 1.5 in from the two longer edges.
10. Mark a line 2.5 inches from the top of the wood.
11. This should divide the wood into six regions. Using a band saw, cut out the bottom left and bottom right portions to make a “T” shape. (See Figure 5)
12. Repeat steps 8-11 on another piece of wood.

13. Use a vice grip to clamp one of the wider walls with the narrow ones as shown in Figure 4
14. Drill a ½ in hole with the ½ in drill bit at the two intersections made in step 6 using a drill press.
15. Repeat steps 13-14 on the other 3 sides of the 2 walls.
16. Use the slotted screwdriver to screw 8 ½-11 x 1 screws into the 8 newly made holes. It should now look like Figure 6.
17. Place the structure of 4 walls on the base (see Figure 7).

Circuitry/Wiring (see Figures 8 and 9)

1. Obtain 4 transistors, 4 6 amp diodes, 4 1 Ω resistors, 18 gauge wire, the 6 row terminal, the 12 volt power source, the perfboard, and the Arduino.
2. Connect the parts as shown in Figures 8 and 9 (the 2 power sources represent the positive and negative coming in from the 12 volt power source going into the 6 row terminal).
3. Connect the base wires of the electromagnets into the black side of the diodes and the top wires of the electromagnet into the white sides.
4. Solder 5 wires to the shown pins on the MPU-6050, and connect it as shown in Figures 8 and 9. In addition, solder all wires down in the perfboard. When soldering, be extremely careful. Make sure the iron doesn't touch your skin. Use safety goggles and tie back long hair
5. Plug in the 12 volt power source into the power surge as shown in Figure 10.

Levitating Structure

1. Mark off four lines 0.75 inches from the edges of a 6 in x 6 in wood (see Figure 11).
2. Mark off two diameters on each 1 inch magnet.
3. Line up the intersection of the diameters with the intersections of the lines (see Figure 11).
4. To find the orientation of the magnets, temporarily turn on the electronics to see which side repels the magnets.
5. Use gorilla glue to glue the magnets to the surface.
6. Using a hand sander, sand a 0.25 inch fillet on all 8 6 inch sides of the wood.
7. Use the mounting screws and phillips screwdriver to attach the gyrometer to the center of the surface. (see Figure 14)
8. Place the surface in the walls (see Figure 13)

Code

1. Open a laptop with the Arduino software (https://www.arduino.cc/en/Main/Software).
2. Download the code from https://github.com/stressmaniac/Electromagnet-2016 or copy the code below
3. Connect the Arduino to the laptop using the USB 2.0 cable.
4. Press the upload button on the software.
5. Plug in the surge protector into an outlet and turn on the surge protector.

Experiment

1. Attach 4 2 x 4 lego blocks together to model the statue. Make sure all the sides are flush.
2. Turn off the surge protector
3. Place the model statue flush with the gyrometer.
4. Begin tilting the structure towards you until the lego structure falls over.

5. Record the angle in the “z” column of the Serial Monitor in the Without Apparatus column.
6. Repeat steps 2-4 11 more times.
7. Turn on your surge protector.
8. Place the model statue flush with the gyrometer.
9. Begin tilting the structure towards you until the lego structure falls over.
10. Turn off your surge protector.
11. Record the angle in the “z” column of the Serial Monitor in the With Apparatus column.
12. Repeat steps 8-11 11 more times.
13. Analyze data.

Program for Reference

```
#include "I2Cdev.h"



#include "MPU6050_6Axis_MotionApps20.h"
#if I2CDEV_IMPLEMENTATION == I2CDEV_ARDUINO_WIRE
   #include "Wire.h"
#endif
MPU6050 mpu;
#define OUTPUT_READABLE_YAWPITCHROLL
#define LED_PIN 13 // (Arduino is 13, Teensy is 11, Teensy-- is 6)
bool blinkState = false;



// MPU control/status vars
bool dmpReady = false;  // set true if DMP init was successful
uint8_t mpuIntStatus;   // holds actual interrupt status byte from MPU
uint8_t devStatus;      // return status after each device operation (0 = success, !0 = error)
uint16_t packetSize;    // expected DMP packet size (default is 42 bytes)
uint16_t fifoCount;     // count of all bytes currently in FIFO
uint8_t fifoBuffer[64]; // FIFO storage buffer



// orientation/motion vars
Quaternion q;           // [w, x, y, z]         quaternion container
VectorInt16 aa;         // [x, y, z]            accel sensor measurements
VectorInt16 aaReal;     // [x, y, z]            gravity-free accel sensor measurements
VectorInt16 aaWorld;    // [x, y, z]            world-frame accel sensor measurements
VectorFloat gravity;    // [x, y, z]            gravity vector
float euler[3];         // [psi, theta, phi]    Euler angle container
```

```
float ypr[3];           // [yaw, pitch, roll]   yaw/pitch/roll container and gravity vector


// packet structure for InvenSense teapot demo
uint8_t teapotPacket[14] = { '$', 0x02, 0,0, 0,0, 0,0, 0,0, 0x00, 0x00, '\r', '\n' };
volatile bool mpuInterrupt = false;     // indicates whether MPU interrupt pin has gone high
void dmpDataReady() {
   mpuInterrupt = true;
}
void setup() {
 pinMode(6, OUTPUT);
 pinMode(9, OUTPUT);
 pinMode(10, OUTPUT);
 pinMode(11, OUTPUT);
 #if I2CDEV_IMPLEMENTATION == I2CDEV_ARDUINO_WIRE
       Wire.begin();
       TWBR = 24; // 400kHz I2C clock (200kHz if CPU is 8MHz)
   #elif I2CDEV_IMPLEMENTATION == I2CDEV_BUILTIN_FASTWIRE
       Fastwire::setup(400, true);
   #endif


   // initialize serial communication
   // (115200 chosen because it is required for Teapot Demo output, but it's
   // really up to you depending on your project)
   Serial.begin(115200);
   while (!Serial); // wait for Leonardo enumeration, others continue immediately


   // NOTE: 8MHz or slower host processors, like the Teensy @ 3.3v or Ardunio
   // Pro Mini running at 3.3v, cannot handle this baud rate reliably due to
   // the baud timing being too misaligned with processor ticks. You must use
   // 38400 or slower in these cases, or use some kind of external separate
   // crystal solution for the UART timer.


   // initialize device
   Serial.println(F("Initializing I2C devices..."));
   mpu.initialize();
```

```
    // verify connection
    Serial.println(F("Testing device connections..."));
    Serial.println(mpu.testConnection() ? F("MPU6050 connection successful") : F("MPU6050
connection failed"));


    // wait for ready
    //Serial.println(F("\nSend any character to begin DMP programming and demo: "));
    //while (Serial.available() && Serial.read()); // empty buffer
    //while (!Serial.available());                 // wait for data
    //while (Serial.available() && Serial.read()); // empty buffer again


    // load and configure the DMP
    Serial.println(F("Initializing DMP..."));
    devStatus = mpu.dmpInitialize();


    // supply your own gyro offsets here, scaled for min sensitivity
    mpu.setXGyroOffset(88);
    mpu.setYGyroOffset(42);
    mpu.setZGyroOffset(98);
    mpu.setZAccelOffset(1785); // 1688 factory default for my test chip


    // make sure it worked (returns 0 if so)
    if (devStatus == 0) {
        // turn on the DMP, now that it's ready
        Serial.println(F("Enabling DMP..."));
        mpu.setDMPEnabled(true);


        // enable Arduino interrupt detection
        Serial.println(F("Enabling interrupt detection (Arduino external interrupt 0)..."));
        attachInterrupt(0, dmpDataReady, RISING);
        mpuIntStatus = mpu.getIntStatus();
```

```
        // set our DMP Ready flag so the main loop() function knows it's okay to use it
        Serial.println(F("DMP ready! Waiting for first interrupt..."));
        dmpReady = true;


        // get expected DMP packet size for later comparison
        packetSize = mpu.dmpGetFIFOPacketSize();
    } else {
        // ERROR!
        // 1 = initial memory load failed
        // 2 = DMP configuration updates failed
        // (if it's going to break, usually the code will be 1)
        Serial.print(F("DMP Initialization failed (code "));
        Serial.print(devStatus);
        Serial.println(F(")"));
    }



    // configure LED for output
    pinMode(LED_PIN, OUTPUT);


}
double Out9=255;
double Out6=255;
double Out11=255;
double Out10=255;


void loop() {
 // put your main code here, to run repeatedly:
 while (true){
   mpuInterrupt = false;
     mpuIntStatus = mpu.getIntStatus();
     // get current FIFO count
     fifoCount = mpu.getFIFOCount();
     // check for overflow (this should never happen unless our code is too inefficient)
     if ((mpuIntStatus & 0x10) || fifoCount == 1024) {
         // reset so we can continue cleanly
```

```
    mpu.resetFIFO();
    Serial.println(F("FIFO overflow!"));
// otherwise, check for DMP data ready interrupt (this should happen frequently)
} else if (mpuIntStatus & 0x02) {
    // wait for correct available data length, should be a VERY short wait
    while (fifoCount < packetSize) fifoCount = mpu.getFIFOCount();
    // read a packet from FIFO
    mpu.getFIFOBytes(fifoBuffer, packetSize);

    // track FIFO count here in case there is > 1 packet available
    // (this lets us immediately read more without waiting for an interrupt)
    fifoCount -= packetSize;
// display Euler angles in degrees
    mpu.dmpGetQuaternion(&q, fifoBuffer);
    mpu.dmpGetGravity(&gravity, &q);
    mpu.dmpGetYawPitchRoll(ypr, &q, &gravity);
    /*Serial.print(ypr[1] * 180/M_PI);
    Serial.print("\t");
    Serial.println(ypr[2] * 180/M_PI);
    Serial.print("\t");*/
    if (ypr[1] * 180/M_PI+4.3>5) {
      //Serial.print("y is pos");
      if (Out9>=20){
        Out9--;
      }
      if (Out11>=20){
        Out11--;
      }
      if (Out6<255){
        Out6++;
      }
      if (Out10<255){
        Out10++;
      }
    }
    else if (ypr[1] * 180/M_PI+4.3<-5) {
      //Serial.print("y is neg");
      if (Out6>=20){
        Out6--;
      }
      if (Out10>=20){
```

```
    Out10--;
  }
  if (Out9<255){
    Out9++;
  }
  if (Out11<255){
    Out11++;
  }
}
else if (ypr[2] * 180/M_PI+1.7>5) {
  //Serial.print("z is pos");
  if (Out6>=20){
    Out6--;
  }
  if (Out9>=20){
    Out9--;
  }
  if (Out10<255){
    Out10++;
  }
  if (Out11<255){
    Out11++;
  }
}
else if (ypr[2] * 180/M_PI+1.7<-5) {
  //Serial.print("z is neg");
  if (Out10>=20){
    Out10--;
  }
  if (Out11>=20){
    Out11--;
  }
  if (Out9<255){
    Out9++;
  }
  if (Out6<255){
    Out6++;
  }
}
else {
  //Out10=255;
```

```
            //Out6=200;
            //Out9=200;
            //Out11=255;
          }
      }
      analogWrite(9,Out9);
      analogWrite(6,Out6);
      analogWrite(10,Out10);
      analogWrite(11,Out11);
      //analogWrite(9,255);
      //analogWrite(6,255);
      //analogWrite(11,255);
      //analogWrite(10,255);
      Serial.print(ypr[1] * 180/M_PI+4.3);
      Serial.print("\t");
      Serial.print(ypr[2] * 180/M_PI+1.7);
      Serial.print("\t");
      Serial.print(Out6);
      Serial.print("\t");
      Serial.print(Out9);
      Serial.println("\t\n");
      Serial.print(Out10);
      Serial.print("\t");
      Serial.print(Out11);
  //    Serial.print("\t\n");
  }
}
```

Findings: Observations/Data Tables/Graphs

Since the data involves a measurement of angle it is considered quantitative data.

Raw Data Table of Change in Angle in Degrees at Which The Model Statue Falls With and Without the Electromagnetic Levitation Stabilization Apparatus (°)

Trial Number	Without Apparatus (°)	With Apparatus (°)
1	14.03	24.39
2	13.67	24.81
3	14.12	23.89
4	13.87	23.39
5	13.73	25.42
6	14.23	24.69
7	14.86	25.09
8	14.92	24.99
9	14.23	24.85
10	14.67	25.66
11	14.03	24.54
12	15.07	25.17

Summative Data Table of Change in Angle in Degrees at Which The Model Statue Falls With and Without the Electromagnetic Levitation Stabilization Apparatus (°)

	Without Apparatus (°)	With Apparatus (°)
Mean	14.286	24.741
Median	14.175	24.83
Mode	14.03	N/A
Range	1.40	2.27
Std. Deviation	0.479	0.633
Variation	0.229	0.401
n	12	12

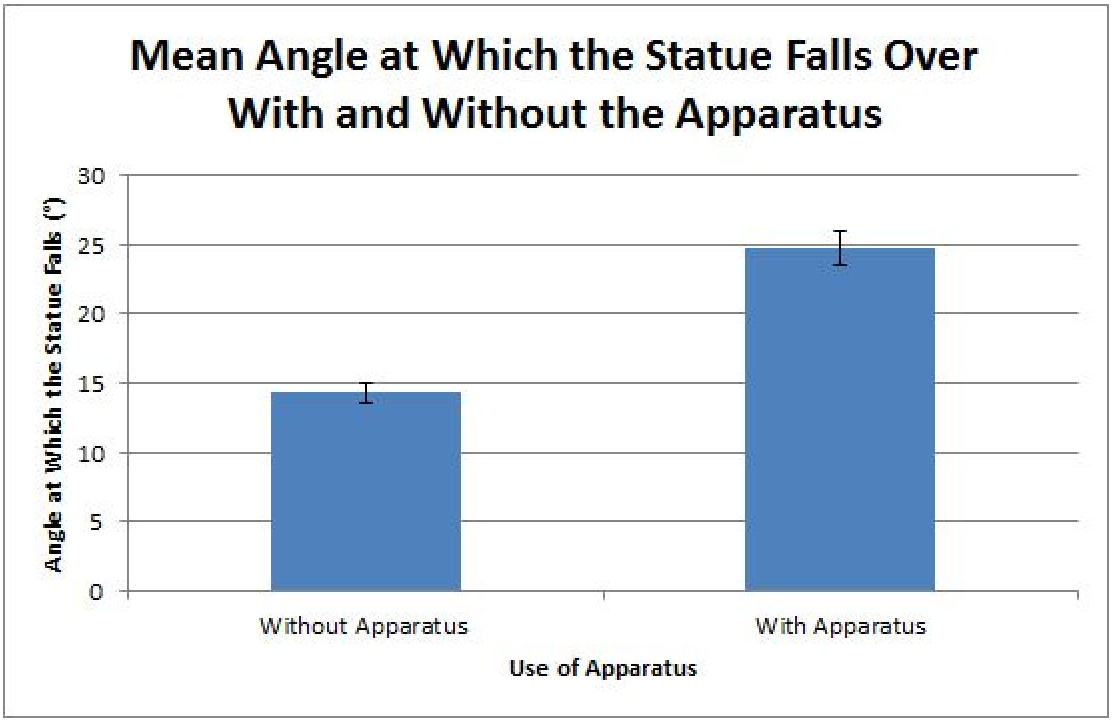

Figure 15: Graph of Mean Angles With and Without the Apparatus

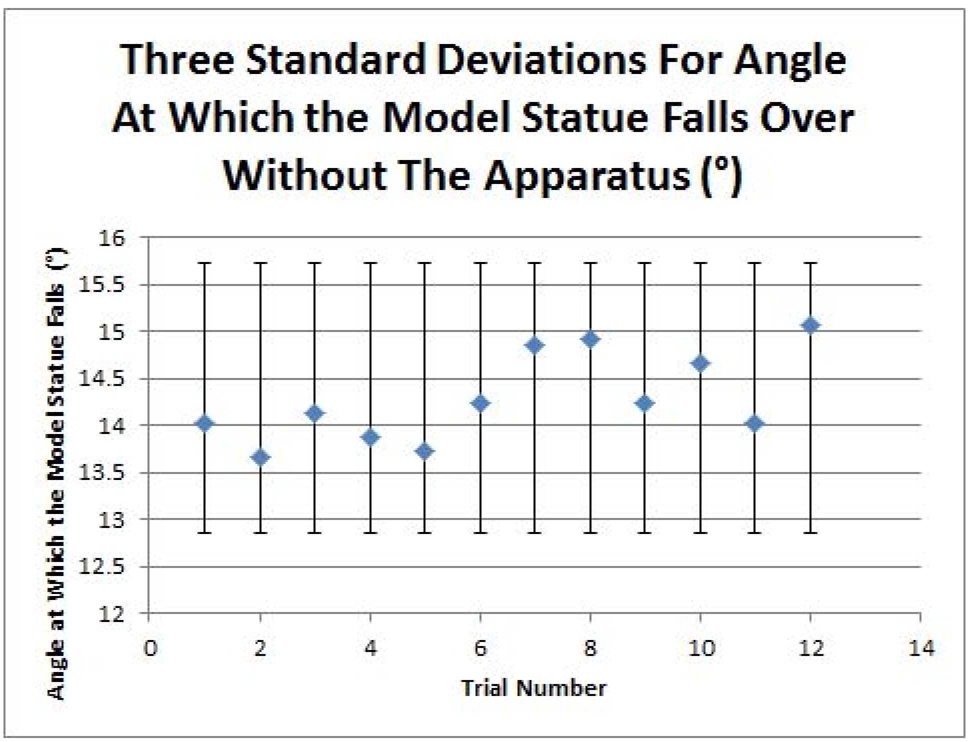

Figure 16: Three Standard Deviation Graphs for Angle at Which the Model Statue Falls Over Without the Apparatus

There are no outliers

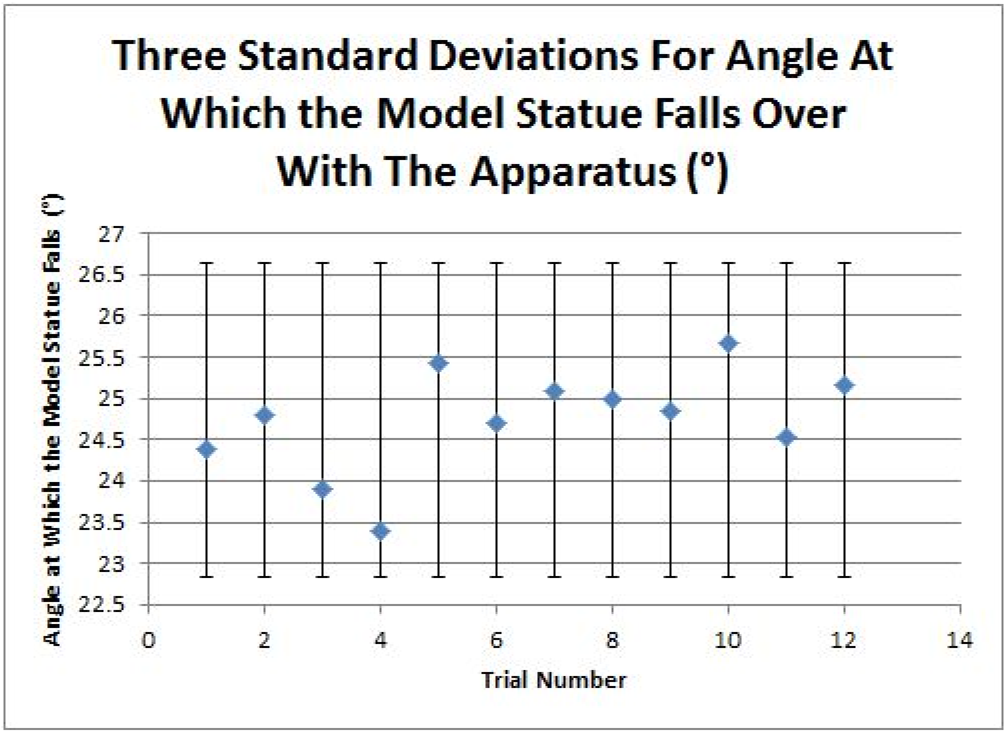

Figure 17: Three Standard Deviation Graphs for Angle at Which the Model Statue Falls Over With the Apparatus

There are no outliers

Results:

Inferential Data Analysis

To obtain the p-value of the data, a t-test was required. A one-tailed independent experiment was conducted. The p-value found using the t-test was used to analyze the quantitative data. This test compares the a set of data to a control set. The control group will be model statue that doesn't use the apparatus while the research group will be the model statue that does use the apparatus. It is a one-tailed experiment because the data analysis tested to see if the apparatus increases the angle at which the model statue falls over significantly. If it were merely a significant difference, it would be two-tailed. The experiment is independent because the model statue is simply a control and isn't influenced by the two levels.

The alpha value was 0.05. The computed p-value using the one-tailed independent t-test was 1.371*10^-23. This p-value is less than the alpha value, 0.05. Therefore, there is a significant increase in angle at which the model statue falls over with the apparatus.

1 tailed independent samples t-test
p value=1.371*10^-23<alpha=0.05
t=-45.625

Discussion of Statistical Results
The p-value, 1.371*10^-23, is less than the alpha value, 0.05. Therefore, the null hypothesis that there will be no significant difference between the angles is rejected. The research hypothesis that the angle at which the statue with the apparatus falls over will be significantly greater than statue without the apparatus is supported.

Because the null hypothesis is rejected and the research hypothesis is supported, the angle at which the model statue fell over with the apparatus was significantly greater than without the apparatus. Therefore, the apparatus significantly increases stability in the statue.

Discussion of Research Results
The goal of this project was to create a cost-effective. apparatus that automatically compensates for movement in the base. Even though this is a scaled down version of the model stabilizer, the cost which is less than $200 is extremely low compared to the $265,000 present solution. In addition, the angle at which the model statue fell over increased by 73% with the apparatus. This increase in angle potentially shows a similar increase in stability. Therefore, the data supports that this apparatus could be successful in preventing the statue from falling over during an earthquake.

The entire experiment was conducted by a human which introduces human error. The experiment required one to tilt the structure until it falls over so the results are influenced by reaction time. One must also hold the structure while reading the value, requiring a stable hand. Also, if the gyrometer moves between trials even though it is screwed down, it will affect results.

The results are extremely similar to the expectations. The expectations stated that there will be a significant increase in angle with the apparatus, and the data supported this prediction. Overall, this apparatus was successful in stabilization of the model statue as supported by the data.

Future Applications/Studies
Although, this project was inspired by buildings and statues, this solution would be more practical when used on the smaller scale. For example, it could be placed in cameras for photo stabilization. It could also be used to transport objects that shouldn't move around such as equipment in the army.

If this were to be used in buildings or under statues, the apparatus would only be turned on under dire circumstances. When turned on it would get power with a supercapacitor which would quickly discharge lots of power to quickly stabilize the building. This would be a last resort to save lives.

Works Cited

Anderson, Sam. "David's Ankles: How Imperfections Could Bring Down the World's Most Perfect Statue." New York Times 17 Aug. 2016: n. pag. Web. 26 Sept. 2016.

This New York Times Article introduced me to the problem of the hairline fractures in the Statue of David. It got me thinking as to how I could make a stabilization apparatus. It also talked about the current solutions.

Corti, Giacomo, Pilario Costagliola, Marco Bonini, Marco Benvenuti, Elena Pecchioni, Alberto Vaiani, and Francesco Landucci. "Modelling the Failure Mechanisms of Michelangelo's David Through Small-Scale Centrifuge Experiments." ScienceDirect (2014): n. pag. Web. 26 Sept. 2016.

This study showed how close the statue is to collapsing. It detailed the centrifuge studies conducted by Italian geoscientists using a model Statue of David. This helped me to see that if the statue tilts 15 degrees, it will collapse

"Damage Control, Engineering." Faultline: Earthquake Engineering. The Museum of Science, Art and Human Perception, n.d. Web. 11 Mar. 2017. <https://www.exploratorium.edu/faultline/damage/building.html>.

This article detailed the current solutions to stabilization. It talked about making buildings flexible so that they can withstand earthquakes.

Diodes Incorporated, "6.0A Silicon Rectifier" 6A05 datasheet, Feb 2003.

I needed a diode to protect my transistor from reverse voltage spikes. I also needed to find a diode that can withstand the high current in my project. This data sheet directed me to the perfect diode.

Invensense, "MPU-6000 and MPU-6050" MPU-6050 datasheet, Aug 2013

This accelerometer and gyrometer datasheet gave me insight on how the product worked and how to wire it up to the Arduino. I had to learn which pins to connect to the Arduino and the datasheet showed me how to do this.

Fairchild Semiconductor, "60V LOGIC N-Channel MOSFET" FQP30N06L (QFET), FQP30N06L datasheet, May 2001

This data sheet was helpful to learn about the specifications of the FQP30N06L N-Channel MOSFET. It told me where the base, emitter, and collector leads are, and how much current can go through it. This was very helpful when making my pulse width modulation circuit.

Schimpf, Paul H. "A Detailed Explanation of Solenoid Force." Int. J. on Recent Trends in Engineering and Technology 8.2 (2013): n. pag. Web. 26 Sept. 2016.

I needed to derive a formula to calculate the force exerted by my four electromagnets. I used this website to understand the formula for magnetic flux. This gave me one part of the equation that I derived.

Vogel, Oliver, and Jürgen Ulm. "Theory of Proportional Solenoids and Magnetic Force Calculation Using COMSOL Multiphysics." COMSOl Conference (2011): n. pag. Web. 26 Sept. 2016.

This gave me the other part of the equation that I derived. It talked about the Maxwell Tensile equation that uses the magnetic flux from the first equation to calculate the force exerted by an electromagnet.