# Depositing Charged Metal Particles

## Senior Design Design Document

Logan Marlow and David Rubrecht
Team 10 - Spring 2017
TA - Sam Sagan

# 1 - Introduction

## 1A - Objective

Metal additive manufacturing cannot be easily scaled to large print volumes with current techniques. Since plastic 3D printing can occur using techniques involving a contained extruder head, akin to a regular inkjet printer, printing volumes of plastic can be as large as the room the printer resides in. The most common method for metal 3D printing is direct metal laser sintering (DMLS)[1]. This technique requires a perfectly level and smooth bed of metal powder and a high powered laser. Mounted overhead, the laser's beam melts a pattern one layer deep onto the bed of powder. By either lowering the bed then brushing another layer of metal powder atop or vibrating the powder, the laser may sinter the next layer of the three dimensional object atop the previous. While accurate and rapid, a problem arises when printing volumes are larger than a few cubic feet. Large chambers tend to induce air currents or non-uniform vibrations in the bed, causing the levelness of the metal powder surface to be compromised. Other techniques, like spray welding, are too inaccurate to be used on precise components[2].

Our goal is to bring us one step closer to constructing an extruder head for a metal 3D printer. Specifically, charging particles of the metal powder and dropping them in a controlled fashion. By accumulated electric charge on a particle, that particle can be levitated by a series of electrical fields. While the electric field generation and maintenance is beyond the scope of this project, charging and dropping particles is an appropriate segment of the larger goal to accomplish in this course.

## 1B - Background

Currently, metal 3D printing is restricted to objects of small volumes. Techniques such as direct metal laser sintering (DMLS) are expensive to use and become increasingly difficult to scale to large manufacturing volumes. They operate by having a perfectly level bed of powder that then has a pattern sintered on it via an overhead laser or electron beam. The pattern is then sunk 1 layer of metal powder deep through vibration or a thin layer of powder is spread over the pattern. More layers are added in this fashion. While this technique allows for a high degree of resolution and speed, it has some glaring limitations. Having such a large surface area of powder exposed to air leads to much of the powder becoming oxidized. Also, the larger the volume of manufacturing space that is attempted, the more difficult it is to prevent convection currents from creating turbulence in the air, causing unevenness in the powder bed surface. In addition, the thermal conductivity of the powder forces the sintering means to either be extremely powerful or the entire volume must be kept at high temperatures. Other methods exist for printing 3D metal designs, but they all either too material inefficient or imprecise to be used widely[1].

Our device will enable a new technique of metal 3D printing; one that is precise, efficient in power and materials, and most of all, scalable.

### 1C - High Level Requirements

- Must drop/deposit particles in consistently less than 100 particles.
- Must drop particles in a consistent location, with less than 10 square millimeter of spread from a 20 millimeter drop.
- Deposited particles must be charged to at least 600 picocoulombs.

## 2 - Design

The overall device will require 4 main modules; power, control, a charging unit, and a dispensing unit. This power supply must be able to reliably convert 120 VAC into 2 different DC voltages, 5V for controls and 24V for higher power modules. The control unit is composed of a microcontroller and a LED that indicates the current state of the device. The charging unit will take the higher voltage power line to power the charging shell and powder. The dispensing unit will also use the higher voltage line to feed a stepper motor driver.

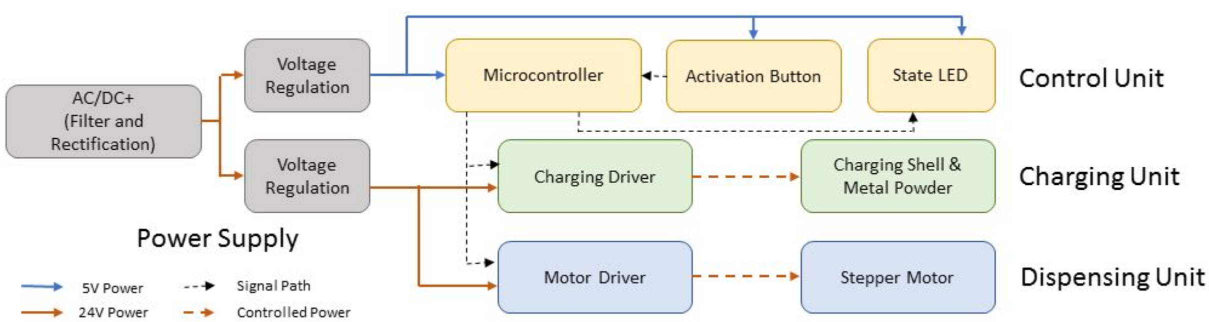



Figure 1 - Block Diagram

## 2A - Physical Design

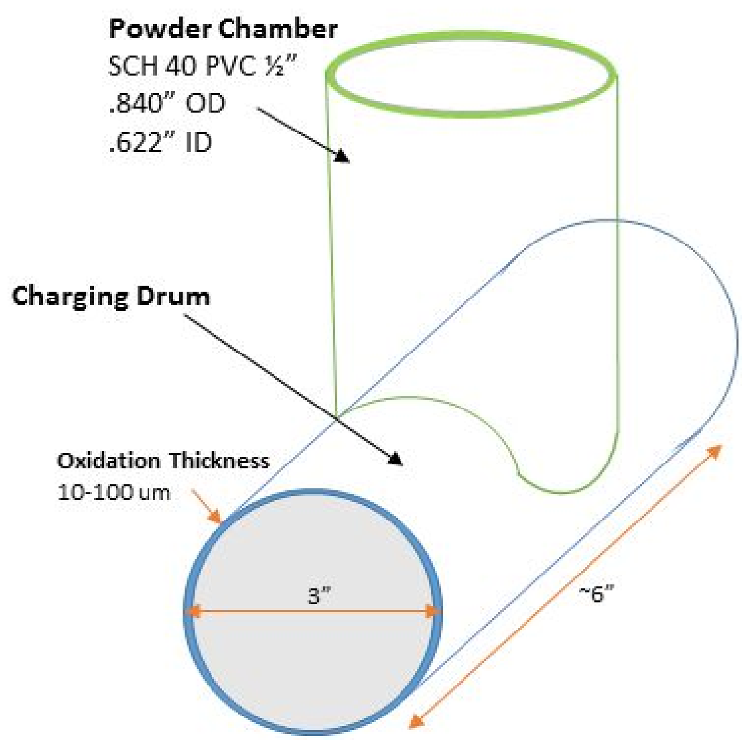



Figure 2 - Main Components

The physical design can be summarized in Figure 2 as 2 main components, the powder chamber and charging drum. Uncharged metal powder will be added to through the top of the powder chamber, which is a vertically oriented schedule 40 ½" PVC pipe. The bottom of the pipe is tightly sealed against the charging drum. This charging drum is a simple aluminum cylinder that has its body oxidized, forming a shell of $Al_2O_3$ less than 100 micrometers thick around the drum. As per Figure 3, the mounting brace (curved metal slotted bar) is attached to the powder chamber by 4 bolts. Since the metal powder will fill the small volume of the PVC pipe, these 4 hex bolts are electrically conducting with the powder.

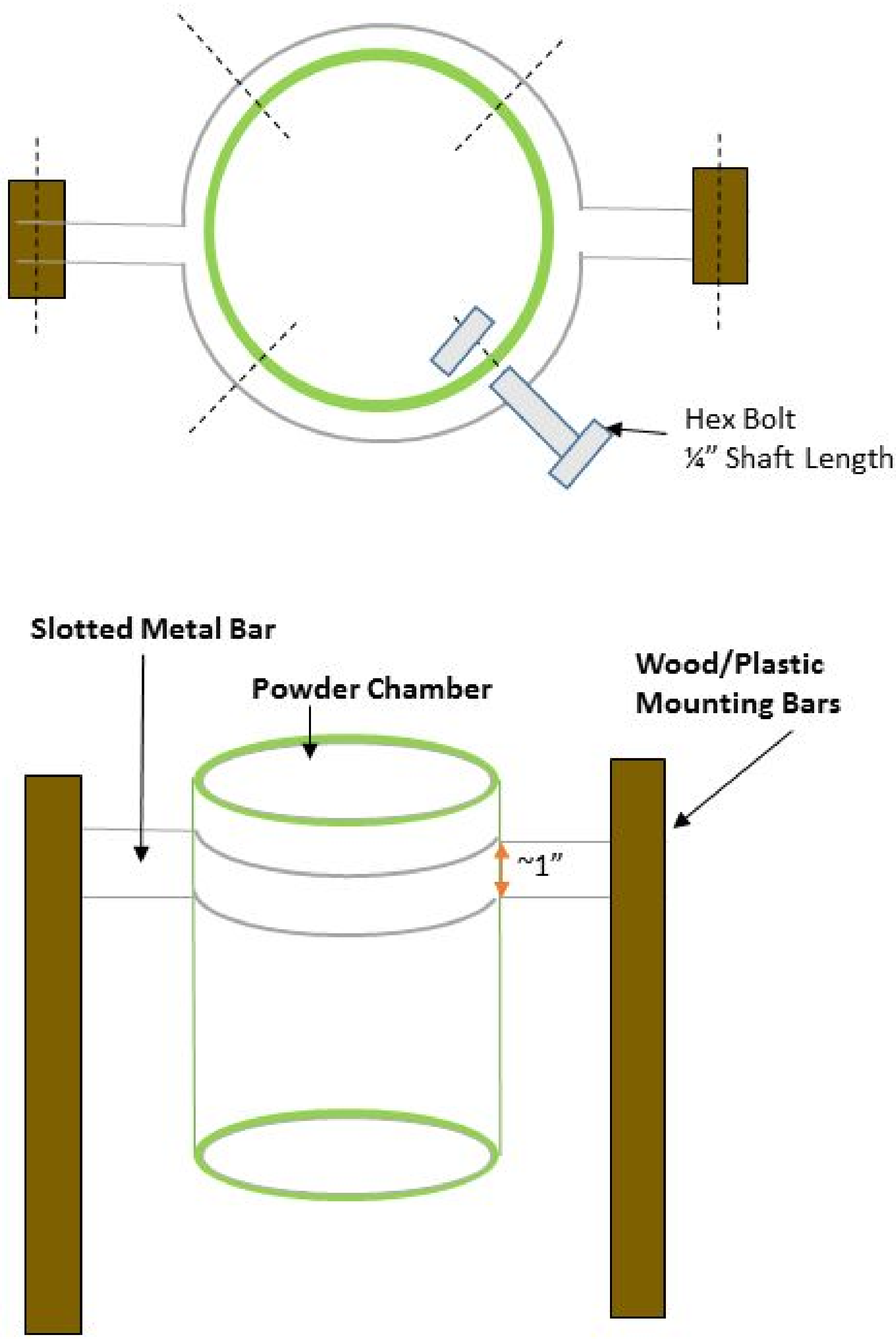



Figure 3 - Powder Chamber Details

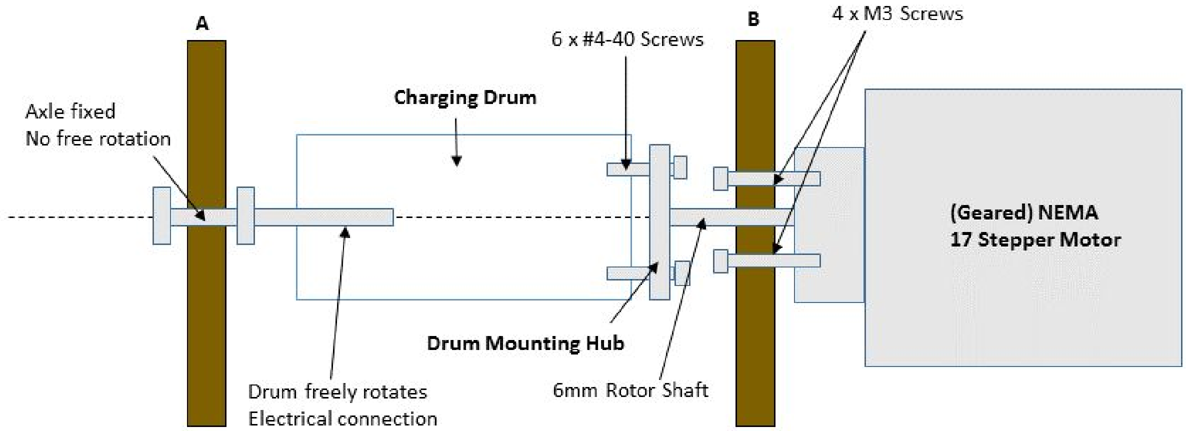



Figure 4 - Drum and Motor Mounting

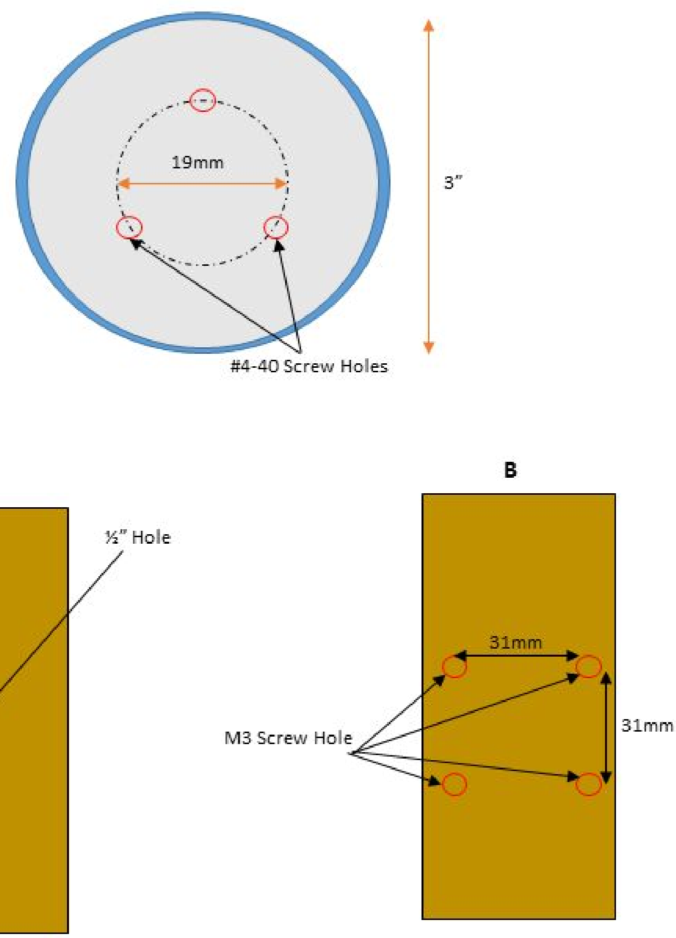



Figure 5 - Drum and Support Holes

As seen in Figure 4 and 5, the drum will be suspended on both sides of its axis of rotation. On side A, a bolt that is fixed to the mounting brace is inserted along the axis of rotation for the charging drum. The drum will then freely rotate about the bolt, and although not fixed, provides an electrical connection between the axis bolt and the charging drum. On side B, the drum is secured to a rotor mounting hub that is coupled to the 6mm of the geared NEMA 17 stepper motor[3]. This securing to the rotor will allow the stepper motor to rotate the drum reliably.

While not explicitly detailed in Figures 2-5, the drum will have 2 small etches midway along the cylinder's length on opposite sides from each other (180 degrees of separation). Measuring less than a millimeter deep each, these etches are used for collecting small amounts of the metal powder. Note, the metal powder in these etches are still electrically insulated from the drum, as the oxidation of the drum will occur after the etches have been added to the charging drum.

## 2B - Power Supply

A twin output voltage power supply is necessary to both adequately energize the stepper motor and charging unit and provide the lower voltage to power some of the control units. AC wall power will be simultaneously transformed, rectified, and regulated into 2 DC voltage rails.

### 2Ba - AC/DC Filter and Rectification

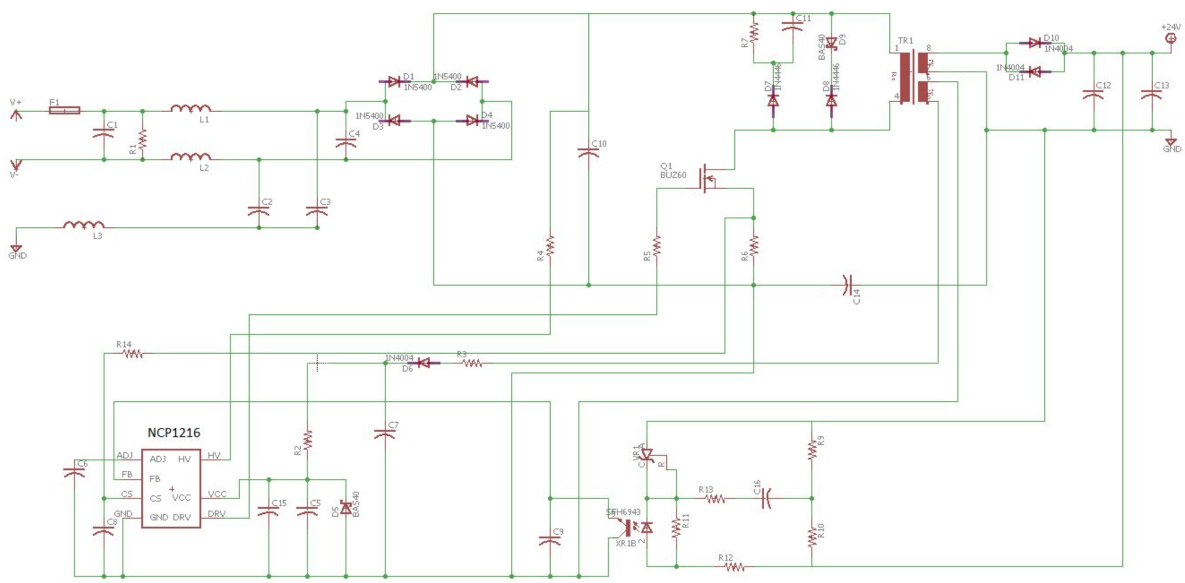



Figure 6 - 120VAC to 24VDC

The AC power from a standard US power outlet must be filtered, transformed, and rectified to produce robust DC power lines for both the low power microcontroller and the power hungry motor/charging unit. Must provide robust DC voltages to be regulated and used throughout the device. Schematic for rectifying and transforming 120VAC to 24VDC is shown in Figure 6, a modification on reference design for the NCP1216 CCM controller IC[14].

| Requirements | Verification |
|---|---|
| (1) Must adequately convert 120 VAC at 60Hz to 1 24V voltage rail.<br>(2) Voltage rail needs to provide >2A at 24 volts. | (1) Using a digital multimeter, probe the outputs of the output voltage rail when power supply is connected to wall power (120VAC). Check to see if the voltage is 24V.<br>(2) Bridge the 24V rail with incrementally smaller resistors, starting at 1 Mohm and ending with 12 ohms. Probing the voltage drop across the resistor, check to ensure each test continues to have 24V across its respective resistor. |

### 2Bb - Voltage Regulation

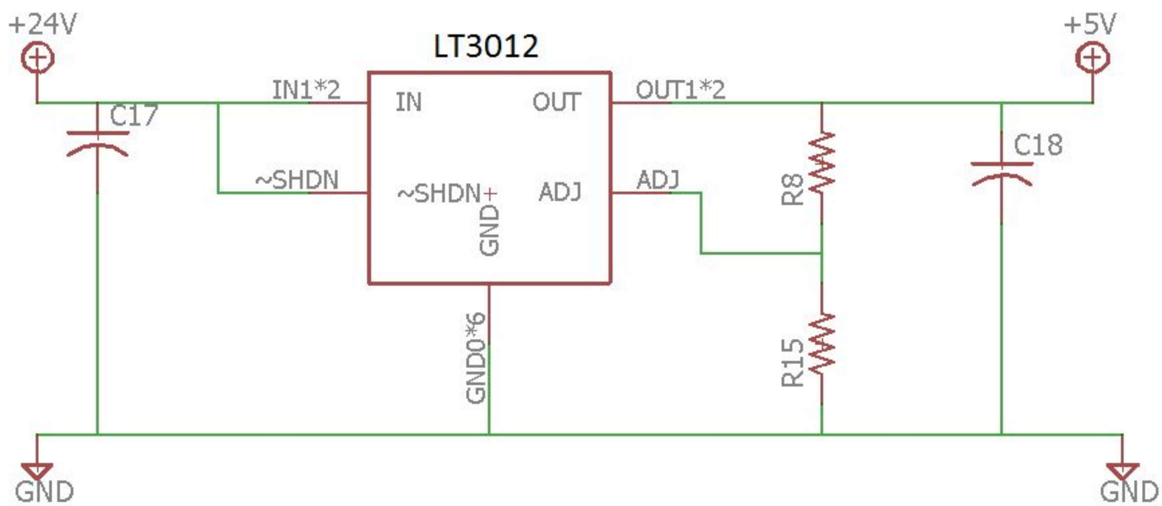



Figure 7 - 24V to 5V Schematic

DC power outputted from the rectifier needs to be effectively regulated and smoothed so as to not disturb the operation of the microcontroller or the driver ICs. While relatively inefficient at higher currents, this regulation has to supply less than 50 milliamps to the rest of the system, so the inefficiency is not a problem. As seen in Figure 7, the linear regulator LT3012 will cleanly clip the 24V down to 5V[15].

| Requirements | Verification |
| --- | --- |
| (3) Lower voltage regulator outputs 5V +/- 5% from a input source of 5 volts.<br>(4) Must be able to supply at least 50 milliamps. | (3) Using a digital multimeter, probe the outputs of the output voltage rail when regulator circuit is given 24V from a power supply. Check to see if the voltage is 5V.<br>(4) Bridge the 5V rail with incrementally smaller resistors, starting at 1 Mohm and ending with 100 ohms. Probing the voltage drop across the resistor, check to ensure each test continues to have 5V across its respective resistor. |

### 2C - Control Unit

An ATmega328P will control the state of the dispensing unit and charging circuit, which will be indicated to the user with a state LED. The state of the device will be dictated through an internal finite state machine and user input through two buttons. In the future, this unit will also control a levitation unit given input from infrared sensors.

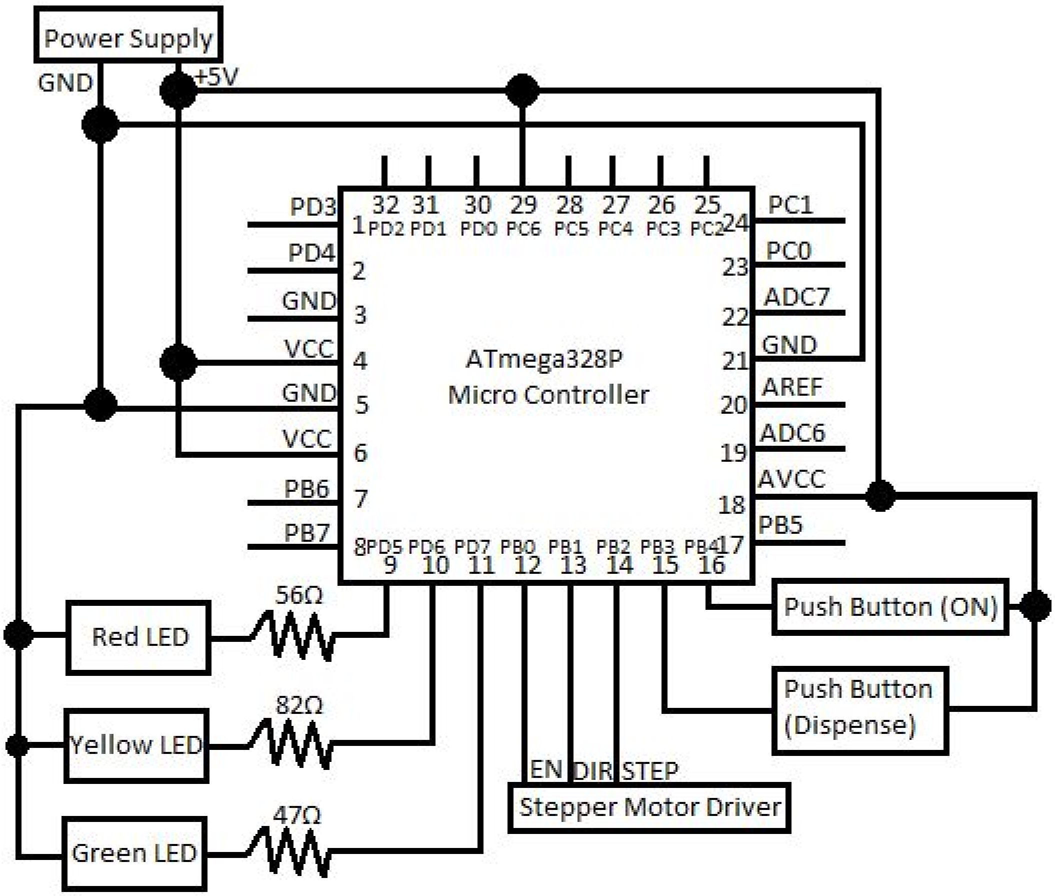



Figure 8 - Control Unit Circuit Diagram

### 2Ca - Microcontroller

An ATmega328 will keep track of the position the stepper motor rotor (counting steps) as well as the time 'On' in the charging circuit. It will use digital output pins to control the two driver circuits[5].

| Requirements | Verification |
| --- | --- |
| (1) The microcontroller must have 6 functional output pins and 2 functional input pins.<br>(2) The microcontroller's output pins must be able to output a 5V (+/-5%) HIGH signal and have a 0V LOW signal.<br>(3) The microcontroller's input pins must be able to detect a 5V (+/-5%) High signal and a 0V LOW signal. | (1) Write unit test code to iterate through each pin and generate an output signal and measure that output with a multimeter. Run a similar unit test where the microcontroller will attempt to receive input from each pin and output from a known working pin to indicate it has received the signal. Measure output with a multimeter and generate input using a 5V DC power supply.<br>(2) Run a unit test where the microcontroller will output to all pins periodically. Measure the output with a multimeter and assert that the high signal is within 5% of 5V and the low signal is within 5% of 0V.<br>(3) Run a unit test where the microcontroller will output from a known to be functioning pin when any of its input pins goes high. Assert that the output signal is only generated when the input is within 5% of 5V. |

### 2Cb - State LEDs

LEDs to simply indicate the current state of the device, and for some basic debugging. The LED will be used to indicate whether the device is in the idle, charging, or dispensing state. The green LED will indicate the device is idle, the yellow LED will indicate that the device is charging, and the red LED will indicate that the device is dispensing.

| Requirements | Verification |
| --- | --- |
| (1) Can be reliably illuminated to be visible from 1 meter away.<br>(2) LED color can be clearly distinguished from 1 meter away. | (1) Connect the LED with a resistor in series to a 5V power supply and observe it from 1 meter away. Assert that the light from the LED is clearly visible.<br>(2) Connect all three LEDs, each with a resistor in series, to a 5V power supply and observe them from 1 meter away. Assert that each color of LED is easily distinguishable from the other two. |

### 2Cc - Activation Buttons

External buttons used to turn on the charging and dispensing units. When the “ON” button is pressed, the charging unit will begin the charge the metal powder in the powder chamber. When the “Dispense” button is pressed the dispense unit will active and dispense 1 unit of metal powder. Uses the 5V power rail to signal the microcontroller a HIGH or LOW signal. Both signals are active high. The final version of the product would have these signals being generated by the 3D printer and not from a user controlled button.

| Requirements | Verification |
| --- | --- |
| (1) Outputs 5V (+/- 5%) as HIGH and 0V as LOW signal.<br>(2) Doesn’t shock user upon contact (insulated from 24V rail). | (1) Using a breadboard and a bench DC power supply, connect 5V to the input pin of the push button and measure the output pin on a multimeter to ensure that the button is passing 5V when pressed and no voltage when it is not pressed.<br>(2) While the button is connected to a 5V DC power supply, measure the voltage of the top of the button. If there is any voltage above noise, then the button is not properly insulated and cannot be used. |

## 2D - Charging Unit

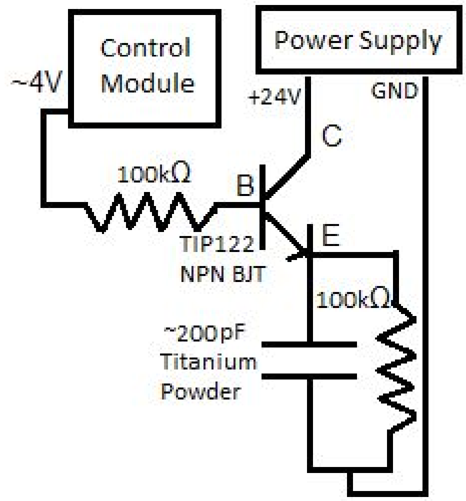



Figure 9 - Charging Unit Circuit Diagram

The charge unit will transfer charge to the metal powder through capacitive charging. The charging unit will consist of a 2N4403 PNP BJT that will be switched on and off by the control unit. The transistor will connect the 24V output of the power supply to the hopper containing the metal powder. The line will be connected to an aluminum ring inside the hopper containing the powder to ensure the powder remains in contact with the 24V input when the transistor is switched on. The ground from the power supply will then be connected to an insulated metal drum that is part of the dispensing unit. The metal powder and rotating drum, separated by a layer of oxidization, will form a capacitor, allowing charge to accumulate in the metal powder. A resistor in parallel with the hopper will ensure that when the charging unit is switched off excess charge will be siphoned off.

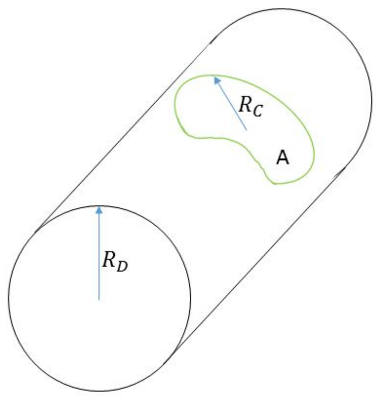
### 2Da - Charging Driver

The charging driver will receive a signal from the microcontroller to indicate if it is to be powered or not. It will then connect the 24V line to the charging shell and powder. To accomplish this, we will use a 2N4403 PNP BJT because it is easy to turn on or off using a signal from the microcontroller, and because it easily accomplishes the intended task.

| Requirements | Verification |
|---|---|
| (1) Must be switched on from a signal of 5V (+/- 5%) and off from signal of 0V.<br>(2) Must be able to pass through 24V (+/- 5%) from power supply with maximum current draw of 20 mA. | (1) Use a breadboard and a DC power supply to test the BJT. Measure the current through the BJT (collector-emitter current) with a multimeter. Assert that the BJT does not enter its on region until the base voltage from the power supply is within 5% of 5V.<br>(2) Construct the Charging Driver circuit on a breadboard and test the voltage at the emitter of the BJT to ensure it is within 5% of 24V. Also measure the current through the BJT (collector-emitter current) and assert that it is less than 20 mA. |

### 2Db - Charging Drum and Metal Powder

Due to the large scale of the charging drum relative to electrons, the charging shell can be approximated using the parallel plate capacitance formula. However, to use the formula, the surface area of the powder adjacent to the drum must be calculated. This can be done by perceiving a circle with radius Rc being projected onto the curved side of cylinder with radius Rd, (negligible incidence angle). For a graphical representation, see Figure 11. Starting with equation (i) and assumptions (ii) and (iii), a formula (vi) can be derived that gives the surface area A. With a powder chamber made from a SCH 40 .5” PVC pipe, Rc is 15.8 millimeters. Also, with a charging drum of 3 inch diameter, Rd is 38.1 millimeters.




$$A = \int_{-\sin^{-1}\frac{R_C}{R_D}}^{\sin^{-1}\frac{R_C}{R_D}} \int_{-\sqrt{R_C^2 - R_D^2 \sin\theta}}^{\sqrt{R_C^2 - R_D^2 \sin\theta}} r\,dz\,d\theta \qquad \text{(i)}$$

$$R_C \leq R_D \quad t = \frac{R_D}{R_C}\sin\theta \qquad \text{(ii, iii)}$$

$$E(b) = \int_0^1 \sqrt{\frac{(1 - b^2t^2)}{(1 - t^2)}}\,dt \qquad \text{(iv)}$$

$$K(a) = \int_0^1 \frac{1}{\sqrt{(1 - a^2t^2)(1 - t^2)}}\,dt \qquad \text{(v)}$$

$$A = 4R_D^2\left(E\left(\frac{R_C}{R_D}\right) - \left(1 - \frac{R_C^2}{R_D^2}\right)K\left(\frac{R_C}{R_D}\right)\right) \qquad \text{(vi)}$$

Figure 10 - Surface Area of Powder on Cylinder

The electrical properties of the charging drum comes down to the resistivity and dielectric constants of both the powder and Al2O3 oxidization shell on the drum. Most reliably, the oxidation layer of the drum has a dielectric constant equal to 9.1 and a resistivity of roughly 10^14 ohms-centimeter. Our metal powder is composed primarily of Titanium (Ti) with small amounts of titanium oxide (TiO) mixed in due to exposure to humid air. Ti behaves as a good conductor, even in powder form, with a resistivity of less than 4.3 x 10^-7 ohms-centimeter and dielectric constant approaching infinity[6]. TiO, however, has a dielectric constant of around 45 with a resistivity of 149 ohms-centimeter[12]. Due to low low exposure times and lack of excessive moisture, oxidation during the charging stage should be negligible. Note, that upon dropping, probability of oxidation increases substantially.

With parallel plate approx and TiO is negligible, C = 1.282e-10 F and the intrinsic parallel R = 6.56e16 ohms. With parallel plate approx and TiO has a 1mm thickness between the titanium and Al2O3, C = 9.133e-11 F and intrinsic parallel resistance R = 195.54 ohms. This should give a range of possible values, however it should be noted that the likelihood of a negligible TiO is high. Assume first set of assumptions for further calculations.

## 2E - Dispensing Unit

An aluminum drum with 2 small etches in the center of the curved side of the cylinder (on either side) will seal the bottom of a ½ inch PVC pipe. With the PVC pipe filled with metal powder and the drum rotated 180 degrees per deposition, the etches will allow small amounts of metal particles to escape the seal of the drum. When one etch reaches a critical point on rotation, the accumulated particles will fall to be deposited in a known location just underneath the drum. This drum will be rotated using a geared stepper motor, specifically a NEMA 17 motor optimized for torque[3].

### 2Ea - Stepper Motor

A geared bipolar stepper motor optimized for torque[3]. This motor's geared shaft will be radially coupled to the rotating axis of the aluminum drum. The selected motor can be driven using 0.8 amps (.4 per phase), allowing plenty of breathing room in the power supply in case of spikes in consumption. After the gearbox, the shaft provides 121.8 Ncm, enough to adequately rotate the drum against the friction induced by the seal on the powder chamber cylinder. Each full step rotates the shaft and drum .35 degrees. It should be noted, the recommended voltage for the motor is ranged between 12 and 24 volts. While our supplied voltage is on the upper edge of that range, that is merely is recommended. Motors operate off of the current supplied and as long as .4 amps is driven to each phase, the voltage is not important.

| Requirements | Verification |
|---|---|
| (1) Must be bipolar and 2-phase.<br>(2) Rotates in discrete steps of at most 1 degree.<br>(3) Step sizes are consistent. | (1) Check the datasheet before purchase and upon unboxing.<br>(2)<br>(a) Generate 2 waveforms that simulate the currents of a bipolar 2-phase motor coils.<br>(b) Using a protractor and piece of tape, walk the shaft orientation some degrees. Record number of steps.<br>(c) Divide degrees rotated by number of steps taken.<br>(3) Repeat test (2) multiple, recording trials. Calculate standard deviation. |

## 2Eb - Stepper Motor Driver

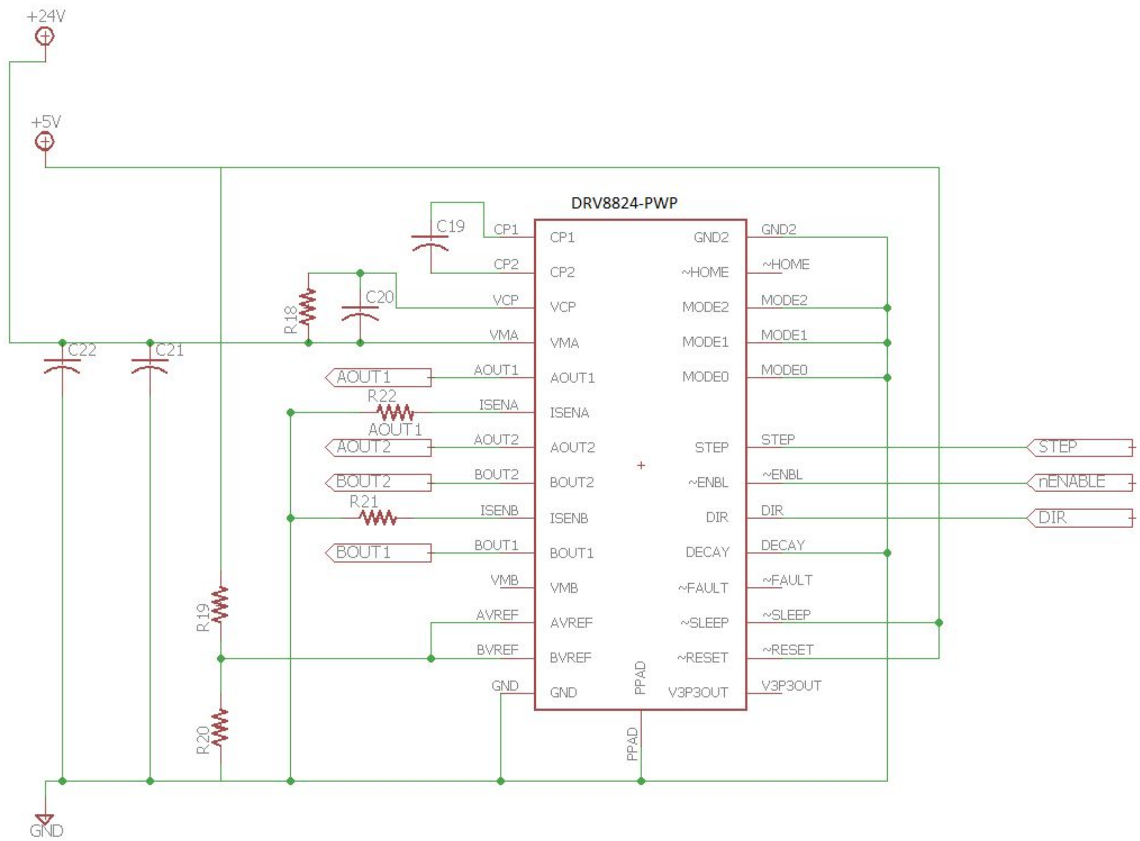



Figure 11 - Motor Driver Schematic

Acting as a communications bridge and a current regulator, the motor driver circuit takes both 24V and 5V power rails with 3 digital 4V inputs from the control module. The 24V rail is used to supply the constant amperage to the stepper coils, with the magnitude of the constant current set by a voltage divider fed into the AVREF and BVREF pins of the driver IC. While the actual waveforms necessary for stepping the motor rotor could be programmed into the microcontroller, it's simpler and costs similar to abstract the waveform and constant current generation with the DRV8824 integrated circuit. Specifications for the motor driver circuit are heavily dependent on the stepper motor itself, however it relatively simple to adjust the constant current magnitude by adjusting the voltage output by the voltage divider external circuit.

| Requirements | Verification |
|---|---|
| (1) Takes 3 digital input signals (3.3V - 5V), for enabling, stepping and direction<br>(2) Takes 24V power rail to output 2 stepper motor coil currents of .4A each.<br>(3) Direction of each coil current must be variable.<br>(4) Current through motor coils must follow 2-phase bipolar order and direction for each step. | (1) Bridging the driver with two 100 ohm resistor, step through the different input combinations. Probe the voltage across the resistors.<br>(a) If enable is low, the voltage across the resistors should have a magnitude of 40V. If enable is high, probing should read 0V.<br>(b) If pulsing a clock signal to the STEP pin, the waveform for the 2 resistors should model two sine waves, with a 90 degree phase difference.<br>(c) Sine waveforms should have a -90 degree offset if the DIR input is set to the opposite state. |

## 3 - Tolerance Analysis

Due to the nature of our project, one of the most critical components is the charging unit. Because this unit is responsible for charging the metal powder it is important that it consistently maintain an appropriate charge on the powder chamber in order for the capacitive charging to work. It is equally important that when the device is placed into the idle state that the charge in the powder chamber be dissipated to reduce the risk of shock or fire when handling the metal powder.

Our target charge on the metal powder is 600 pC. The charge on a capacitor is given by:

$$Q = CV$$

Equation 1 - Charge of a capacitor

The theoretical value of the capacitance of the metal powder is between 91.33 pF and 128.2 pF. Therefore the voltage on the capacitor should not drop below 6.6V. In our original design, we intended to use a TIP122 NPN BJT to act as the switch for the testing unit; however upon running several simulations, one of which is pictured in Figure 12, it became obvious that the TIP122 would not meet our voltage requirements as it would only create a voltage drop across the capacitor in the 5V range for the calculated range of the capacitance. For this reason we switched out the Tip122 for the 2N4403 PNP BJT. Figure 13 shows one of our simulations of the new circuit with the PNP transistor. Testing in a range of capacitances from 50 pF to 300 pF, the PNP BJT consistently maintains a voltage of 23.99V across the capacitor. This leads to a theoretical charge of between 2191 pC to 3075.5 pC. This is well above our theoretical minimum requirement of 600 pC.

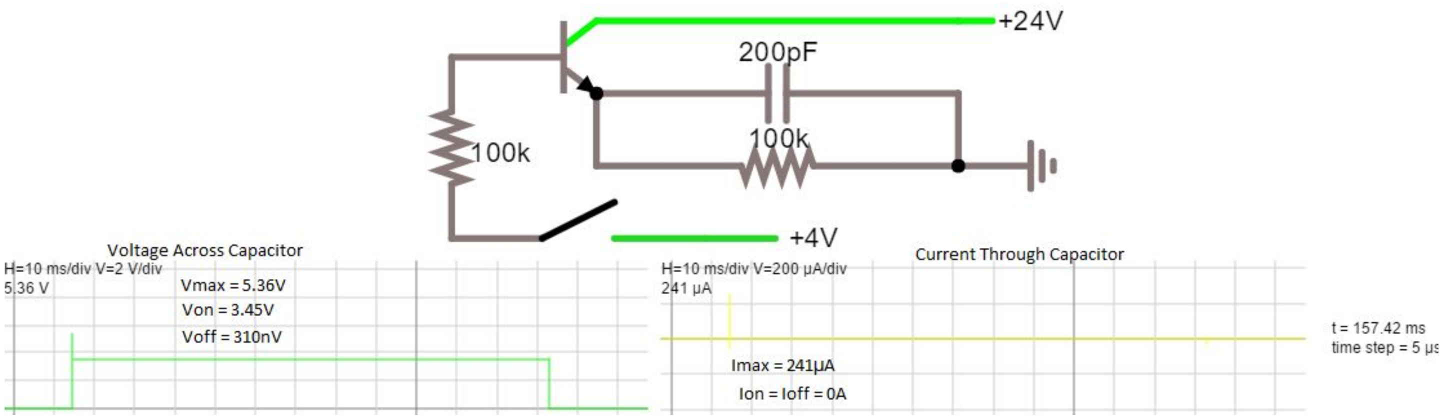



Figure 12 - Charging Unit Simulation Using NPN BJT[4]

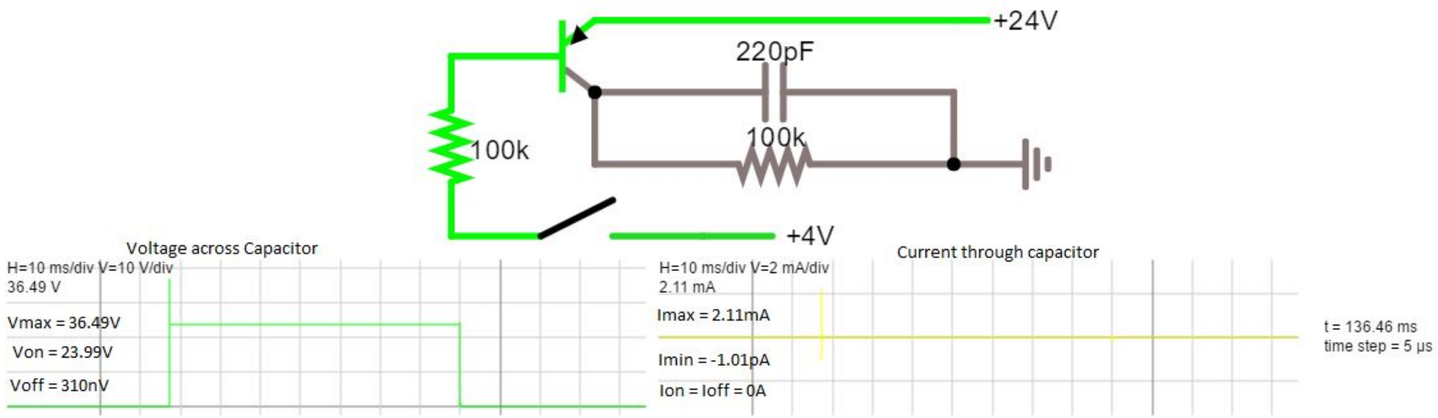



Figure 13 - Charging Unit Simulation Using PNP BJT[4]

## 4 - Costs

Though the whole project, including other aspects of the extruder head, will extend well beyond the course, the development costs will only cover labor during this course. Given a $40 hourly wage, 10 week-hours, development time of 8 weeks with a team of 2 partners, the costs can be calculated as shown below.

(40 $/hour) * (10 hour/week) * (8 weeks) * (2 members) * 2.5 = $16,000

Our physical parts (PVC, aluminum rolls, bolts/screws) and labor costs will be $110.

| Part | Description | Cost |
|---|---|---:|
| TI DRV8824PWP | Motor driver IC | 3.57 |
| Stepper Motor 17HS13-0404S-PG5 | Bipolar 2-phase stepper motor | 27.64 |
| Atmega328p PCB Socket | 28-pin, DIP, .3" wide | 0.95 |
| PWM Current Mode Controller | ON Semi IC, brains of power circuit | 1.14 |
| Linear Voltage Regulator | LT IC, easily (inefficiently) regulates 24V to 5V power | 3.14 |
| Wire PCB Connectors | Secures external motor wire to PCB using screw compression in a solderable socket | 2.11 |
| 120 VAC Female Plug Connector | Female plug for 120 VAC cable, mounts to side of housing | 0.79 |
| ATmega328P | Microcontroller | 2.11 |
| Power Cord | Power cord that uses US standard 3 strip connectors | 0.97 |
| Transistor with Optocoupler | SFH6156A-2, Transistor Output Optocouplers Phototransistor Out Single | 0.78 |
| Voltage Shunt Regulator | TL431A, Voltage References Adjustable Precision Shunt Regulator | 0.39 |
| **Total** | | **43.59** |

Totalling parts, labor and machine services, the cost comes to $16,153.59.

## 5 - Schedule

| Week | Logan Marlow | David Rubrecht |
|---|---|---|
| 2/27/17 | Finalize Eagle custom libraries | Finalize Eagle PCB layout |
| 3/6/17 | Order components and custom PCB | Finalize and order physical item in machine shop |
| 3/13/17 | Breadboard control and charging circuits. Test and verify. | Breadboard power and motor driver circuits. Test and verify. |
| 3/20/17 | PCB control and charging circuits. Test and verify. | PCB power and motor driver circuits. Test and verify. |
| 3/27/17 | Accumulate charge data with machined prototype. Check expected charge magnitude | Attach motor to PCB. Test rotation charge drum using power supply and motor |
| 4/3/17 | Attach electrical module to mechanical prototype | Test and verify final prototype |
| 4/10/17 | Extra time allotted for setbacks and bug fixing. | Extra time allotted for setbacks and bug fixing. |
| 4/17/17 | Prepare Final Presentation | Begin Final Report |

## 6 - Safety and Ethics

The primary area of concern for our device is in the charging unit. Metal powder can be very volatile and can even explode under certain circumstances. According to Particles.org, “(1) the dust must be suspended in air or gas supporting combustion, (2) must have particle size capable of propagating a flame, (3) dust concentration must be in the explosive range…, (4) must be above minimum ignition temperature…, (5) there must be an ignition source of sufficient energy.”[11].By insuring the charging unit prevents electrical arcing from occurring we can be reasonably sure our device will not have an ignition source to set off a reaction. To ensure this the charging unit will be turned off when not in use and all charge stored will be bled off using a parallel resistor. The metal powder will also be insulated from conductors that it could possibly arc to by the powder chamber. The flash point of our intended test metal, titanium, is

480 degrees fahrenheit (249 degrees celsius)[7]. The charging unit of our device does not inherently generate any heat, so the metal powder should be kept at room temperature, well below the flash point. We can be sure of this as the metal powder has relatively low resistance according to the experimental findings of Montes, Cuevas, and Cintas[8]. Furthermore, our hopper design, which is intended to keep the charged metal in electrical contact in order to facilitate capacitive charging, will prevent the metal from dispersing in the air. Thus, any threat of fire or explosive hazard has been substantially reduced. Though our device is intended to separate small portions of metal dust and drop them through the air, these miniscule portions are not substantial enough to be in the explosive range or to propagate a flame.

Another area of concern is the power supply. As with any power supply, there is a concern for electrical shock, burns, and fire. Our power supply must adhere to the US safety standard UL60950-1 to reduce the chance of injury occurring while the device is in use[10].

The completed form of this project would allow metal fabricators to manufacture their products at a faster rate, but this has the consequence of possibly reducing the number of jobs available in this industry. It is also true that we cannot be sure what types of items will be manufactured using our device and it is conceivable that someone could use it to produce weapons, or some other means of bringing harm to others. These issues conflict with the IEEE code of ethics #9 because our device can potentially be used to harm others or cause them to lose their jobs[9].

Unfortunately there is no way for us to control how our device will be put to use. We do not believe that the possibility of misuse of our device warrants that we should not develop it, as it is equally likely that it could be used to fabricate devices that will greatly benefit mankind or lower the cost of parts that are difficult to produce using current methods. Given the potential for our device to both do harm and good, we feel that the benefits outweigh the possible harm.

## References

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