Depositing Charged Metal Particles

Senior Design Design Document

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Team 10 - Spring 2017
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3 May 2017

Abstract

In a new type of metal additive manufacturing, we lay the groundwork for an extruder head that will soon allow liquid metal to be deposited in a similar fashion to plastic 3D printers. Overall, the goal is to levitate charged metal particles, then heat those particles to liquid state while suspended in air. Here, we took on the first half, getting enough electric charge onto titanium powder and dispensing in a controlled fashion.

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 was 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 was 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.

2 - Design

The overall device has 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 takes the higher voltage power line to power the charging shell and powder. The dispensing unit also uses the higher voltage line to feed a stepper motor driver.

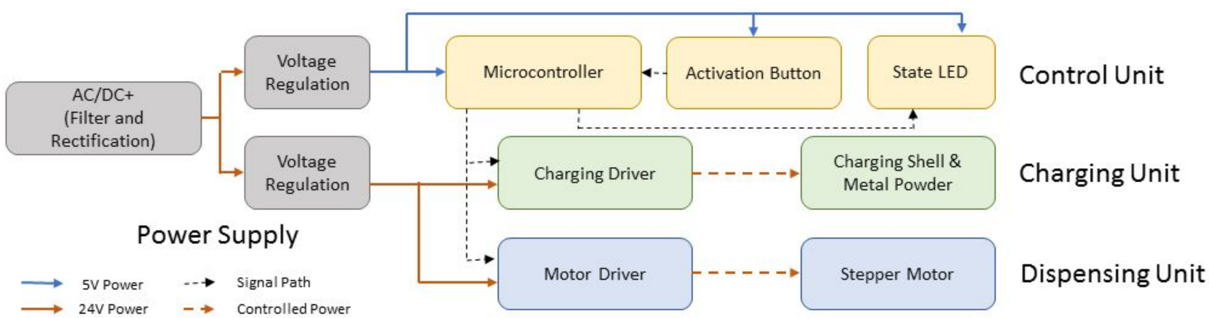


Figure 1 - Block Diagram

2A - Physical Design

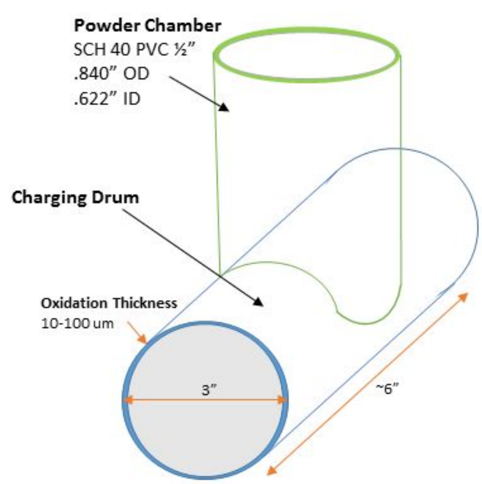
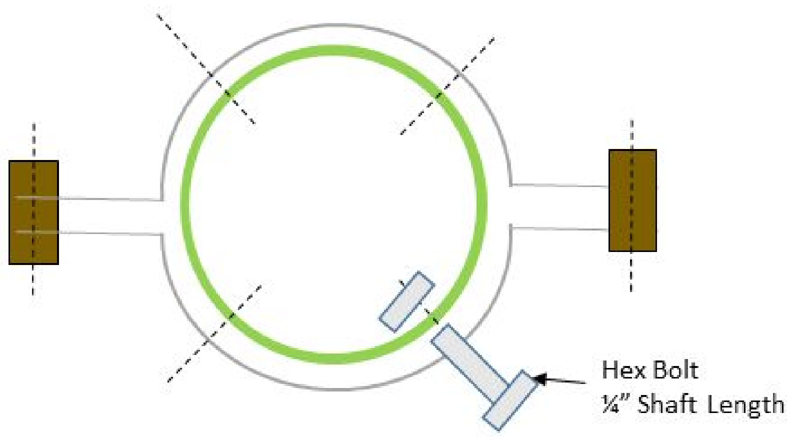


Figure 2 - Main Components

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 Al2O3 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.



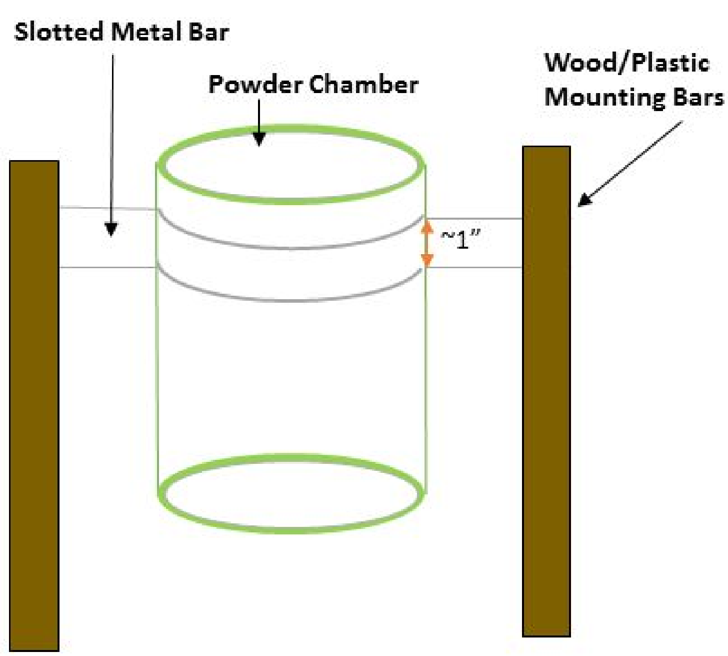


Figure 3 - Powder Chamber Details

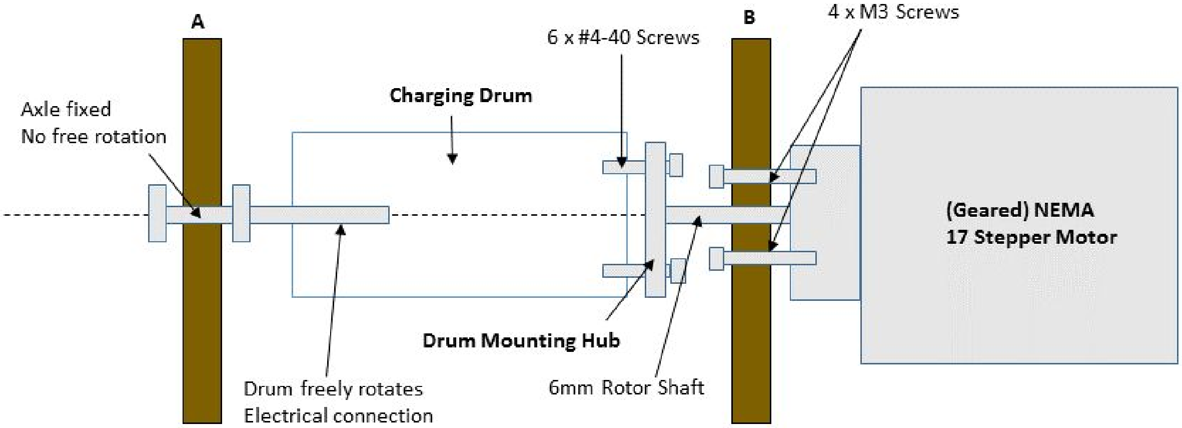


Figure 4 - Drum and Motor Mounting

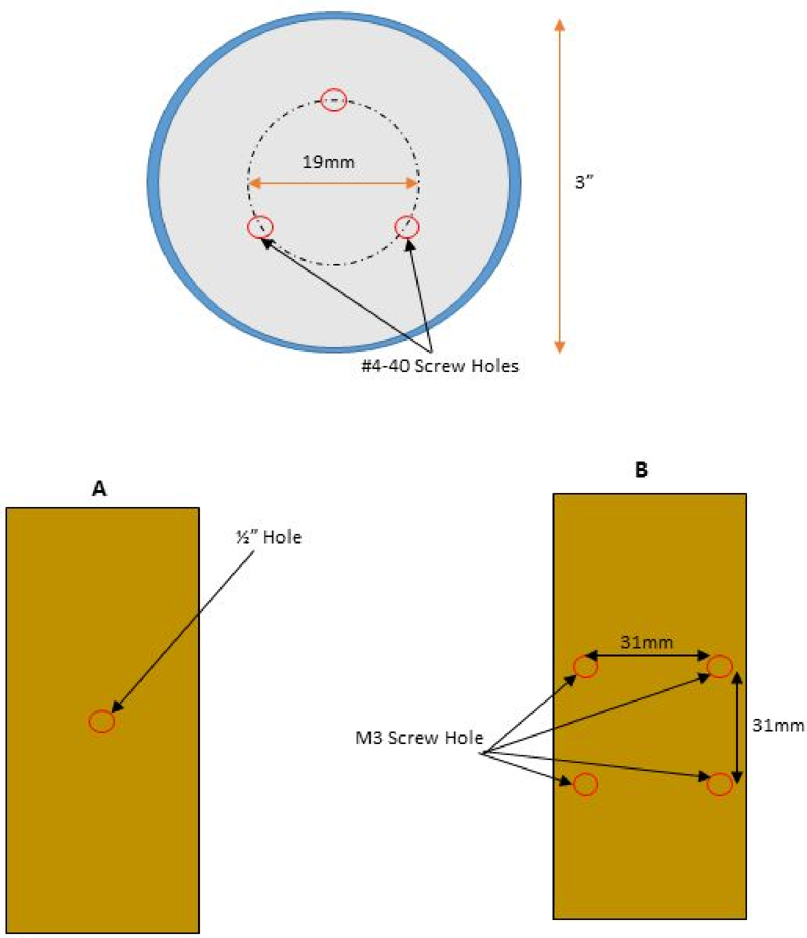


Figure 5 - Drum and Support Holes

As seen in Figure 4 and 5, the drum is 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 then freely rotates 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 is simultaneously transformed, rectified, and regulated into 2 DC voltage rails.

2Ba - AC/DC Filter and Rectification

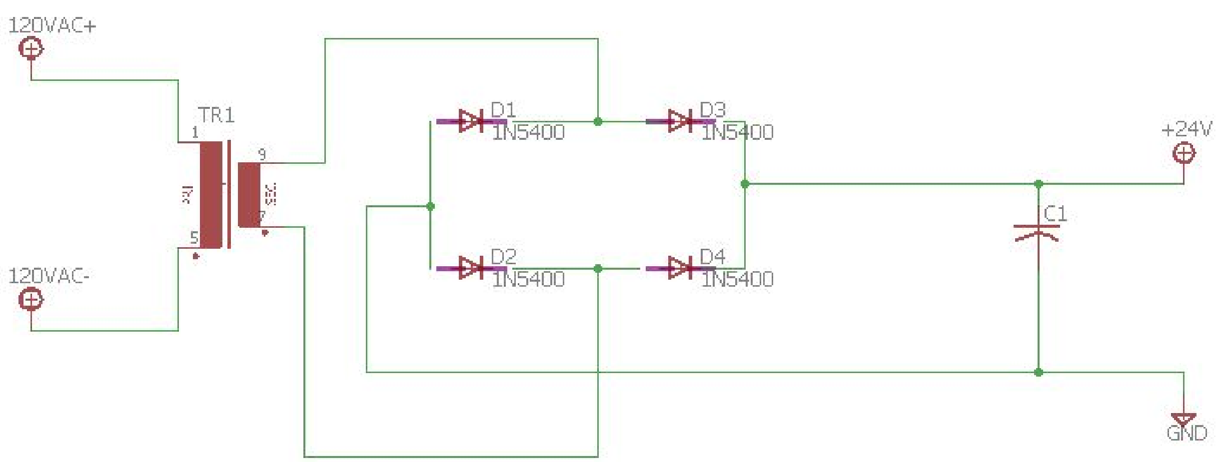


Figure 6 - 120VAC to 24VDC

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. It provides robust DC voltages to be regulated and used throughout the device. Schematic for rectifying and transforming 120VAC to 24VDC is shown in Figure 6, using the standard bridge and full wave rectification with capacitive filtering..

As shown in Table 1, the rectification and filtering of 120VAC to 24VDC was successful. Using a series of loads applied across the supply terminals, the voltage across and current through the load was measured. The measured voltage was within 7.5% of the target 24V, which while the target 5%, was more than enough to power the charging driver and motor driver in the device. Also, under full load of the device, the supply successfully delivered approximately 1 amp.

Load [Ohm]	Voltage Supplied [V]	Current Supplied [A]
1M	22.22	0.01m
100k	22.21	0.225m
33k	22.24	0.673m
3.3k	22.05	6.66m

Table 1 - 24V Rail Verification

2Bb - Voltage Regulation

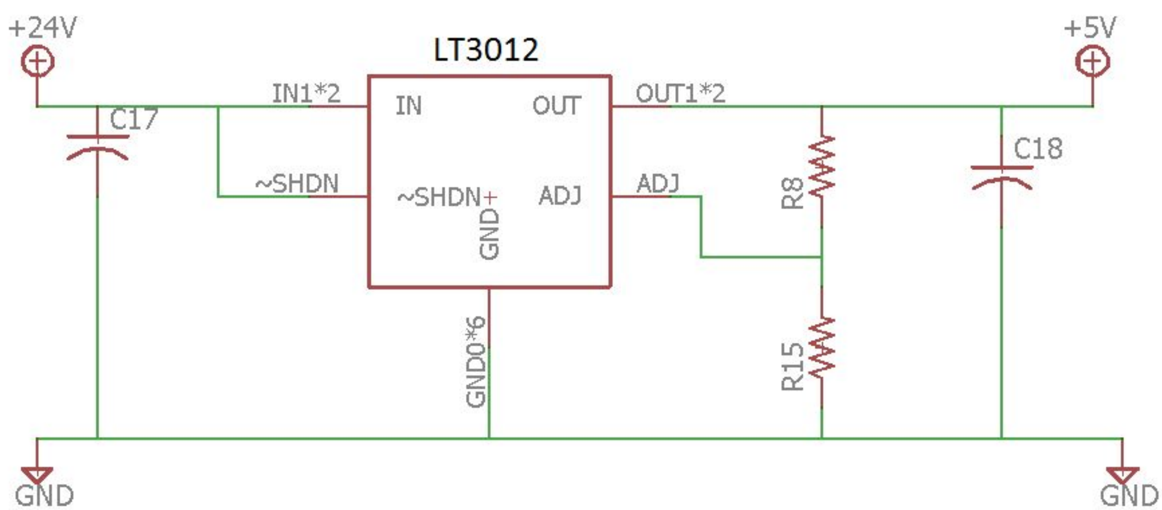


Figure 7 - 24V to 5V Schematic

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].

As shown in Table 2, the linear regulation of 24VDC to 5VDC was successful. Using a series of loads applied across the supply terminals, the voltage across and current through the load was measured. The measured voltage was within 6% of the target 24V, which while the target 5%, was within the margins of error for the microcontroller and motor driver in the device.

Load [Ohm]	Voltage Supplied [V]	Current Supplied [A]
1M	5.380	0.00u
100k	5.380	54.6u
33k	5.379	.163m
3.3k	5.377	1.63m
330	5.365	16.3m

Table 2 - 5V Rail Verification

2C - Control Unit

An ATmega328P controlled the state of the dispensing unit and charging circuit, which was indicated to the user with state LEDs. The state of the device was 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.

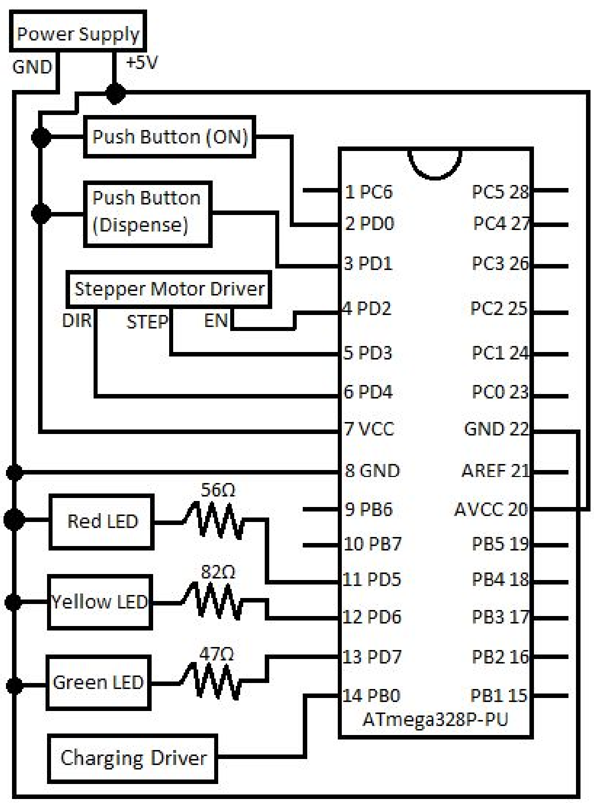


Figure 8 - Control Unit Circuit Diagram

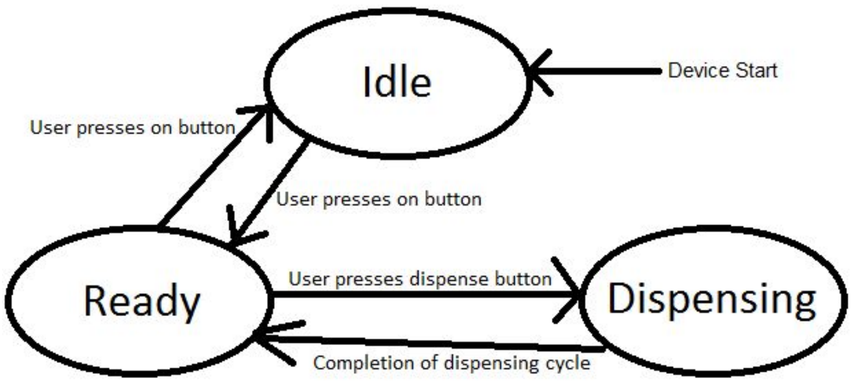


Figure 9 - Control Unit State Diagram

State	Indicator LED	Motor	Charging Unit
Idle	Green	Off	Off
Ready	Yellow	Off	On
Dispensing	Red	On	On first half cycle/ Off second half cycle

Table 3 - Control Unit State Description

2Ca - Microcontroller

An ATmega328 tracked the position of the stepper motor rotor (counting steps) as well as the time ‘On’ in the charging circuit. It used digital output pins to control the two driver circuits[5].

To verify the microcontroller we first tested the code on an Arduino Uno that we knew was fully functional. This was done because the Uno uses an ATmega328P chip and by running this test we proved that the code would implement the desired behavior. After the code was verified we began programming ATmega328P chips on a breadboard. This Process took longer than expected as many of the chips we tried to use were faulty. Luckily, we eventually found a functioning chip that passed all of our tests and were able to get correct behavior out of the microcontroller using its internal eight MHz clock.

2Cb - State LEDs

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

Testing the LEDs was initially done by connecting them to a five volt power supply with a 50 ohm resistor in series to see that they were functional. After that they were checked against the requirements described in Table 5 of Appendix A.

2Cc - Activation Buttons

External buttons used to turn on the charging and dispensing units. When the “ON” button was pressed, the charging unit began to charge the metal powder in the powder chamber. When the “Dispense” button was pressed the dispense unit activated and dispensed one unit of metal powder. Used the 5V power rail to signal the microcontroller a HIGH or LOW signal. Both signals were 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.

Oddly enough the buttons were one of the only parts of our design that did not work as expected. The buttons passed all of our initial testing on a breadboard; however, during the final build the buttons exhibited bad behavior after being soldered to a perfboard. Because the buttons only began misbehaving after being soldered to the perfboard, we believe the conductive underside of the board may be to blame. The nature of the behavior was such that the buttons would allow voltage to pass without being pressed, or sometimes even when a hand was moved toward them without making contact with the button. In hindsight we believe that replacing the buttons with a serial connection would be a superior method of controlling the state machine because the intended purpose of the device will require it to interface with a 3D printer, which would be possible with such a serial connection without the need of buttons. The buttons were added originally because we assumed it would be a simple way to allow a user to control the state machine by hand, but this assumption proved unreliable.

2D - Charging Unit

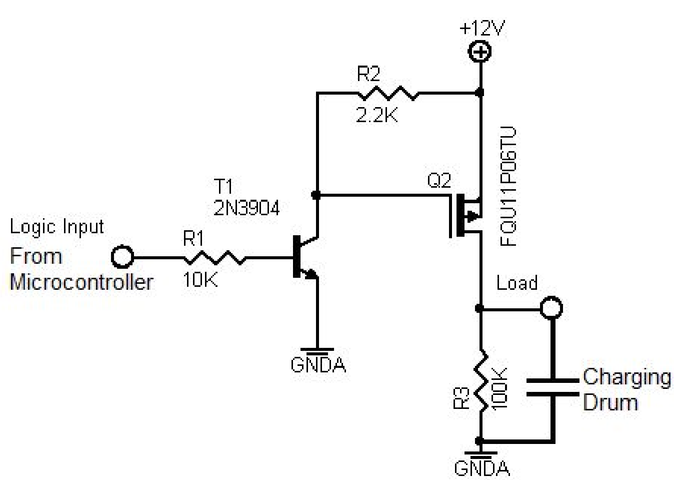


Figure 10 - Charging Unit Circuit Diagram

The charge unit transferred charge to the metal powder through capacitive charging. The charging unit consisted of a series of transistors that were switched on and off by the control unit. The transistors connected the 24V output of the power supply to the powder chamber. The line was connected to a copper ring inside the chamber to ensure the powder remained in contact with the 24V input when the transistors were switched on. The ground from the power supply was then connected to an insulated metal drum that was part of the dispensing unit. The metal powder and rotating drum, separated by a layer of oxidization, formed a capacitor, allowing charge to accumulate in the metal powder. A resistor in parallel with the powder chamber ensured that when the charging unit was switched off excess charge was safely dissipated. Importantly, the charging unit is switched off halfway through the dispensing cycle in order to cause the charged metal particles to drop. This is because the charge on the rotating drum and on the metal particles will cause them to be attracted to each other, making it necessary to discharge the unit before the particles can be dispensed.

2Da - Charging Driver

The charging driver received a signal from the microcontroller to indicate if it was to be powered or not. It then connected the 24V line to the powder chamber. To accomplish this, we used a 2N3904 NPN BJT in series with a FQU11P06TU P-MOS. It was necessary to use multiple transistors in order to prevent the high voltage from leaking through the gate of the BJT and damaging the microcontroller while still allowing the circuit to be switched using a low voltage signal.

The charging driver was originally simply a 2N4403 PNP BJT that would control the 24V supply across its emitter and collector using a signal from the microcontroller at its base. While this initial design passed all of our initial requirements, when we began assembling the final product we were alarmed to find that the BJT allowed 21V to leak through the base to the microcontroller. The microcontroller was only rated for a maximum of 20V, so this was quite alarming. The circuit was then redesigned to use a series of transistors rather than a single BJT. The new design passed all of the specifications out lined in Table 4 as well as the new requirement that it not leak voltage back into the microcontroller.

2Ea - Stepper Motor

A geared bipolar stepper motor optimized for torque[3]. This motor's geared shaft is 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.

To verify the selected stepper motor's design and performance, we drove the stepper motor using a BigEasy driver to validate its operating coil current and phase type. Not surprisingly, it operated correctly with .4A per coil and used 2 sinusoidal waveforms offset by 90 degrees to drive the rotor in full steps. However, it did not provide enough torque for the final product. Therefore, the stepper motor failed the requirements.

2Eb - Stepper Motor Driver

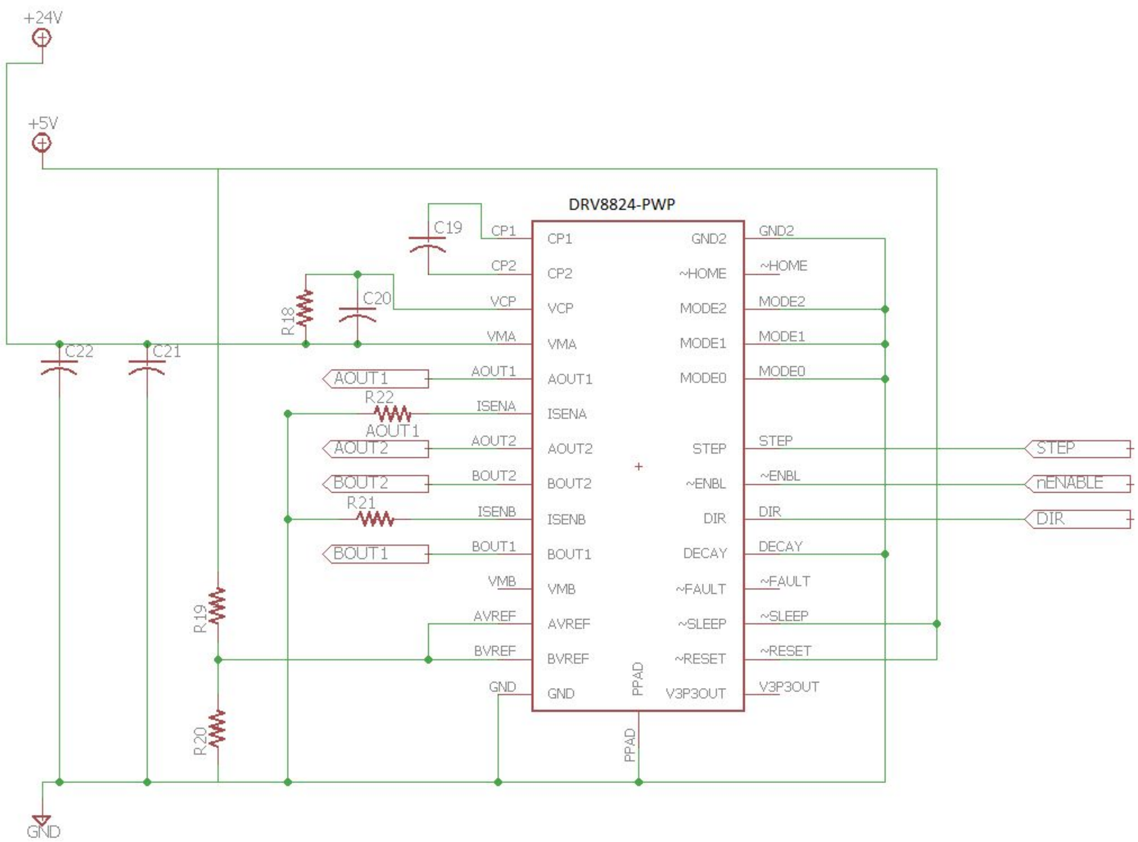


Figure 11 - Motor Driver Schematic

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.

In verification, we attached the motor driver to a "testing" stepper motor. Measuring the currents during operation, .4A was measured at it's peak. Also, due to the stepper motor expectedly rotating in full step increments, the output waveform was of 2 sinusoidal waveforms with 90 degree offset. Requirements passed, verification was successful.

3 - Costs

Summing Table 4 with the labor costs from development and machining, the total comes to $16,759.17.

3A - Parts

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
Linear Voltage Regulator	LT IC, easily (inefficiently) regulates 24V to 5V power	3.14
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
Total		**39.17**

Table 4 - Parts List and Cost

3B - Labor

Though the whole project, including other aspects of the extruder head, will extend well beyond the course, the development costs only covers 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 were calculated as shown below.

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

The machining labor took approximately 18 man hours, which if at the same pay rate, yields another $720 for labor.

4 - Conclusion

Accomplishments

While the end goal was not accomplished of depositing charged particles, nearly every module was successful. Power was delivered cleanly to every component, the notoriously difficult stepper motor control was accomplished, charging the metal powder was functional, and the device managed to excellently transition between different states.

Future Work

As mentioned before, this project is only one half a larger goal. After upgrading to a larger stepper motor, an array of electrically charged plates and infrared sensors needs to be added to accomplish the levitation of the metal particles. Also, since this extruder head must be incorporated into a 3D printer, it will need to interface with a larger computer. A serial interface can accomplish that task. Overall, there is more work to do, work we are glad to do.

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5 - Appendix A Requirements and Verifications Table

Module	Requirements	Verification	Status
AC/DC Filter and Rectification	(1) Must adequately convert 120VAC at 60Hz to 24V, within 5%. (2) Must be able to supply at least 1A	(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. (2) With all circuits active, (motor and charging circuit active), the device is drawing approximately 1A. If all circuits have power (illuminated, moving), it is drawing approximately 1A.	Y
Voltage Regulation	(1) Lower voltage regulator outputs 5V +/- 5% from a input source of 24 volts.	(1) Using a digital multimeter, probe the outputs of the lower output voltage rail when regulator circuit is given 24V from a power supply. Check to see if the voltage is 5V.	Y

	(2) Must be able to supply at least 80mA.	(2) With the controller circuit active, (LEDs illuminated), the device is drawing approximately over 80mA. If all components have power (illuminated, changing state), it is drawing approximately 80mA.	
Microcontroller	(1) Controller transitions from idle to ready turning on the charging unit and the yellow led while turning off the green led when the on button is pressed in the idle state. (2) Controller transitions from ready to dispensing turning on the the motor and toggling the charging unit halfway through the cycle. The red led should be on and the yellow led should turn off. This state should complete automatically and return to the ready state when done. This transition only takes place in the ready state. (3) Controller transitions from ready to idle turning off the charging unit and the yellow led while turning on the green led when the on button is pressed in the ready state.	(1) Press the on button while the device is in the idle state and observe the state change. (2) Press the dispense button while the device is in the ready state and observe the state change. (3) Press the on button while the device is in the ready state and observe the state change.	Y

State LEDs	(1) Can be reliably illuminated to be visible from 1 meter away. (2) LED color can be clearly distinguished from 1 meter away.	(1) Stand 1m away and observe the leds. Assert that you can see the leds. (2) Stand 1m away and observe the leds. Assert that you can discern when the device changes state from this distance.	Y
Activation Buttons	(1) Outputs 5V (+/- 5%) as HIGH and < 0.5V as LOW signal. (2) Doesn’t shock user upon contact (insulated from 24V rail).	(1) Probe either side of the button with a multimeter. Assert that when the button is not pressed that the voltage across it is < 0.5V, and when pressed that it is 5V (+/- 5%) (2) Assert that touching the button does not induce shock.	N
Charging Driver	(1) Must be switched on from a signal of 5V (+/- 5%) and off from signal less than 2V (+/-5%). (2) Must be able to pass through 24V (+/- 5%) from power supply with maximum current draw of 20mA. (3) The circuit must not exceed 1V (+/-5%) on the logical input terminal when it is switched off. (4) The circuit must not exceed 6V (+/-5%) on the logical input terminal when it is switched on.	(1) Measure the current through the switching circuit with a multimeter. Assert that the circuit does not enter its on region until a base voltage is applied. (2) Test the voltage at the output of the circuit and verify it is within 5% of 24V. (3) Test the voltage at the input terminal when the circuit is switched off and 24V is applied across the load. Assert that the voltage does exceed the requirement. (4) Test the voltage at the input terminal when the circuit is switched on and 24V is applied across the load. Assert that the voltage does exceed the requirement.	Y
Stepper Motor	(1) Must be bipolar and 2-phase.	(1) Given a constant current source, simulate 2 sine	N

	(2) Rotates in discrete steps of at most 1 degree. (3) Step sizes are consistent.	waves, each 90 degrees apart. (Or attach to driver circuit). If drum rotates in discrete intervals of less than 1 degree (or after 180 steps the divot has rotated to opposite orientation), the step sizes are 1 degree. (2) Changing the direction on the driver circuit, count another 180 steps. If divot returns to original position, the step sizes are consistent.	
Stepper Motor Driver	(1) Takes 3 digital input signals (3.3V - 5V), for enabling, stepping and direction (2) Takes 24V power rail to output 2 stepper motor coil currents of .4A each. (3) Direction of each coil current must be variable. (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. (a) If enable is low, the voltage across the resistors should have a magnitude of 40V. If enable is high, probing should read 0V. (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. (c) Sine waveforms should have a -90 degree offset if the DIR input is set to the opposite state.	Y
Physical Design	(1) Safely apply a 24V voltage across metal powder to an insulated base.	(1) Attaching a 24V power supply to the copper basin and the lead on the charging drum, let metal	Y

	(2) Rotate at least 180 degrees, while holding small amounts of metal particles that are insulated from other electrical connections. (3) The charge to mass ratio for dropped particles must be at at least 4.08e-6 [C/g].	powder to rest in the powder chamber for a few seconds. Removing the leads without turning off the power supply, probe the leads across the metal powder. If the voltage has remains at 24V, the charge on the metal powder is within the range. Also, if the powder does not burst into flames, good job. (2) With the stepper motor active and stepping in one direction, watch the divot on the drum. Check if the divot traverse at least 180 degrees.	

Table 5 - R&V