E90 Report: Designing a Ceramic Printhead for a RepRap 3-D Printer

Luke Arnone
Advisor: Prof. Erik Cheever
Swarthmore College Department of Engineering

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1 Abstract

Building on an open-source RepRap 3D printer platform, an extruder for porcelain clay paste is developed and tested. Using a syringe-based, air pressure-driven extruder, objects are fabricated at a 3.3 mm resolution and 1.5 mm layer height, with a maximum object material volume of 20 cc.

Contents

2 Introduction

2.1 Background

2.1.1 3D printing

3D printing is an additive manufacturing process that works by building up layers of material to create a solid object. This process can be accomplished in a myriad of ways, however, the most widely used is fused deposition modeling (FDM), whereby a material, often molten plastic, is extruded in a thin bead by a computer-guided print head to complete each layer of the 3D object (Fig. 1). 3D printers are produced for a broad range of levels of use, from industrial selective laser sintering metal printers to hobbyist-grade products that can be built from kits. The RepRap project printers lie on the low end of this spectrum. The goal of the RepRap project is an open-source initiative to design a 3D printer that is built with as many 3D printed parts as possible, with the ideal of a self-replicating machine.

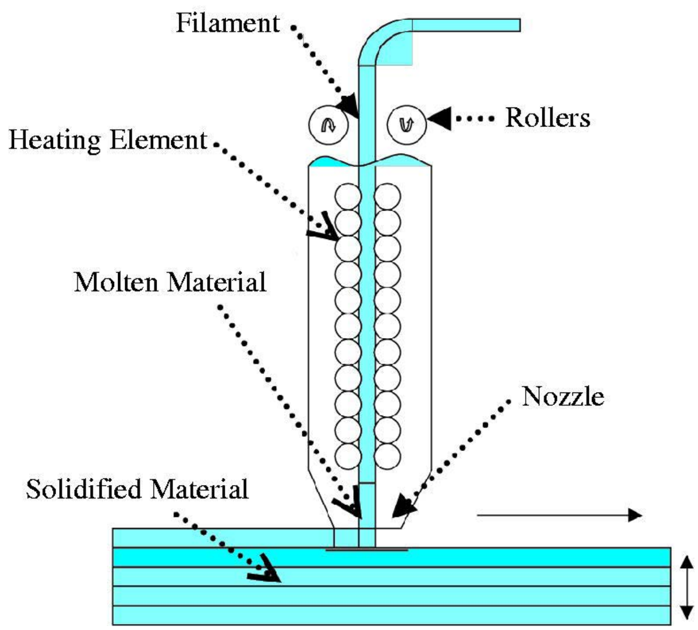

Figure 1: Cutaway diagram of FDM in plastic [1].

2.1.2 Ceramic material

Porcelain paste (Fig. 3) is a suitable material to use in FDM printing. It has a smooth consistency, thanks to a small, homogeneous particle size, and extrudes smoothly from a

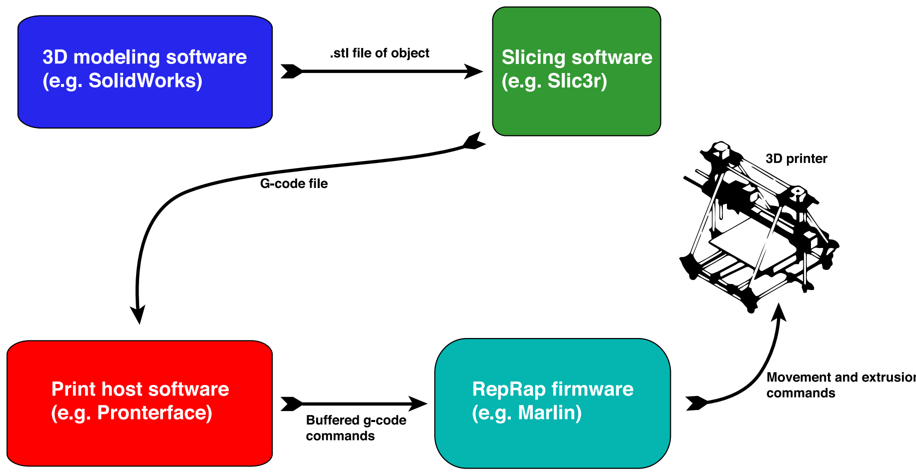

Figure 2: 3D printing workflow for a RepRap printer.

syringe. Wet clay binds readily to itself, and requires no heating or cooling to prepare it for extrusion. Once an object has been printed, the clay is allowed to dry, creating a brittle (bone-dry) object that must be fired in a kiln to a suitable temperature before it can be used. An additional firing can be made after glazing the piece.

Clay is a complex material, and an exploration of its properties alone could fill the space of several more projects entirely. For the purposes of this report, only basic information is included.

2.2 Existing solutions

Various groups have explored printing in ceramic material. A popular method is powder printing, where layers of ceramic powder are bound together with water or another binding agent. This allows for high resolution prints with highly complex shapes, as the unfixed powder acts as support for the printed part. The drawbacks of this method are the health hazards of free clay dust, which is carcinogenic, and the extensive post-processing required to finish a part. Additionally, the costs of commercial powder printing machines can be prohibitive.

Designers have achieved some success with a basic print head of a clay paste-filled syringe attached to a source of compressed air. The drawbacks of this system, however, are numerous. Because of the non-linear nature of the relationship between the air pressure, the amount of clay left in the syringe, and the flow rate of the clay, the pressure can often need to be adjusted by hand throughout the print. Additionally, oozing problems result when pressure is turned off, due to the latent pressure in the line between the compressor and syringe. Unfold, a leading exponent of ceramic extrusion for 3D printing based in Belgium, has dealt with this problem by modifying the print commands such that the model is one

Figure 3: Porcelain clay paste.

continuous toolpath, and the extruder never needs to be turned off [2]. Another issue is the finite volume of the syringe, which is limited to be small both by the commercial availability of massive syringes and the need for it to be precisely and often quickly moved by relatively small motors along a gantry. This constrains the build volume of the printer, or necessitates switching in a new syringe mid-print. Though the air pressure solution has many drawbacks, it remains the simplest and thus far most effective design for ceramic paste FDM printing, and is the primary focus for this project.

2.3 Motivation and goals

The RepRap project is an open-source initiative to design a 3D printer that is built with as many 3D printed parts as possible, with the ideal of a self-replicating machine. The upshot of this is increased accessibility to low-cost 3D printing solutions. Many RepRap designs exist, almost all of them FDM printers. This project seeks to create a low-cost system for FDM of ceramic paste for use in RepRap printers, and establish the calibration and tuning for this system, as well as best practices for its use.

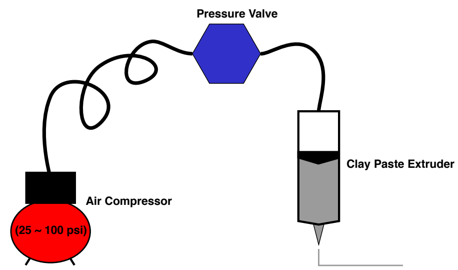

Figure 4: A simple pressure driven extruder design.

3 Cartesian control platform

3.1 Mechanical design

The movement of the Cartesian axes of the 3D plotter that forms the printhead controller of the printer is broken down into x-, y-, and z-axis movements (Fig. 5). The x-axis movement is provided by a gantry of two smooth rods on which the printhead carriage moves on linear bearings (Fig. 6). A toothed belt attached to the carriage is moved by a stepper motor mounted on one end of the gantry. The y-axis movement is provided by moving the print bed itself, perpendicular to the movement of the printhead carriage (Fig. 7). This movement is also controlled by a stepper motor linked to the print bed by a toothed belt. The z-axis movement is provided by two threaded rods on which the x-axis gantry is suspended (Fig. 8). The threaded rods are rotated in sync by two parallel stepper motors. The movement is guided by two smooth rods parallel to the threaded rods, attached to the x-axis gantry by linear bearings.

3.2 Electrical design

The motion of the Cartesian axes and the rate of extrusion in the existing RepRap design are controlled by Marlin firmware on an Arduino Mega microcontroller with a RAMPS (RepRap Arduino Mega Pololu Shield) mounted on top (containing stepper motor drivers, endstop pins, MOSFET terminals, and other necessary electronics). The Marlin firmware receives G-code commands from Pronterface, a 3d printing interface program, and translates them into stepper motor movements. The entire system is powered by a 12V DC power supply salvaged from an old PC.

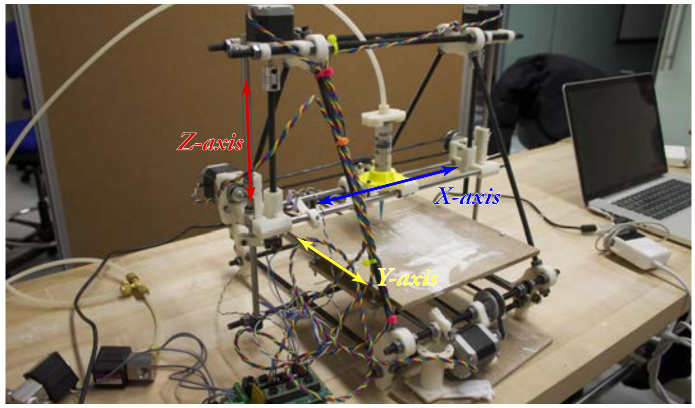

Figure 5: Axis control.

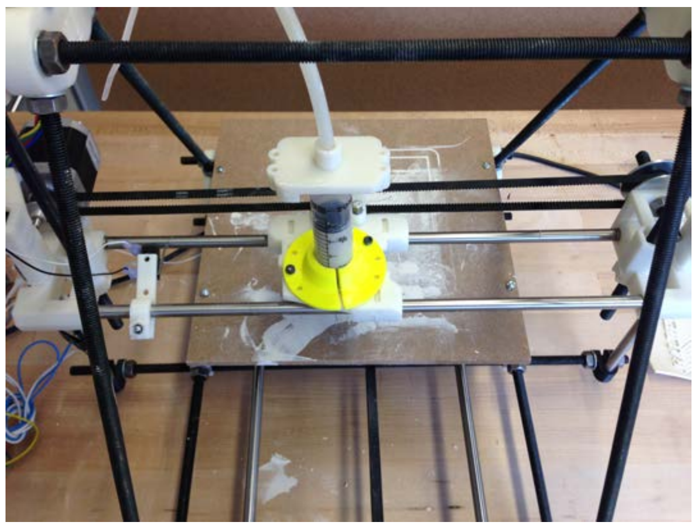

Figure 6: The x-axis gantry of the Prusa Mendel.

3.3 G-code control

G-code is a numerical control language used for controlling machining tools. The RepRap firmware makes use of a small portion of this extremely powerful and flexible language [3]. The most commonly used commands are G1 commands, which describe linear movement at a feedrate in X, Y, and Z space. The G1 command also supports extrusion, insofar as the it is also controlled by a stepper motor. A generic G1 command takes the form "X(next x- coordinate value) Y(coordinate) Z(coordinate) E(length of material to be extruded) F(feedrate)". The language also supports commands called "M-codes", or "machine commands", which offer miscellaneous functions to be selected. In the RepRap

Figure 7: Y-axis belt and plate.

firmware, M-codes are used to change the state of individual pins on the microcontroller, thus turning on or off various parts of the machine, such as heaters or fans.

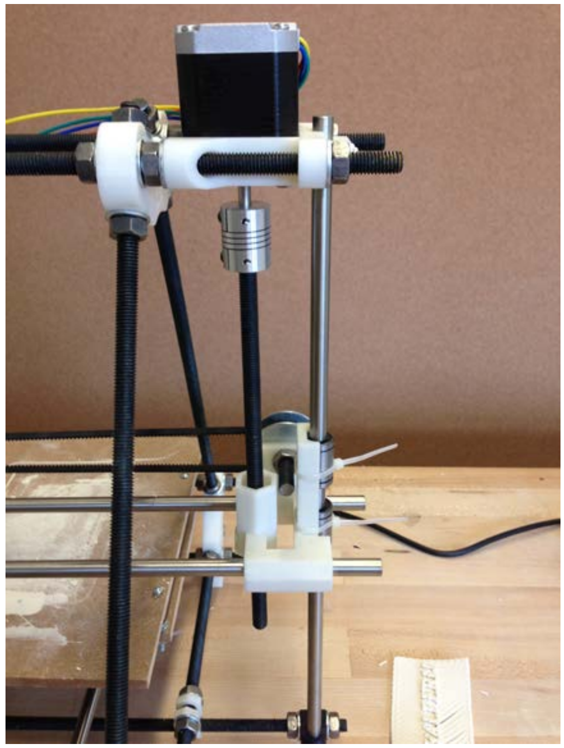

Figure 8: Z-axis threaded rod and smooth guide rod.

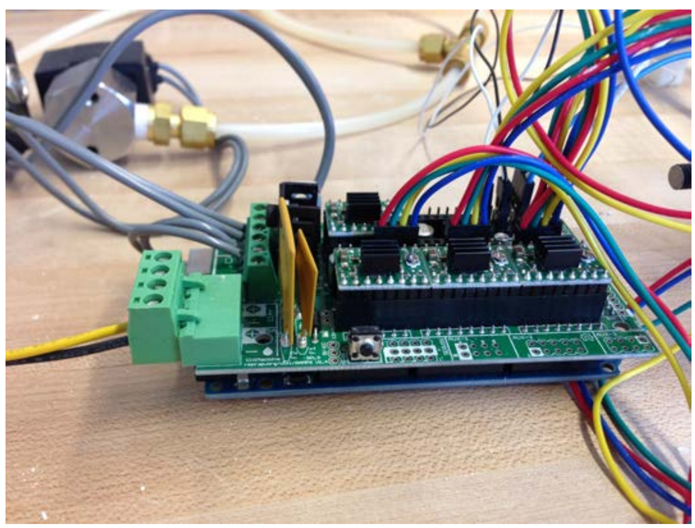

Figure 9: RAMPS electronics.

4 Extrusion

4.1 Stepper motor-driven extruders

The plastic filament extruder incorporated in the RepRap is driven by a geared stepper motor, which can receive commands that synchronize it with the movement of the stepper motor-driven Cartesian axis controls (Fig. 10). The first attempt at integrating a ceramic extruder was a stepper motor-driven positive displacement pump (PDP). A Moineau pump design was 3D printed using a commercial FDM printer (Fig. 11). Unfortunately, due to the tolerances required to operate the pump without leakage or jamming, this solution was abandoned.

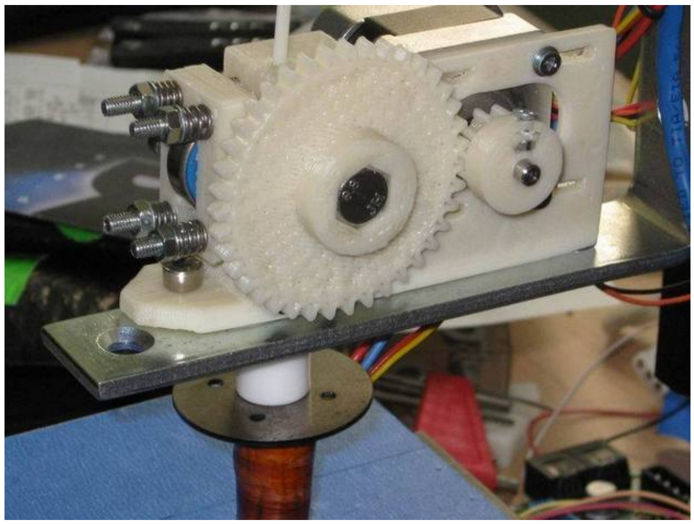

Figure 10: Wade's Geared extruder, a popular RepRap plastic filament extruder [4].

4.2 Air pressure-driven extruder

A second design was proposed, inspired by solder paste depositors. A source of compressed air was used to push on clay paste in a medical syringe, depositing it in a controlled fashion. A source of compressed air was attached to a solenoid valve, which controlled flow of air to a clay-filled syringe. A second line was connected from the syringe to a solenoid valve opening to atmospheric pressure. Without this blow-off valve, the pressure in the syringe would remain high even when the valve connecting the syringe to the compressor was closed, and material would continue to ooze out. When the blow-off valve is opened shortly after the closure of the pressure valve, the flow of material stops near-instantaneously.

The system is powered by an air compressor capable of ∼100 psi (∼7 bar). Two STC 12V two-way stainless steel solenoid valves were used, along with 1/4" tubing and Swage-

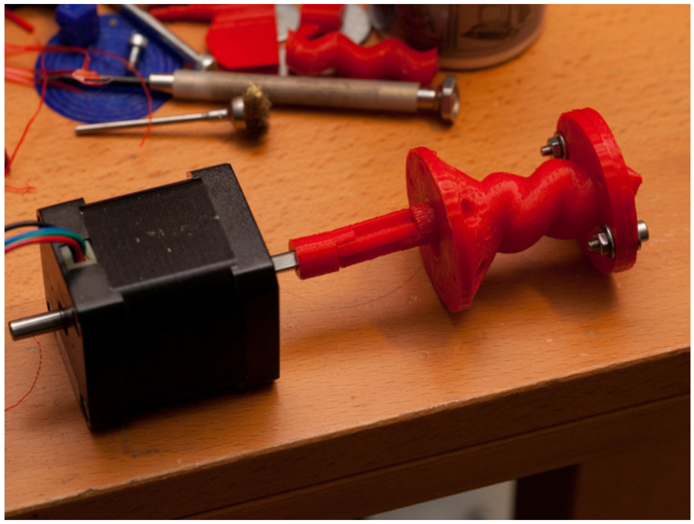

Figure 11: A stepper Moineau PDP [5].

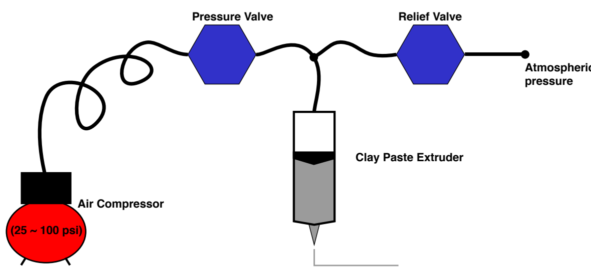

Figure 12: Solenoid valve system.

lok fittings. The syringe was attached to the tubing with a 3D printed adapter (Fig. 15) and sealed with a bored-out syringe plunger. The extruder was attached to the x-axis carriage with a 3D printed quick-change mount using a friction fitting (Fig. 17 and 18).

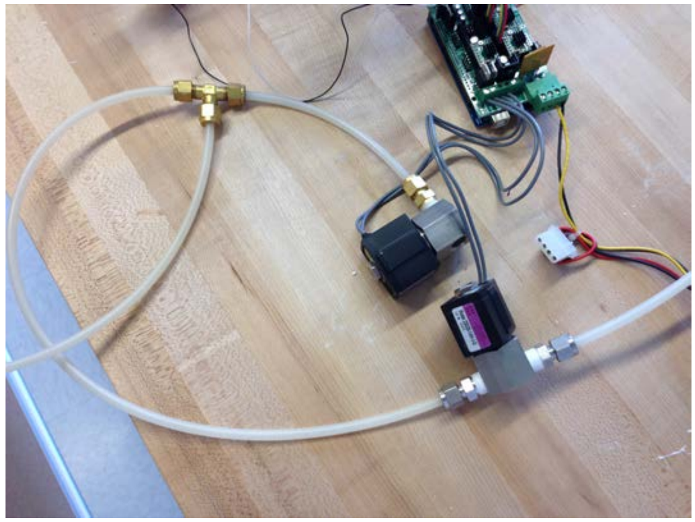

Figure 13: Solenoid valves attached to RAMPS electronics.

Figure 14: The air compressor.

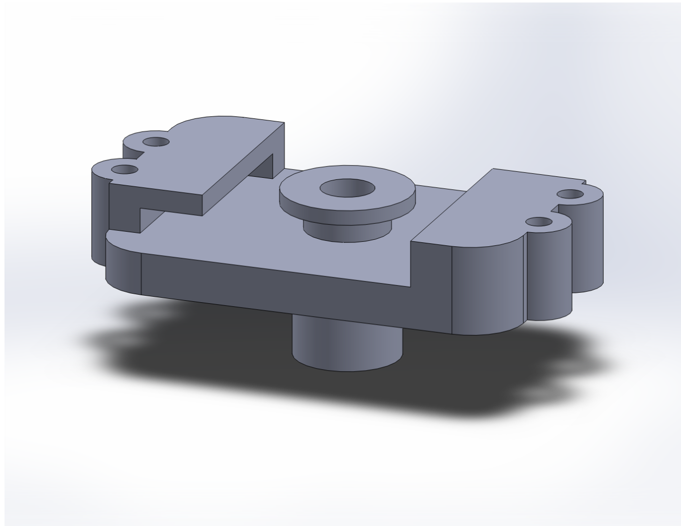

Figure 15: CAD model of the air pressure syringe adapter.

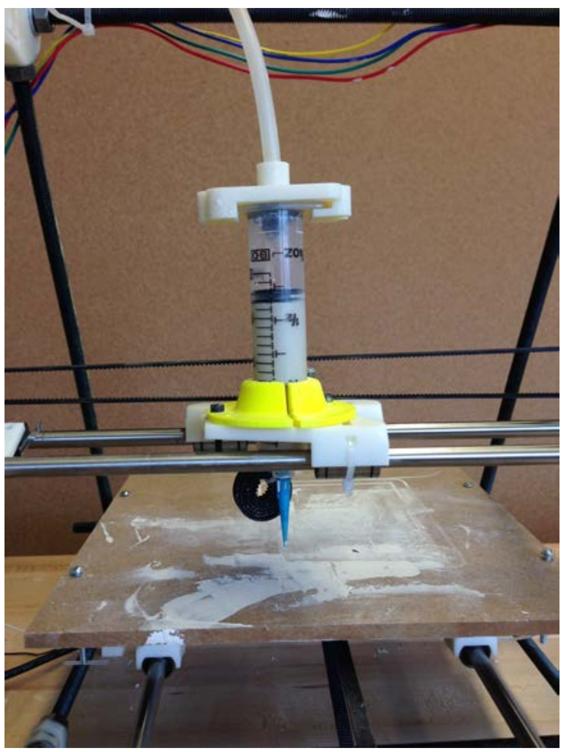

Figure 16: Finished clay-filled extruder.

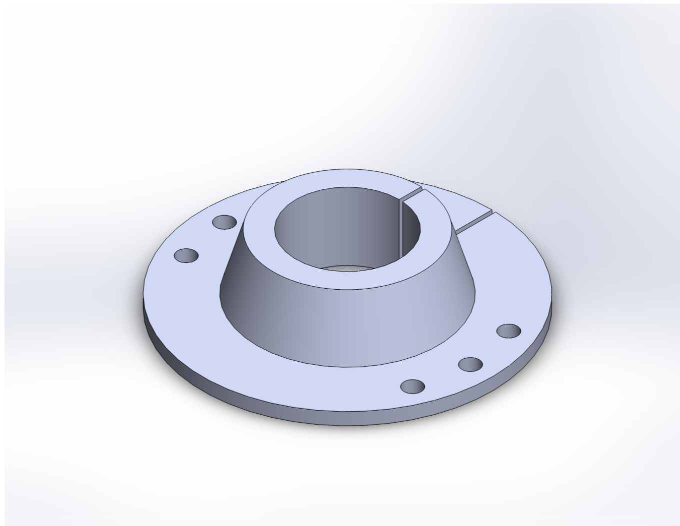

Figure 17: CAD model of the quick-change mount.

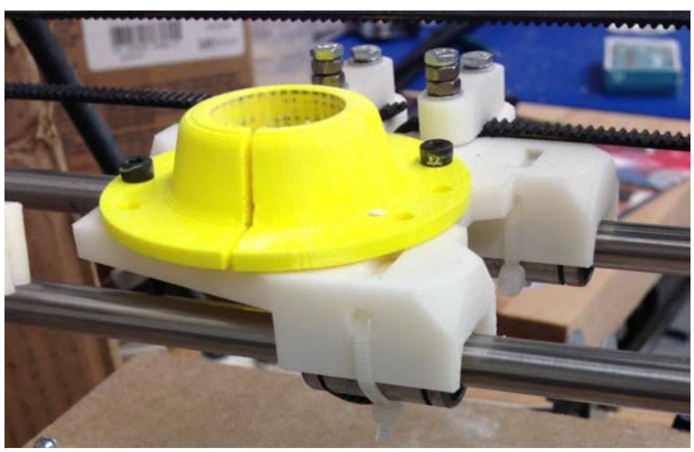

Figure 18: Quick-change friction fit extruder mount.

5 Firmware integration

Since most plastic filament extruders are driven by stepper motors, the commands for extrusion are expressed as distances for a stepper motor to rotate, in the same format as the axis control commands. This includes the capability for variable extrusion rate, synchronized with the speed of the extruders movement across the build surface. Because the syringe extruder design was a fixed-speed extruder with only two states (on or off), the firmware had to be modified to accommodate it.

An initial attempt to rectify this issue was to perform a check every time a command was processed to see if the commanded extrusion length was positive and turn the clay extruder on if it was. A MOSFET circuit controlled by an Arduino Uno was constructed in anticipation of this need. However, the Marlin firmware processes commands from the interface software as quickly as it can and stores the stepper commands in a buffer, so the switching of the clay extruder was desynchronized from the movement of the axes, rendering it ineffective. Fortunately, another modification to the firmware could make use of this buffering to effectively synchronize the movements of the axes with the state change of the extruder.

The RAMPS has several MOSFET terminals used for controlling an optional heated print bed and fan, which were unused in the clay-printing configuration. These terminals are perfect for controlling solenoid valves, and can have associated M-code commands for switching them on and off. In the firmware, cases for switching each terminal on and off were bound to unique M-code commands, which would be stored in the buffer in line with movement commands. The calculation of how to convert stepper extruder movements to valved extruder movements could then be shifted to a higher level, the explicit G-code commands handed to the firmware.

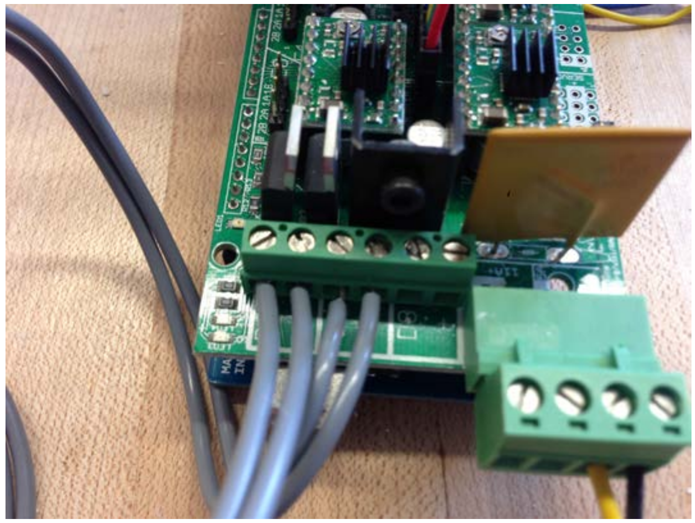

Figure 19: RAMPS MOSFET terminals.

6 G-code processing

The commands to turn the fan and heater on are bound to M106/M107 and M126/M127 respectively in the Marlin firmware. When either of these commands was interpreted, the firmware would change the state of the pin associated with the heater or the fan to what was commanded. These pins are connected to MOSFETs, as both devices draw a significant amount of current. For ease of use, the fan and heater pins were renamed as valve pins, though their functionality was essentially the same. The solenoid valves were attached to the terminals associated with the now-designated valve pins, and the M-codes were manually tested in the Pronterface command line. In order to continue to use Slic3r with minimal disruption, a simple Python script was written to process the .gcode text file. Every time extrusion is interrupted in Slic3r-outputted G-code, the extruder is given a retract command (e.g. E-1.000), and every time extrusion is about to begin, the extruder is primed with a small amount of material (e.g. E1.000). The script replaces every instance of these commands with commands to switch off the pressure to the extruder and vent; and turn on the extruder pressure, respectively (Fig. 20).

```
G1 X85.108 Y98.452 E0.18940
G1 X85.108 Y97.037 E0.10004
G1 X84.629 Y96.558 E0.04793

M107 ;(pressure off)
M126 ;(relief open)
G4 P150 ;(wait for pressure drop)
M127 ;(relief close)
G1 Z1.300 F7800.000
G1 X114.186 Y95.186

M106 ;(pressure on)
G4 P50 ;(wait for startup)
G1 X123.147 Y95.186 F3600.000 E1.05397
G1 X123.147 Y104.147 E1.05397
G1 X114.186 Y104.147 E1.05397
G1 X114.186 Y95.342 E1.03564
G1 X115.371 Y95.940 F7800.000
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Figure 20: Example modified G-code.

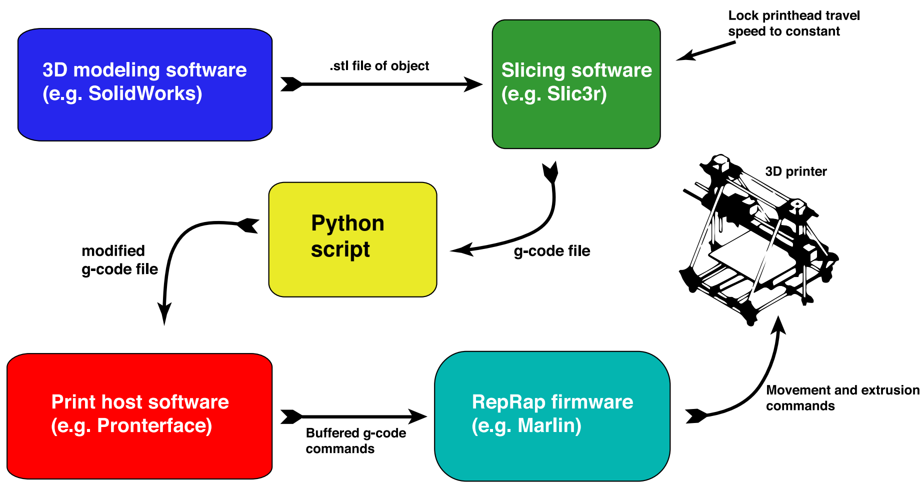

Figure 21: Modified workflow for printing with clay paste.

7 Usage best practices

7.1 Mixing clay

Laguna WC-617, a porcelain clay blend designed for throwing on the wheel, was used in this project. Conveniently, if dry clay has not been fired, it can be relatively easily reconstituted into workable material with the addition of water to pulverized scraps. The

Swarthmore College Art Department had both pre-mixed clay and dry scraps available for use. For speed, water was added to pre-mixed clay to wet it down into a paste. However, for precision and replicability, known quantities of water should be added.

To wet down moist clay, 1 cm-thick slices were cut from a larger block and rolled out onto a table. Water was added, and a fork was used to incorporate the water into the clay to create a homogeneous paste with the qualitative texture of "slightly thicker than toothpaste". This process was repeated for a number of other slices of clay. The resultant paste batches were mixed together with putty knives to further homogenize the clay and remove air bubbles.

To mix clay from dry powder, small quantities of powdered clay were added to batches of .5 L of water until the desired consistency was achieved. By this method, the mixture was homogenized with a large kitchen whisk and de-aired by physical agitation, i.e. striking the mixing vessel on a hard surface. Using recycled clay, it is paramount that the dry clay scraps be pulverized and sifted to ensure consistent chunk size. Very fine pebble sized (< 2 mm diameter) pieces and smaller are ideal. A mixture of larger pieces amongst powdered clay will result in pockets of drier clay in the final mixture which are hard to detect. These can be eliminated by sieving the paste through a > 30-mesh sieve, however, this process is labor-intensive and preferably avoided.

7.2 Loading the syringe

Once the clay paste has been mixed to the appropriate consistency and most air bubbles have been eliminated, it must be loaded into syringes that serve as the material vessel for the extruder. By removing the tapered luer-lock end of a syringe of the same type as is to be loaded, a handy clay loader can be fashioned [2].

A clay loader is used to suck up clay paste from an (ideally) airless mass of material. This dose of paste can then be transferred to an empty syringe by placing the opening of the loader into the top of the empty syringe and pushing the clay in with the plunger.

7.3 Calibration and settings

Due to various factors (measurement precision, humidity, mixing quality, pressure regulator imprecision and drift) outside reasonable control of the user, the exact rate of extrusion for a given pressure will vary from batch to batch. In order to compensate for this variability, the specific rate of extrusion must be determined empirically. In Pronterface, a macro is used which pressurizes the extruder for 1 second then releases the pressure. Using this macro, the length of clay paste extruded in 1 second can be physically measured (with a ruler or calipers) to determine the feedrate for the batch of paste in the extruder in mm/sec, the feedrate units required by Slic3r. This test can be repeated several times for confidence. The print settings in Slic3r should then be modified to synchronize the printhead movement with the rate of extrusion.

Figure 22: Mixing clay paste with putty knives.

Figure 23: An empty clay loader, made from a modified syringe.

The sliced .stl object is stored in a .gcode file which can then be processed into a .gcode

Figure 24: Sucking clay into the loader.

Figure 25: A full clay loader.

file that includes commands for starting and stopping the paste extruder and loaded into the print host software.

7.4 Printing and post-processing

Two options are available for printing: directly onto the MDF (medium-density fiberboard) printbed, or onto a removable square of flat material; in this case, sheetrock was used (due to easy availability). Both materials allow for good adherence of the first layer of clay paste, but using individual sheetrock squares allows for multiple objects to be printed in close succession without scraping down the print bed or waiting for long drying times. A

Figure 26: Pushing clay from loader to syringe.

Figure 27: Prepared syringes.

potentially more effective solution is to use thin slabs of plaster, a material which is used

Figure 28: Calibrating the feedrate by extruding for periods of 1 second.

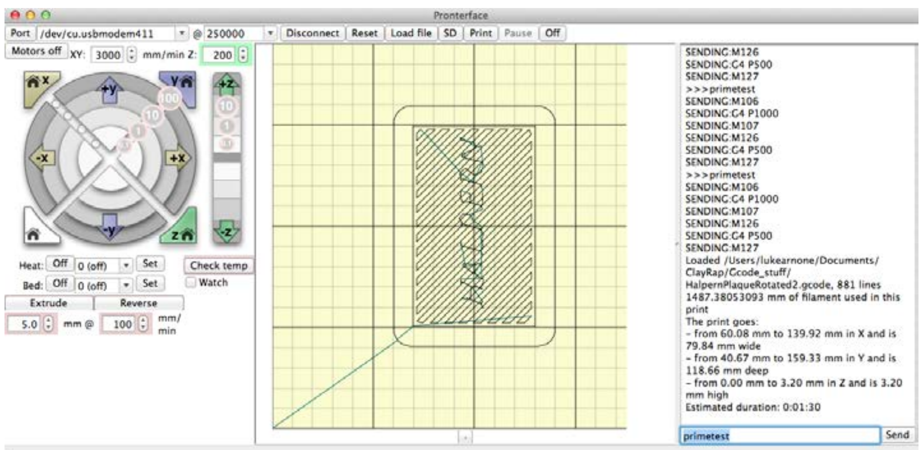

Figure 29: The Pronterface print host software during a print.

in traditional pottery for various purposes due to its fast-acting absorbency.

Once a print is completed, it can be left on its print surface to dry completely, at which point it will lose adherence and detach. In this state, the clay is hard and solid, but also very brittle; it is known to potters as "bone-dry". Once a piece is bone-dry, it can be bisque fired, usually to a temperature of ∼1000°C (n.B. firing temperatures are measured in terms of pyrometric cones which measure heat work, not temperature, though for the purposes of this report, final firing temperatures will be used for ease of understanding). This initial firing drives off the chemical water and other impurities bound up in the clay

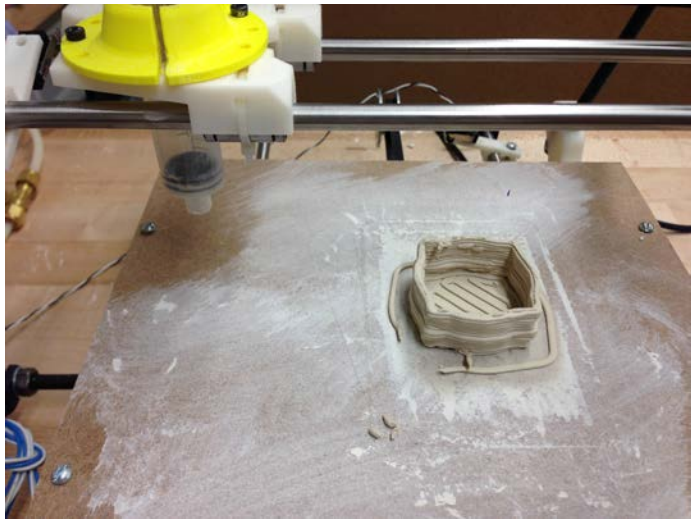

Figure 30: A small object printed directly on the MDF printbed.

and makes the object durable enough to be handled and absorb glaze. After glazing, the piece is fired again, this time (for this particular clay body) to ∼1200°C. The final fired object is dense, strong, and waterproof.

8 Results

An array of test objects was printed, at a range of different clay viscosities, print feedrates, and air pressures. Even within the same batch of mixed clay paste, there was a fairly high variability in empirically determined feedrates. This could be the case due to drift in the pressure supplied by the air compressor, which prompted tweaking which in turn affected the resultant extrusion rate. It is often less work to tune the pressure of the compressor to make the extrusion rate match some pre-determined value than to hold pressure constant and adjust the measured feedrate in the slicing software.

Attempts to print with luer-lock plastic dispensing tips had varying degrees of success. With clean nozzles with tip openings >1 mm, consistent extrusion rates were achieved throughout a single charge of a syringe. However, with repeated use (even when nozzles were soaked in water to loosen clay and subsequently cleaned), the extrusion rate drops off rapidly as clay begins to build up in the nozzle during a print. Due to this issue, after initial successful prints at relatively high resolution (1.5 mm), test prints were completed with no additional nozzle attached to the extruder. A solution to this issue could simply be to buy a large quantity of luer-lock dispensing tips and treat them as single-use, though this might not be cost effective or ecologically conscionable.

Fig. 33, a test of how tall an object could be before collapse, reveals that - for this

Figure 31: Halpern nameplate post-print.

Figure 32: Dried Halpern nameplate.

particular viscosity of clay - above a height of $\sim$ 3cm the weight of additional layers of clay begins to compress the lower layers, decreasing the effective layer height and increasing the gap between the top of the object and the tip of the extruder nozzle. The result is the "wriggling" effect that can be seen on the topmost layers of the part. A small fan or low-power hair dryer could be added to speed the drying time of prints, though this would have to be carefully monitored so as to avoid warping of the part due to uneven drying.

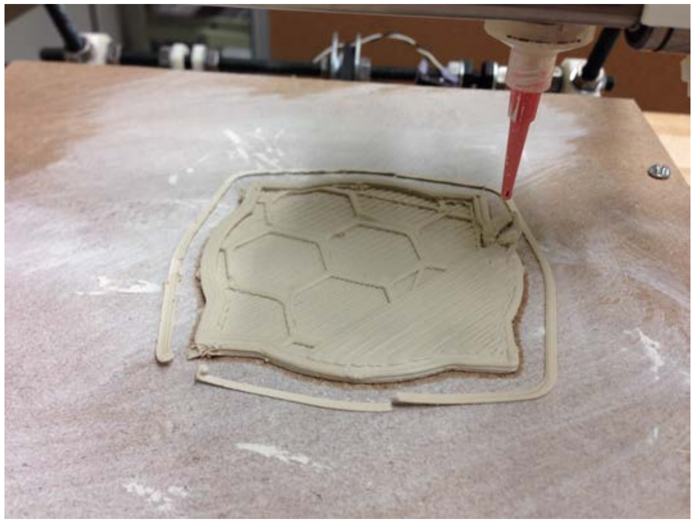

Figure 33: High-resolution print attempt.

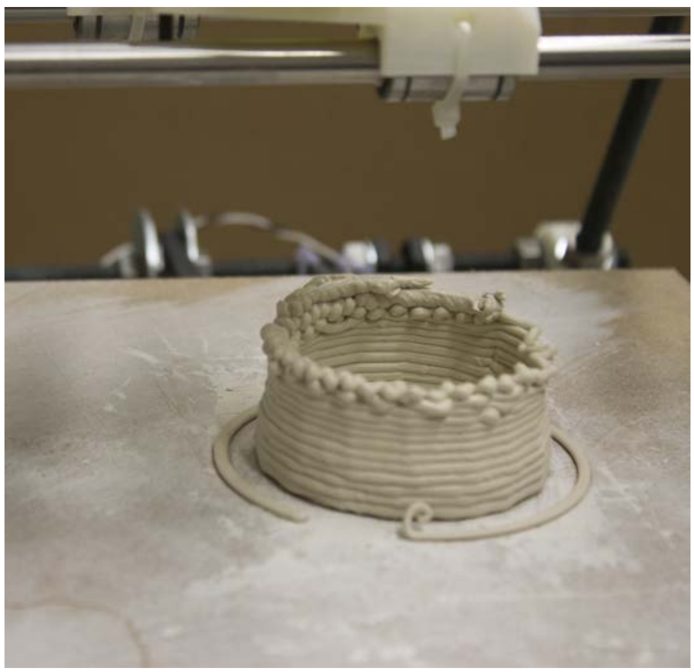

Figure 34: Slumping shown in height test print.

Future work should include a more careful characterization of the relationship between the clay to water mass ratio and extrusion rate at a given pressure, but for the purposes of finding a workable mixture for testing, 3000 g of dry powdered clay to 1 L of water is an acceptable "toothpaste" viscosity that represents a balance of flowability and structural stability. Likewise, it is unreasonable to expect to print objects at a feedrate greater than 60 mm/s, due to the rapid movement of the printbed. Finally, the system was not tested with pressures greater than 8 bar ($\sim$ 116psi), but using higher pressures without reinforcing the connection between the syringe and tubing or conducting strength tests of the syringes themselves seems unwise. bounds on usable clay viscosities, air pressures, and print feedrates.

9 Future work

The opportunities for future work on this project are numerous. Chief among them is increasing the build volume of the machine, most logically accomplished by using a larger syringe as housing for the extruder. Commercially available syringes are produced up to sizes around 140 cc, though these might necessitate a redesign of the x-axis carriage. Designing a control system to automatically adjust pressure during a print to maintain a constant flow rate of clay seems impractical - too many variables to measure, and the system is nonlinear. Increasing the print resolution is another logical further step. I abandoned this exploration in favor of printing as many objects as possible, but resolution increases represent the most significant increases in functionality besides increasing build volume. Finally, all of these enhancements are enabled by a more rigorous characterization of the behavior of the material being used. An analysis of the relationship of clay/water ratios to flow rate or an exploration of different clay bodies is also possible.

10 Conclusion

This project successfully demonstrated a method for extruding ceramic paste for use in FDM printing with a RepRap Prusa Mendel 3D printer, though it is compatible with any printer using Marlin firmware. Numerous small objects were printed at a resolution (layer height) of 2 mm. The project provides a platform for further exploration of ceramic 3D printing by both engineers and artists.

11 Acknowledgements

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