Real-time Active Mixing of Multi-part Silicone for 3D Printing Composite Materials for Smart Materials

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ABSTRACT

3D printing silicone rubber often relies on effective mixing of two part silicone. This is primarily done through the premixing of the silicone rubber before printing, this paper explores the option of mixing the silicone rubber as it is being printed. Mixing silicone rubber as it is printed allows for more flexibility in the types of silicone rubber that could be used. The specific type of mixer used in this paper is an active mixer.

Keywords

3D Printing, Silicone Rubber, Mixing, Composite Materials

1 Motivation

A Fused Deposition Modeling (FDM) printer is being designed to produce complex composite silicone rubber structures. The composition of the silicone rubber will be varied during the printing process, to allow for fully customised structures. Only the extrusion and mixing mechanism is being developed as then it can be attached to standard FDM printers. The produced structures will be used for sensory application through the use of a conductive composite silicone rubber, the conductivity changes when the silicone rubber is deformed.

Applications for such structures is in soft robots[1, 2] or use as a pressure sensor[3]. All of these applications have limited complexity in the design as they are cast, possibly requiring multiple casts in the case of [2]. The use of FDM printing of these objects would have reduced the effort required to create casts and increase the speed of developing prototypes. The extrusion mechanism requires development in control of flow rate, mixing ratio control, etc. The control of mixing ratio between various composites of silicone rubber allows for varied structures. Control of flow rate dictates traversal speed of the FDM printer. Low rates of flow can significantly slow the printer, while high hates of flow may require the FDM printer to move faster than it is capable.

This report will cover the development and testing of the mixer in the extrusion mechanism. The mixer requires the ability to fully mix multi-part silicone capable of varying compositions. For example, using two part silicone and three inputs of the mixer, input one could have part A of the silicone, input two could have part B, and input three could have part B mixed with carbon black. By varying the ratios of input two and three, the properties of the output silicone will change.

2 Background/Literature Review

There are a variety of existing methods implemented when 3D printing silicone rubber. A common approach is to prepare the silicone before printing to minimise complexity of the printer [1, 4, 5, 6, 7, 8, 9, 10]. The mixing of viscous fluids can be done effectively [11, 12], and even has been used in 3D printing of thermite [12]. There are two primary approaches to mixing of fluids, passive [11] and active [12].

2.1 Curing

Printing multiple layers of silicone can be a challenge due to the slow drying time of the silicone. There are multiple approaches to this problem depending on the type of silicone rubber being used [1, 7, 9, 8]. Some silicone rubbers can have cure speed accelerated through light, be it UV or IR light [7, 9, 8]. Cure acceleration can also be achieved through heat [1, 6].

2.2 Printing

Ignoring the requirements for preparation of silicone rubber, there were a variety of approaches of printing the silicone rubber. The use of electrostatic force to assist the silicone rubber temporarily adhering to the print bed [4], this requires the silicone rubber to mixed with materials that facilitate the use of electrostatic force. This approach allowed for improved printing resolution, though restricted the prints to being only a single layer [4].

The use of support structure is a common approach for building complex shapes in 3D printing. Support structure for the 3D prints of silicone is not the same as support structure for standard FDM 3D printing. The use of a recyclable micro-gel support system has been explored [5], allowing for 3D printing of complex silicone structures. A more limited but similar approach to support is 3D printing a mould as the silicone is being printed [6], this approach can be taken advantage to create moulds that can survive volcanization of the silicone rubber.

2.3 Material

Composite silicone rubbers result in unique useful properties that can be taken advantage of [2, 3, 13]. The addition of conductive powders into the silicone rubber allows the silicone rubber to be used as a sensor [2, 3, 13]. Using these silicone sensors as a pressure sensor is a common application as the conductivity of the silicone rubber changes as the material is deformed [13, 3]. Pressure sensors aren't the only useful sensor that can be made that takes advantage of change in conductivity as the silicone experiences deformation. Another possible application is measurement of the deflection of a soft gripper [2]. It is also possible to also mix other particles into silicone rubber for different uses, it has possible applications within the medical industry to be used as a drug delivery method [10].

3 Design

This design section covers the current state of designs for the 3D printer after all testing, shown in the results section, has been done.

3.1 Syringe Pump

3.1.1 The Problem

The extrusion of silicone rubber from a syringe is a slow process due to the high viscosity of silicone rubber before curing. Increasing the speed of extrusion helps significantly with printing of silicone rubber as it allows a higher 3D printing speeds. Increasing the velocity of the silicone rubber results in higher required pressures.

Another aspect that should also be considered is that uncured silicone rubber is compressible. This can cause results when testing method of extruding silicone as it induces a delay between compression and extrusion.

3.1.2 The Solution

The syringe pump that has been designed is shown in Figure 1. Pressure is applied to the syringe plunger from the stepper motor by moving the carriage up and down. Due to the single stepper motor being used in the design and limited space for the syringe pump the stepper motor is not axially aligned with the syringe. This misalignment results in the carriage becoming twisted and increasing the friction on the threaded rod. To account for this twist, a linear rail has been added to the opposite size of the carriage to reduce twist. Though this solution does not completely remove the induced twist.
The syringe pump is also designed to be capable of taking many different types and sizes of syringes. The syringe interface on the top of the syringe pump can be quickly redesigned and laser cut to accommodate larger syringes. Longer syringes can also be used as the carriage that can translate upto 250mm.

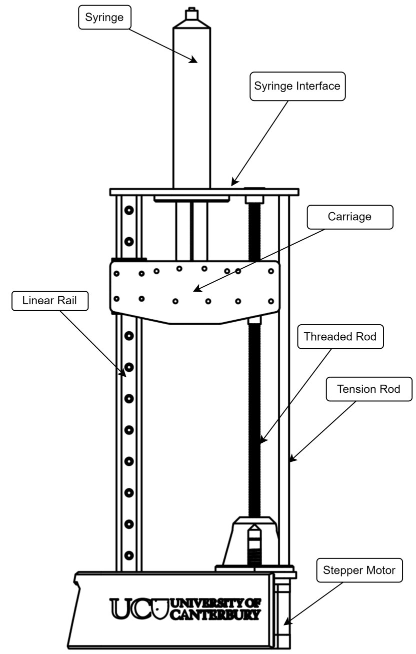

Figure 1: Syringe Pump Design

The compressibility of silicone rubber though a factor that affects the silicone pump, has very little impact. Expansion of the syringe, flex in the frame the silicone pump, and expansion of the tubing used to transport silicone have a very similar effect on printing as the compressibility of the silicone rubber. Due to this, the compressibility of the silicone can be ignored as an effect by itself and grouped with other similar effects and account for them through a single method to account for the delay.

3.2 Static Mixer

3.2.1 The Problem

With two part silicone rubber requiring to be mixed before it begins curing, finding an approach to effectively mix the silicone is required. The solution that has been created to full-fill this roll is an active mixer. Before creating an active mixer, all other systems should be proven to be fit for purpose to minimise points of failure.

3.2.2 *The Solution*

The static mixer requires the two part silicone to be pumped through it, while minimising leaking. Figure 2 shows the designed implementation. Part A and Part B of the silicone rubber is pumped through two holes on the top of the mixer body (green cross-section), they are combined into a single stream before entering the static mixer. The static mixer is clamped against the output hole for the combined silicone rubber stream using mixer clamp nut (blue cross-section). An o-ring is also used to improve the seal between the static mixer and mixing body.

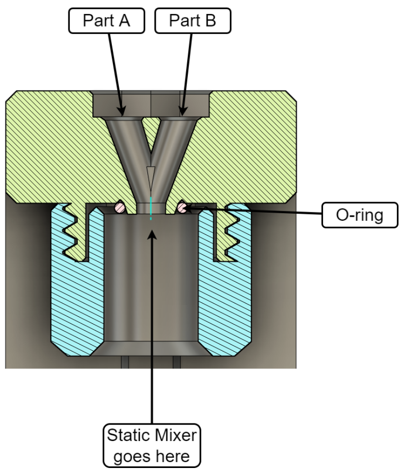

Figure 2: Static Mixer extruder head design

The mixer body is attached a FDM printer and has the silicone fed to the mixing body using two silicone pumps. This can be seen in Figure 3.

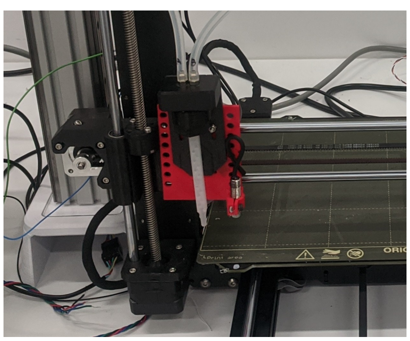

Figure 3: Static Mixer attached to FDM printer

3.3 Active Mixer

3.3.1 *The Problem*

Decreasing the back pressure added by the static mixer helps with improving the consistency of the 3D printer. The mixer design being implemented is shown in Figure 4, this mixer design holds strong similarities to the thermite mixer [12].

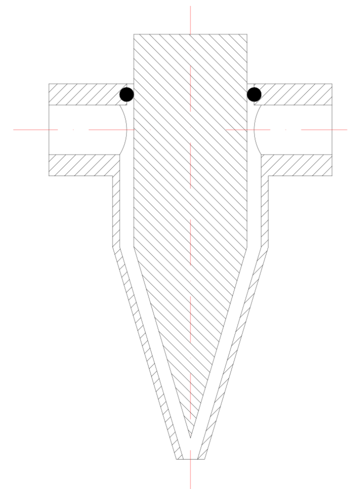

Figure 4: Core Concept of active mixer based on [12]

3.3.2 *Impeller*

The impeller was designed to minimize difficulty to manufacture while still being fit for purpose. This was done by decreasing the number of manufacturing steps. Figure 5 shows what the impeller looks like. The coupler interface has a 6mm diameter, while the main body is 4mm in diameter, the impeller then tapers to a point. This taper is intended to be inside a disposable dispensing tip and follow the internal taper of the dispensing tip.

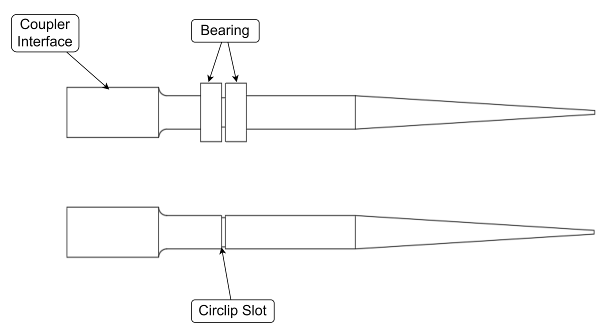

Figure 5: Design of Impeller

Two bearings is being used to keep the impeller aligned correctly when installed inside the mixer body. To stop the impeller translating along the rotation axis a circlip is added between the two bearings inside the circlip slot.

3.3.3 Mixer Body

Figure 6 shows the full assembly for the mixing body. The body is made of four stacked parts, each part serves a different function. Part one, the top part in Figure 6, is used to hold bearings in place. Part two, primarily is used to hold bearings in place, but also has features to accommodate a seal with part three. Part three is the primary mixing body, having an input for both parts of the two part silicone rubber and allowing the silicone rubber to contact the impeller for mixing. There are also features to allow for o-rings to seal between part two and part four. Part four is the final part in the stack and has a luer-lock thread to accommodate the disposable dispensing tip. At the base of this thread an o-ring is placed to seal the dispensing tip to the mixing body and help lock the dispensing tip in place. The dispensing tip has a 0.41mm nozzle diameter.

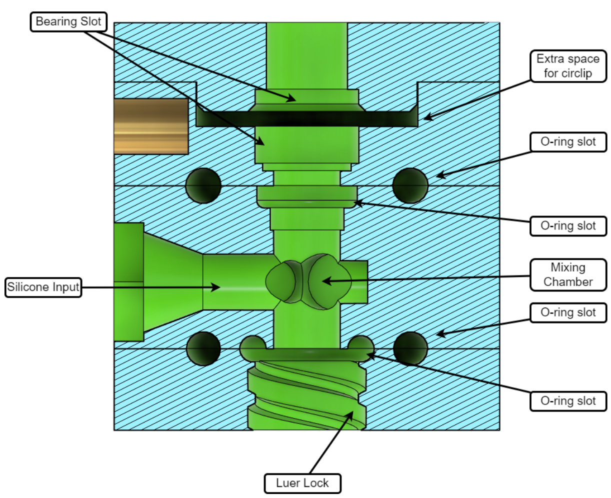

Figure 6: Design of mixing body

Figure 7 shows the mixing body with the impeller and bearings installed.

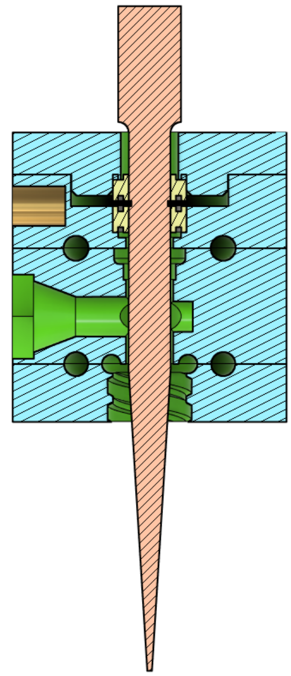

Figure 7: Mixing body with impeller

Figure 8 shows an external view of the mixing body. The two inputs for the silicone are separated by 120^o. This is why Figure 6 and Figure 7 only show one of the silicone inputs. Each input has a hexagonal shape to accommodate an M5 nut to be epoxied into place, this nut is for attaching a tubing adapter.

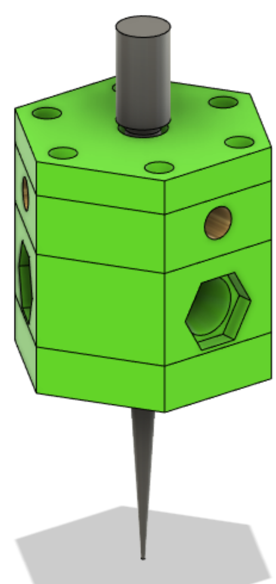

Figure 8: 3D view of the mixing body

3.3.4 Work Head

The work head attaches the mixing body to the 3D printer and attaches a stepper motor to the impeller for mixing. Figure 9 shows the work head design. Above the mixing body, the work head has been designed to allow easy access to the coupler that is installed between the stepper motor and the impeller. This easy access allows the coupler to be adjusted to align the impeller and stepper motor to reduce deflection of the impeller tip.

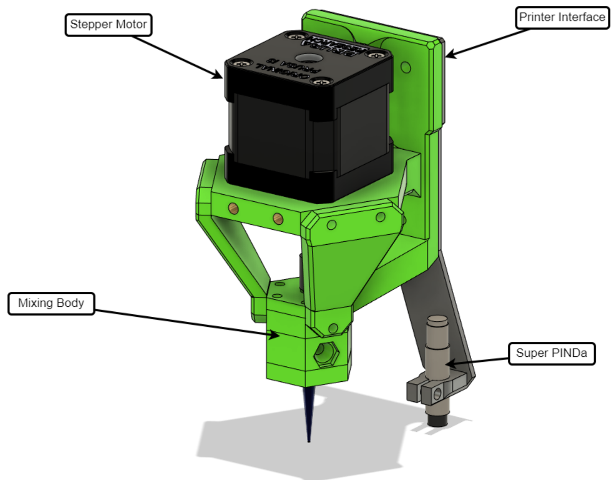

Figure 9: 3D view of full head

The stepper motor is controlled by an Arduino Nano and a stepper motor driver. Driving the stepper motor is enabled and disabled through Gcode as the Arduino Nano is connected to the 3D Printer controller board.

3.4 Print Settings

3.4.1 The Problem

The settings used for the silicone 3D printer have major bearing on the output of the printer. Filament diameter affects the amount of extruded silicone per mm of travel. Max volumetric speed affects the maximum volume of silicone that can be extruded per second. The temperature of the print bed affects the silicone cure speed and quality. Custom g-code can be used to add behaviours that can make using the printer simpler or account for quirks that printing silicone rubber has. Changing the types of infill also can have significant bearing on the internal strength of the printed parts as it can change the way the silicone cures.

3.4.2 Settings

Table 1 shows the settings that were changed from default to have the 3D printer successfully print silicone. The slicer used was the PrusaSlicer.

Table 1: Settings used for the printer

Print Setting	Value
Filament Diameter	35.71 mm
Max Volumetric Speed	2mm$^3/s$
Bed Temperature	80^oC
Bottom/Top Infill Pattern	Monotomic
Layer Height	0.2mm
Retraction Length	0.1mm (can't be zero)
Retraction Lift Z	1mm

- Filament Diameter - 35.71mm
  - Originally calculated based on syringe diameters, then experimentally tuned to improve filament layer height accuracy.
- Max Volumetric Speed $2mm^3/s$
  - Experimentally tuned to achieve acceptable printing speed.
- Bed Temperature - 80^oC
  - Chosen to increase speed of curing of the silicone, though this high of temperature may have detrimental effects on the curing process.
- Bottom/Top Infill Pattern - Monotomic
  - This is the default, though should be mentioned as there are likely better options that could improve print quality. For example conenctric may improve results.
- Layer Height - 0.2mm
  - Standard layer height produced by 3D printers and is a layer height that is easy to measure for.
- Retraction Length - 0.1mm
  - Would be zero but is required for retraction to be enabled, as this retracts the filament and that doesn't work with silicone rubber due to the slow change in flow rate.
- Retraction Z lift - 1mm
  - Lifts the z-axis by 1mm when filament retraction occurs. Done to reduce damage to printed parts due the nozzle being dragged through the printed part.

3.4.3 *Custom G-code*

Custom G-code has been added to improve simplicity of use with the 3D printer and improve print quality.

Start G-code:

```
G28 ; home all axes
G1 Z5 F5000 ; lift nozzle
M42 P73 S255 ; Start mixer
G1 E1.5 X3 F1500 ; Sit still and extrude to get the
flow rate running a consistent speed
G4 S60 ; Wait for a minute for flow rate to stabilize
```

End G-code:

```
M104 S0 ; turn off temperature
G1 Z5 F5000 ; lift nozzle
G28 X0 ; home X axis
G28 Y0 ; home Y axis
M42 P73 S0 ; Stop mixer
M84 ; disable motors
```

4 RESULTS

To produce an effective Silicone 3D Printer the printing mechanism requires tuning.

4.1 Active Mixer

Initial testing displayed in Table 2 was conducted to increase the velocity of the printer while still thoroughly mixing the silicone before extrusion. The mixer is run at 30 rpm for all tests.

Table 2: Testing flow rates

Test No.	Volumetric Flow Velocity (mm^3/s)	Filament Diameter (mm)	Print Thickness (mm)
Test 1	1.3	19.9	null
Test 2	2	19.9	null

Further testing was done to tune the filament diameter, the results are shown in Table 3. The filament diameter of 19.9mm results in over extrusion, to choose the next filament diameter an equation was created. Equation 1 calculates the new filament diameter (d_{new}) based on the old filament diameter (d_{old}) and the ratio of the thickness of the printed silicone (t_p) and the target thickness (t_t). The ratio is applied to the area of the filament resulting in the square root in Equation 1.

$$d_{new} = \sqrt{\frac{t_p}{t_t} d_{old}} \tag{1}$$

Table 3: Testing filament diameters and pre-extrusion amount

Test No.	Pre-extrusion amount	Filament Diameter (mm)	Print Thickness (mm)
Test 2	1	19.9	null
Test 3	0.5	19.9	0.23-0.46
Test 4	0.5	30.18	0.26-0.28

Figure 10 shows the 3D printed silicone squares for test 3. There is notable damage to the squares four and eight, due to the nozzle being dragged through the square as they being printed.

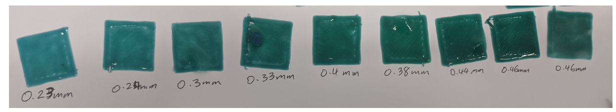

Figure 10: The nine silicone squares printed for test 3

5 Discussion

Each test in the results had different inputs, this has been done to tune different parts of the 3D printer. Test 1 and 2 were conducted to increase the max print speed of the printer. These values were only tuned to a point where the printer was achieving the 9 square prints in approximately 10 minutes. Due to the slow response time that the silicone changes flow speed relative to changes in pressure applied from the syringe pumps, too high of a max volumetric flow velocity can result in under-extrusion.

Due to the initial filament diameter of 19.9mm resulting in over extrusion, the max volumetric flow velocity setting countinued to result in over-extrusion when increased. Test 1 was conducted at $1.4mm^3/s$ for the volumetric flow velocity. Over-extrusion still being present allowed further increase of the volumetric flow velocity to $2mm^3/s$ for test 2. Test 2 had over-extrusion occurring, as such the max volumetric flow rate can still be further increased. No further testing has been done, though further testing is required for more certainty in results and fault finding.

Test 3 and Test 4 were conducted to reduce the significant over-extrusion that was occurring. Test 4 with a filament diameter of 30.18mm produced the most consistent results with the smallest variation in print thickness, and closest average thickness of the silicone to the target thickness of 0.2mm. Further development is required to have the printed thickness be equal to target thickness.

6 Further Development

6.1 Active Mixer

6.1.1 *Nozzle Wobble*

Due to the approach of having the impeller and stepper motor having a rigid attachment any miss-alignment of the impeller and stepper motor with any other part of the printing head results in wobble of the output nozzle. This wobble can be mitigated through trial and error of making small adjustments to how everything is mounted, though this can take a long time.

If the impeller and stepper motor only pass rotation around a single axis between the objects this would minimize wobble. The requirements of such a system would be that there can be minor position displacement, upto approximately 3mm of displacement between the the impeller and stepper motor, and minor rotational displacement of upto approximately 5^o.

Due to no longer having the rigid attachment between the impeller and stepper motor the impeller may not be able stay axially aligned. An extra bearing should be added that is further from the existing bearings. This may require a change in impeller design or could be added to the part that removes the requirement for rigid attachment to the stepper motor.

6.1.2 Sealing

Currently the active mixer body has significant leaking problems, silicone leaks from between the different layers of the body and given enough operation time the silicone can leak through the layers of the 3D printed body.

Multiple steps can be taken to reduce the problem with leaking. Improved tolerances around seals, reduce the number of layers in the mixing body, and machining the mixing body out of piece of uniform material (nylon, aluminium, steel, etc).

6.1.3 Multi-layer Printing

In the current state, the 3D printer is incapable of printing more than a single layer effectively. This is due to that the silicone being used cures in 30 minutes, the cure time is faster at higher temperatures though can have negative effects on the cured silicone rubber if cured too quickly. As a new layer is being printed atop a existing layer, the new layer can flow off the layer. Figure 11 is a representation of what would happen if two layers were to be printed.

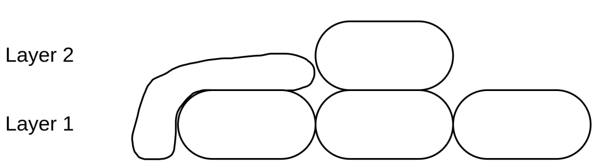

Figure 11: Silicone flow on two layer print

A possible method to keep the silicone from flowing after being printed is to heat the outside to cure the surface rapidly. Figure 12 shows a possible configuration for a shroud that could direct hot air, shown in red, towards the end of the nozzle.

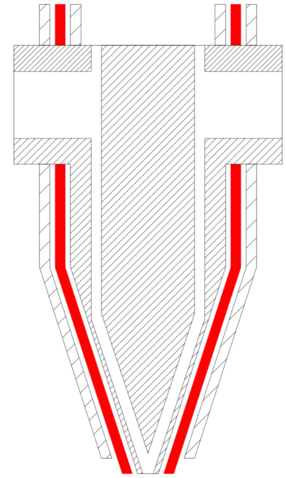

Figure 12: Active Mixer with hot air shroud

6.2 Slicing and Related Curing Complications

Currently the slicer software is generating G-code designed for an FDM printer using a thermoplastic, as such the slicer relies on the properties of thermoplastics to print. Silicone once printed cannot be "uncured" like a thermoplastic can be reheated, as such adhesion between layers and even internal adhesion within a layer may not be as strong.

The less cured silicone is when new silicone is printed beside it, the better the bond between the two strips of silicone. This means a modified slicer would have to minimise the amount of time between printing a strip of silicone and a neighbouring strip of silicone. Figure 13 shows an example of changing how a square is printed, the adhesion between silicone strips could be improved. By doing the full perimeter of the square in approach Figure 13.1 it takes 31 units before the side by side printing at the red circle location occurs. Figure 13.2 is printing the entire square by repeatedly moving back and fourth, reducing the distance traveled to 16 units for side by side printing and there by decreasing time the silicone has had to cure within the red circle.

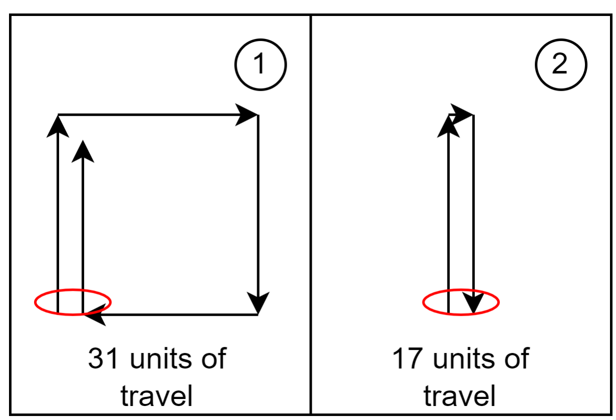

Figure 13: Travel distance before side by side printing

6.3 Multi-Material Printing

Currently the silicone printer has only been tested with silicone rubber mixed with silicone dye. Testing and development of systems capable of handling composite materials is required. The mixing of carbon black or other materials into the silicone rubber will have unknown effects of the printer. These unknown effects come from material propriety changes, like changes in viscosity or curing times.

Once the silicone rubber composites have had testing done, multi-material printing become a possible path to explore. Due to the way the silicone mixer has been designed it is possible to change the composition of the silicone rubber being printed during a print. This allows behaviour similar to the Prusa MMU2S, changing the printing material during a print.

7 Conclusion

The developed 3D printer is capable of printing object with consistent dimensions. Currently more development is required for the produced prints to have dimensions of the targeted dimensions. Printed thickness is 0.07mm thicker than target thickness, and target width and depth accuracy isn't known due to nozzle wobble. Nozzle wobble is possible to reduce but currently requires significant time and effort to fully remove, further development of the active mixer is recommended to fix this problem.

The syringe pump is effective and is capable currently handling syringes filled with silicone rubber mixed with silicone rubber dye. The syringe pump has not been tested using different silicone rubber composites, like a carbon black mixed with silicone rubber. Due to the effect of using smaller internal diameter tubes with the syringe pump, changes in the properties of the silicone rubber composites could have significant detrimental effects on flow.

Slicer settings are currently tuned to produce accurate prints when ignoring physical limitations in the active mixer. Current settings have a focus on quickly producing prints to speed up testing of different settings, as such currently the printer heated bed is set to 80^{o}C, this high of a temperature can result in reduced quality of silicone rubber once cured.

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