NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

INTELLIGENT SYSTEMS DIVISION, ENGINEERING LAB

DEVELOPMENT OF A SOFT MATERIAL 3D PRINTER FOR ADVANCING CAPABILITIES IN SOFT ROBOTICS AT NIST

SOP for Soft Material Printer

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Audience: Users who are required to print on the soft material printer.

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Disclaimer

Certain trade names and company products are mentioned in the text or identified in certain illustrations. In no case does such an identification imply recommendation or endorsement by the NIST, nor does it imply that the products are necessarily the best available for the purpose.

Change Log

Problem Statement & Scope

The purpose of this documentation is to provide step-by-step instructions guiding users on how to use the soft material printer.

The scope shall be limited to describing the current methods for printing and should be updated if changes are made to the printer.

Goal

To provide a reference to users when printing elastomers or other soft materials with the soft material printer.

Requirements

Before using the soft material printer, the user should undergo appropriate safety training and prepare the Lulzbot Cura environment to simplify working with the printer.

Safety Training

To use the soft material printer, you must have undergone NIST's chemical safety training. If you have not completed this training, contact either your advisor or the division's current Safety Manager to get the proper training assigned.

After completing the safety training, you should also familiarize yourself with the Soft Robotics Material Manufacturing SOP.

Download the GitHub Repository

1. Contact Jennifer Case (jennifer.case@nist.gov) to get access to the GitHub repository.
2. [Optional] Download GitHub Desktop to manage repositories on the computer:

   https://desktop.github.com/

3. Pull the exploratory-soft-printer using GitHub Desktop or a preferred Git manager to desired location.

Lulzbot Cura Environment

1. If needed, download Lulzbot Cura from https://lulzbot.com/support/cura.
2. Add the Taz Pro printer to Cura:
   (a) Settings »Printer »Add Printer...
   (b) Select the TAZ Pro printer.
   (c) Select the SE | 0.5 mm | Nickel Plated Copper tool head.
   (d) Select Add Printer.
   (e) Another screen should appear that specifies various parameters including the Start Gcode and End Gcode. If you already have the Cura software installed and the TAZ Pro added, this window can be found via Settings »Printer »Manage Printers... »TAZ Pro »Machine Settings.
   (f) Edit Start Gcode (this Gcode can also be copied and pasted from `Start_and_End_Gcodes.txt` in the `exploratory-soft-printer\Documentation` folder):

```
;This G-Code has been generated specifically for LulzBot TAZ Pro
    with SE Tool Head - edited by J. Case 8/22/2023 for printing
    soft materials
;
;The following lines can be uncommented for printer specific fine
    tuning
;More information can be found at https://marlinfw.org/meta/gcode/
;
M73 P0                  ; clear LCD progress bar
M75                     ; Start LCD Print Timer
G26                     ; disable fans
M107          ; disable fans
M420 S0                 ; disable leveling matrix
G90           ; absolute positioning
```

```
M82           ; set extruder to absolute mode
G92 E0          ; set extruder position to 0
G1 X240 Y270 Z60 F3000   ; move to printing position
M117 Fast purge (~3.8 min); progress indicator message on LCD
G1 E500 F130
M400          ; wait for moves to finish
M117 Slow purge (~12.5 min); progress indicator on LCD
G1 E1500 F80
M400
M117 Printing...        ; print complete message
```

(g) Edit End Gcode (this Gcode can also be copied and pasted from `Start_and_End_Gcodes.txt` in the `exploratory-soft-printer\Documentation` folder):

```
M400                                    ; wait for moves to finish
G1 X240 Y270 Z60 F3000                  ; move to cooling position
M400            ; wait for moves to finish
M77           ; End LCD Print Timer
G90                                     ; absolute positioning
M18 X Y E         ; turn off x y and e axis
M117 Print Complete.                    ; print complete message
```

(h) Select the Hot End tab.

(i) Change the nozzle size to 1 mm.

3. Add "Elastomer" as a material to Cura:

(a) Settings »Material »Manage Materials...

(b) Select Import.

(c) Navigate to the `exploratory-soft-printer\Documentation` folder and open `elastomer.xml.fdm_material`.

(d) Select close.

(e) On the right side of the screen, change the material to Elastomer.

(f) On the right side of the screen, under Print Setup, select Custom.

(g) Open up the Material submenu that should have appeared and change Printing Temperature Initial Layer to 0, as shown in Figure 1.

(h) Additional tuning will need to be specified in the future with regards to material diameter and nozzle size since these will likely influence the print speed.

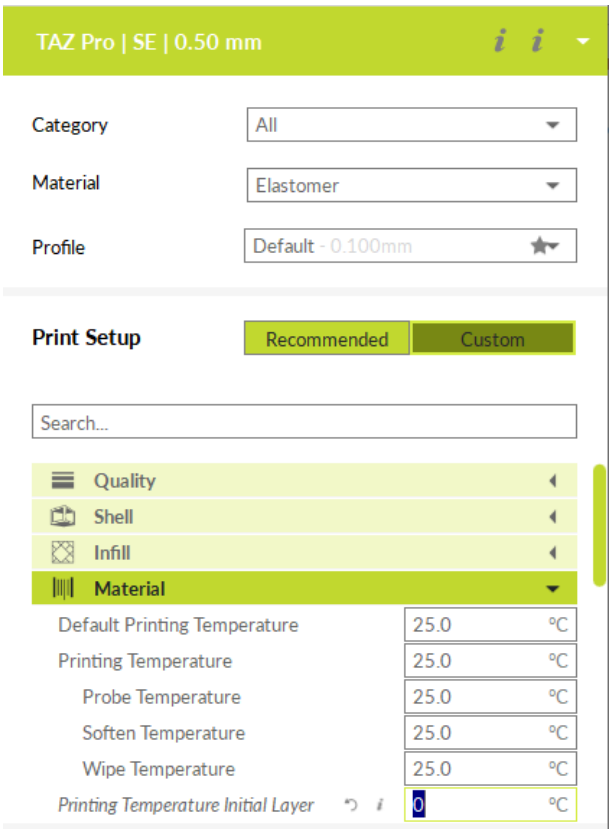

Fig. 1. Screen capture showing Printing Temperature Initial Layer.

1. Introduction

The Soft Robotics Lab (SRL) at NIST has developed a soft material printer (Coral) capable of printing 2-part elastomers using direct ink writing techniques [1–3]. Similar to the work of Walker *et al.* [4], this printer is adapted from an off-the-shelf open-source fused deposition modeling 3D printer. This printer has replaced the thermoplastic filament extruder with a custom-built syringe pump, printhead, and heated chamber. This document explains how to assemble, run, and maintain the printer. Assembly instructions for each of the equipment (i.e., syringe pump, printhead, and heated chamber) can be found in the exploratory-soft-printer\equipment folder.

2. System Overview

[picture of printer and printer components with descriptions]

2.1. Installing the Printhead

2.2. Installing the Syringe Pump

2.3. Installing the Heated Chamber

3. Loading Material

Once a material is loaded into the printer, continuing to print the material is relatively simple and only requires manufacturing the material, preparing the syringes, and loading the syringes. However, when a material is first loaded into the printer, it will require the additional steps of preparing the tubing and priming the tubing. If you are changing materials, it is possible to cap tubing to preserve the unprinted material for later use. These tubes can then be reinstalled into the printer later.

In this section, we explain how to manufacture the material including preparing the syringes and preparing the pump system including preparing and priming the tubing and loading syringes into the pump.

3.1. Manufacturing Material

2-part elastomers are mixed *in situ* during printing. Additives are added to one or both parts of the elastomer to improve printability of the material. When preparing the materials, do not combine Part A and Part B of the elastomers.

A tool has been created to help determine weights needed to manufacture materials. Currently this tool only supports Dragon Skin 10 Very Fast (Smooth-On, Inc.) using a mix ratio from [4]. As new materials are tested and validated, they will be added to the tool.

Recommended steps for manufacturing materials:

1. Open the tool exploratory-soft-printer\tools\material_fabrication.xlsx.
2. Navigate to the sheet specifying the desired print material.
3. Entered the desired weight of material to manufacture.
4. [Optional] Enter a custom ratio for the material. Note that only the standard ratio has been tested for printing and using a custom ratio is not guaranteed to yield good results. Materials that go through the printer need to be able to maintain their structure after printing and need to cure fast enough to support additional layers without curing so fast that they cure inside the print nozzle.
5. Record weights of each material/additive so they are readily available during fabrication.
6. Collect the following in an appropriate material fabrication area:

- Base material (e.g., 2-part elastomer),
- Additives (e.g., thickener, thinner, accelerant, decelerant, pigment),
- mixing cups,
- mixing utensils (e.g., plastic knives, craft sticks),
- [Optional] pipettes,
- paper towels,
- vinyl gloves[1],
- goggles,
- [Optional] lab coat,
- scale,
- [Optional] centrifugal mixer,
- vacuum oven.

7. Place the mixing cup on the scale and tare it.
8. Pour the recorded number of grams of Part A of the material into the mixing cup ensuring to mix the material with a mixing utensil beforehand if needed. The mixing utensil can be used to help control the pouring of the material to minimize overpouring and mess. Set the mixing utensil onto a paper towel and use a paper towel to clean excess material off of the bottle before sealing it.
9. Add additives to the mixture by taring the scale and following a similar procedure. If the additive is liquid, it may be preferable to use a pipette to minimize overpouring and mess.
10. When all components are added to the mixing cup, mix everything together manually with a mixing utensil or using a centrifugal mixer.
11. [Optional] Degas the material with a vacuum desiccator/chamber/oven if desired.
12. Repeat process with Part B if required.

3.1.1. Preparing Syringes

Recommended steps for preparing the syringes:

1. Collect the following:

   - Prepared materials,
   - mixing utensils (may be reused from manufacturing),
   - paper towels,
   - vinyl gloves,
   - goggles,
   - [Optional] lab coat,
   - luer lock syringes,
   - socket luer locks to 1/8" barbed connector (McMaster, 51525K283),
   - [Optional] syringe holder[2].

2. Add one of the socket luer locks to the end of the syringe and remove the plunger.
3. If you are using a syringe holder, place a syringe in the syringe holder and gently scrape the material from the mixing cup into the top of the syringe.

   If you are not using a syringe holder, grasp the syringe and mixing cup with one hand such that the edge of the mixing cup connects to the hole at the top syringe and gently scrape the material from the mixing cup into the top of the syringe.
4. When the syringe is filled, clean up any spills with paper towels and place the plunger back in the syringe.
5. Remove air by pushing down on the plunger until material appears in the luer lock connector.

[1] [Warning] Nitrile or latex gloves may inhibit curing. The risk is higher with latex gloves.
[2] Design and assembly instructions for a laser cut syringe holder for 50 mL syringes (McMaster-Carr, 7510A656) are provided in exploratory-soft-printer\equipment\syringe-holder.

3.2. Preparing Pump Setup

To print the material, the prepared syringes are loaded into the syringe pump. From there, the material has to travel through tubes to the printhead where the material will be mixed and printed. Here, we explain how to load/unload the syringes into the syringe pump, how to install tubes to print a new material, how to prime the tubes to prepare for printing, and how to uninstall primed tubes when swapping materials.

3.2.1. Loading/Unloading Syringes

Recommended steps for loading/unloading syringes:

1. If the pump's plunger is driven down, drive it back up either by using the printer's LCD interface or by switching the pump control to the external controller and using the external controller.
2. Remove the pump's syringe holder by unscrewing the knobs.
3. Unload syringes from the syringe barrels if needed.
4. Load prepared syringes into the syringe barrels.
5. Replace the syringe holder and tighten knobs to hold the syringes in place, see Figure 2.

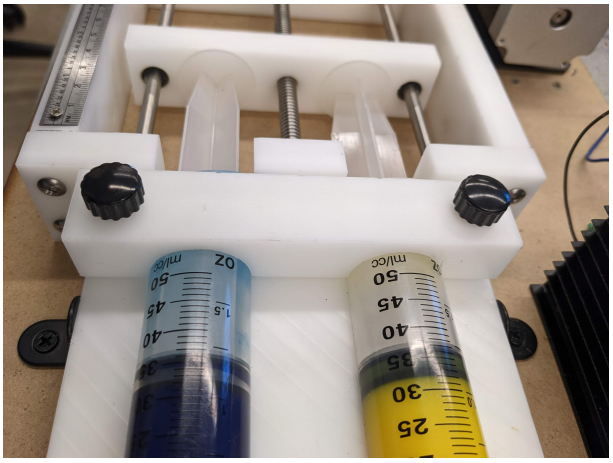

Fig. 2. Syringes installed in the syringe pump.

3.2.2. Installing Tubes

Recommended steps for installing tubes (if you are re-installing already primed tubes, skip to step 3):

1. Collect the following:

   - 1/8" ID clear tubing (McMaster, 6516T14),
   - tape measure or ruler,
   - cutting tool (e.g., scissors),
   - zip ties or velcro cable ties,
   - vinyl gloves if reinstalling primed tubes.

2. Cut 2 lengths of 2 m tubing.
3. Connect one end of each tube to the barbed inputs of the printhead, see Figure 3.
4. Add zip ties or velcro cable ties to hold the tubing to the 3D printer's drag chain, see Figure 4, to keep the tubing out of the way during printing.

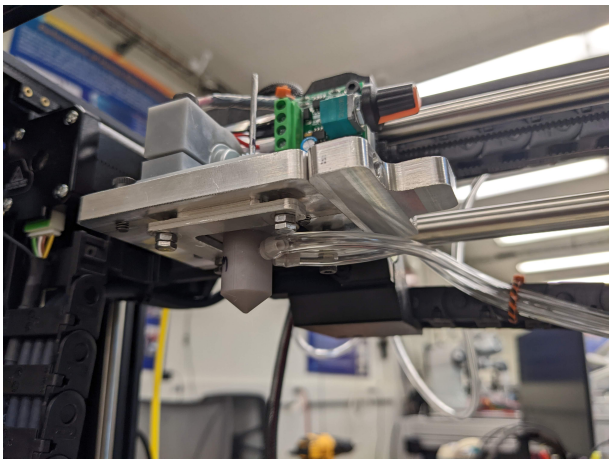

Fig. 3. Tubes installed on the printhead.

Fig. 4. Tubes ziptied to the printer's drag chain.

5. [Optional] If you are using the heated chamber, feed the tubes through holes in the back wall of the heated chamber.
6. Connect the other ends of the tubes to the syringes loaded into the syringe pump.
7. If you re-installed already primed tubes, clean any spilled material with paper towels and ethanol.

3.2.3. Priming Tubes

Recommended steps for priming the tubes:

1. Power the printhead.
2. Drive the syringe pump forward until a mixed material comes out of the printhead either by using the printer's LCD interface or by switching he pump control to the external controller and using the external controller. If the printhead gets clogged during process, be sure to stop the syringe pump to prevent bursting along the line due to built-up pressure.
3. Clean the printhead following the instructions in Section 5.

3.2.4. Uninstalling Primed Tubes

Recommended steps for uninstalling primed tubes:

1. Collect the following:

   - two barbed plugs for 1/8" ID tubing (McMaster, 5463K75),
   - paper towels,
   - ethanol,
   - vinyl gloves,

   Optional cutting tool.

2. Remove the zip ties or velcro cable ties holding the tubes to the 3D printer's drag chain.
3. Pull the tubes off the printhead and plug with the barbed plugs.
4. If the tubes are installed through the heated chamber, pull them through the heated chamber.
5. Clean any spills with the paper towels and ethanol.
6. Clean the printhead following the instructions in Section 5.

4. Printing Parts

G-code can either be generated manually or through a slicer program like Lulzbot Cura. Section 4.1 explains how to generate g-code using Lulzbot Cura. It is not recommended to generate g-code manually unless the user is very familiar with manually generating g-code and the firmware of the printer.

4.1. Generating G-code

If you are using Lulzbot Cura it is recommended to follow the set-up instructions given in Section .

1. Import the .stl file you want to print into Cura and place it on your desired location on the bed.
2. Confirm that the correct printer and material are selected.
3. Under Print Setup on the right, select Custom.
4. Under the Quality menu:
   (a) Change the Layer Height to 0.5 mm.
   (b) Change the Initial Layer Height to 0.5 mm.
5. Under the Shell menu:
   (a) Change the Wall Thickness to 1 mm.
   (b) Change the Top Layers to 2.
   (c) Change the Bottom Thickness to 2 mm.
6. Under the Infill menu:
   (a) Change the Infill Density to 100%.
   (b) Change the Infill Layer Thickness to 0.5 mm.
7. Under the Speed menu:
   (a) Change the Print Speed to 15 mm/s.
   (b) Change the Infill Speed to 15 mm/s.

(c) Change the Wall Speed to 15 mm/s.

(d) Change the Outer Wall Speed to 15 mm/s.

(e) Change the Inner Wall Speed to 15 mm/s.

(f) Change the Top/Bottom Speed to 15 mm/s.

(g) Change the Initial Layer Speed to 15 mm/s.

(h) Change the Initial Layer Print Speed to 15 mm/s.

8. Under the Build Plate Adhesion menu:

   (a) Change the Build Plate Adhesion Type to None.

9. Under the Materials menu:

   (a) Change the Diameter such that the feedrate of the syringe pump matches the desired feedrate. To do this, use the following equation:

$$D = \sqrt{\frac{4dtv}{\pi v_{e,d}}} \tag{1}$$

   where D is the diameter of the "filament" that we are looking for, d is the nozzle diameter (should be the same as Line Width in the Quality menu), t is the layer thickness (i.e., Layer Height found in the Quality menu), v is the feedrate along the axes (i.e, the speed specified in the Speed menu), and $v_{e,d}$ is the desired extrusion feedrate. When using this equation, watch out for units; Marlin code expects feedrate in mm/min and Cura's user interface uses mm/s.

10. Under View, select Layer View and inspect the print pattern to ensure it is what was expected.

11. Save the G-code to a file.

4.2. Running a Print

1. Save the G-code onto a USB.
2. Load the USB into the Lulzbot printer.
3. Turn the printer on.
4. Use the menu to run the print.
5. Since this is an experimental printer, the user should stay close by and alert during the print to prepare to kill the print should something go wrong.

5. Cleaning the Nozzle

After every print, the nozzle needs to be cleaned of either cured or partially cured elastomer. It is recommended to wait for the elastomer to cure completely if possible since this will make cleaning easier and faster. The following steps explain how to clean the nozzle.

1. Collect the following:

   - paper towels,
   - ethanol,
   - vinyl gloves,
   - cotton swabs,
   - toothbrush,
   - tweezers.

2. Carefully unscrew the pressure knob to remove the nozzle from the printhead.

3. Pull the nozzle out from the [mount].
4. Pull the [mixer] off the nozzle and let the nozzle hang while the [mixer] is cleaned.
5. Use the tweezers and/or your fingers to pull the cured or partially cured silicone.
6. Use the toothbrush to brush in between the [knobs] of the [mixer] to clear away any hard to reach elastomer.
7. Wipe down the [mixer] with ethanol and paper towels.
8. Use the tweezers to pull out any cured or uncured elastomer from the nozzle, scraping along the sides as needed.
9. Use the cotton swabs to clear away any hard to reach elastomer.
10. Wipe down the nozzle with ethanol-soaked cotton swab and paper towel as needed.
11. Wipe down the gasket with ethanol and paper towel as needed.
12. Reassemble the nozzle and place it back into the printhead.

6. Using the Heated Chamber

7. Maintenance

7.1. General

After every print, the print should be removed and the printbed should be cleaned of any excess elastomer. The waste container should also be emptied or replaced if needed.

7.2. Syringe Pump

7.3. Printhead

With the clip on the top, the red and black wires on the right (pins 3 and 4) are for the thermocouples on the filament heater, with the red wire next to those (pin 5) connected to the heat sink on the 5V fan cooling the stepper motor. Next, the red and black wires under the clip (pins 11 and 12) are for the 5V fan. Pins 15 and 16 are for the filament heater, and pins 17-20 are for the stepper motor.

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7.4. Heated Chamber

References

[1] R. L. Truby and J. A. Lewis, "Printing soft matter in three dimensions," *Nature*, vol. 540, no. 7633, pp. 371–378, 2016.

[2] J. Z. Gul, M. Sajid, M. M. Rehman, G. U. Siddiqui, I. Shah, K.-H. Kim, J.-W. Lee, and K. H. Choi, "3d printing for soft robotics–a review," *Science and technology of advanced materials*, vol. 19, no. 1, pp. 243–262, 2018.

[3] Y. L. Yap, S. L. Sing, and W. Y. Yeong, "A review of 3d printing processes and materials for soft robotics," *Rapid Prototyping Journal*, 2020.

[4] S. Walker, U. Daalkhaijav, D. Thrush, C. Branyan, O. D. Yirmibesoglu, G. Olson, and Y. Menguc, "Zero-support 3d printing of thermoset silicone via simultaneous control of both reaction kinetics and transient rheology," *3D Printing and Additive Manufacturing*, vol. 6, no. 3, pp. 139–147, 2019.