# Fast Robotic Soft Matter 3D Printing for Neurosurgical Phantoms Fabrication: Proof of Concept

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**Abstract:**

The recent introduction of three-dimensional (3D) printing (also known as additive manufacturing) techniques into the field of medicine and neurosurgery has provided methods for fabricating patient-specific models for neurosurgical training, teaching, simulation, and pre-surgical planning. Soft matter technology, using a granular gel as the supporting material for 3D printing photopolymer hydrogels, now permits printing of anatomically complex models with realistic textures and tactile properties.

However, there hasn't been a promising soft matter 3D printing system that could be used for fabricating neurosurgical patient-specific models. A major limitation is that current soft matter 3D printing technologies are unavailable to directly print these models with the same anatomical size in a timely fashion.

The aim of this project is to create a robotic soft matter 3D printing (RSM3DP) system using the soft matter 3D printing technology for fast fabrication of patient-specific models with anatomically realistic appearance and textures.

The prototype system consists of a SCARA (4-axis) robotic arm, two large-volume-closed-loop-pressure-controlled hydrogel dispensing pumps, and a high-level controller for coordinating and synchronizing the robot and the pumps. The method consists of path planning for single and multi-material 3D printing, fast motion control of the robotic arm, and precise hydrogel dispensing control. Models are directly fabricated from hydrogels extruded into the granular gel. It significantly improves the time and cost for fabricating similar sized models, making it feasible to fabricate neurosurgical anatomical models for surgeons to practice/prepare in advance of surgical cases, or for realistic teaching exercises.

**Key words:**

Soft matter, 3D Printing, Robotics, Additive manufacturing, Neurosurgical Phantoms

## 1 Introduction

Modern 3D printing technology, also known as additive manufacturing (AM), has been developed for decades, and has been rapidly improving because of advancing computer-aid design (CAD) software, decreased cost of materials and equipment, and more applications. The growth of 3D printing in manufacturing industry and consumer markets has been largely increasing because of the ability to fabricate arbitrary shapes. 3D printing has also been commonly applied in biomedical fields and modern research, for applications including scaffolds for tissue engineering, artificial human organs, and anatomical models for surgeries (a.k.a. surgical phantoms)[1–3].

### 1.1 Soft Matter 3D Printing

Because of the complex human anatomy and variations of each individual body, 3D printing technology is becoming an ideal tool for surgeons to use in preparing for difficult surgical procedures. There exists an increasing need to fabricate customized soft matter objects, such as human surgical anatomy (such as cardiovascular surgeries, neurosurgeries, etc.), for surgical training and pre-operational planning and training. In recent research, a modern 3D printing technology, soft matter 3D printing (a.k.a. 3D bioprinting), has utilized granular gel as supporting material in 3D printing for hydrogel polymer extrusion. Soft matter 3D printing provides not only the ability to fabricate models with soft-touch textures, but also provides great flexibility for fabricating complex-shaped models without huge waste of supporting materials [4].

### 1.2 Soft Matter Extrusion

Most of the current soft matter 3D printing systems and fused filament fabrication (FFF) systems share the standard 3D printing mechanism: a material extruder and a Cartesian motion platform. The main difference between them is the printing material and material extruder. Unlike FFF, soft matter 3D printing usually uses a soft matter extruder with liquid polymer, hydrogel, living cells, etc., while FFF uses a hot-end filament extruder with plastic filament. Soft matter extruders commonly consist of a syringe pump and a blunt-tip needle, and are built as a printhead assembly of the 3D printer, such as a modern bioprinter. Most of the soft matter extruders feature low-volume syringes and small-diameter nozzles/needles for printing small objects with high precision and resolution [5–7]. There are two major limitations on this kind of syringe pump setup: one is the carriage payload of the soft matter extruder at the end-effector of the 3D printer, and the other is the printing volume[8]. The carriage payload of the soft matter extruder at the printhead will determine the dynamic performance of the 3D printer motion. As the mass and moment of inertia of the printhead increases, it will result in unwanted vibration and impact on the accuracy of robotic motion repeatability for printing [9]. The printing volume is usually limited by the syringe size (usually 1 ml or smaller) on most bio-printers because of the need to reduce the carriage payload at the printhead for high-precision motion, and the ease of high-precision extrusion control with rigid small-bore syringes.

### 1.3 The New Robotic Soft Matter 3D Printing Platform

To achieve the goal of fast robotic soft matter 3D printing for fabricating patient-specific anatomical models in a timely manner, we require fast robotic motion of the printhead (i.e. the end effector of the 3d printer), using a soft matter extruder providing fast and accurate extrusion with a large-volume reservoir. A soft matter 3D printing system satisfying these requirements has not been reported previously.

In this article, we report a new robotic platform for soft matter 3D printing for fabricating soft-textured anatomical models, such as soft tissues, blood vessels, nerves, etc. It includes a 4-axis robotic arm, a large-volume-closed-loop-pressure-controlled hydrogel extruding system, and a high-level controller for coordinating and synchronizing the robot and the pump.

The purpose of our study was to test the hypothesis that the new robotic soft matter 3D printing platform would present fast printhead motion coordinating with the soft matter extruding system, while requiring less time for fabricating complex-shaped models at clinically-required resolution (~0.25mm)[10].


**Figure 1. Robotic soft matter 3D printing system setup.**

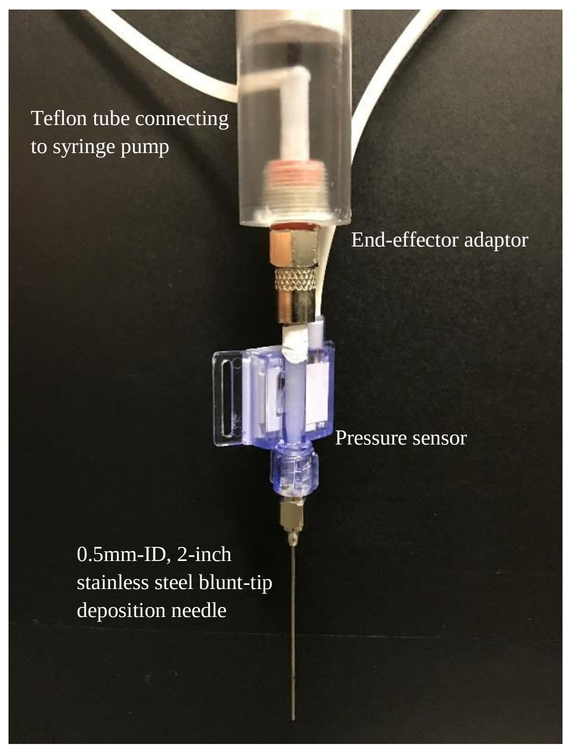


**Figure 2. An end-effector adaptor incorporating a pressure sensor and a blunt-tip needle, and a Teflon tube connecting the syringe pump.**

## 2 Methods and Materials

In this section, we provide a general description of the new robotic 3D printing platform for fast fabricating soft matter objects by the modern soft matter 3D printing technology, extruding liquid polymer in granular gel. To investigate the idea of fast printhead motion and soft matter extrusion, a 4-axis SCARA industrial robot and an “off-the-end-effector” (Bowden-style) soft matter extrusion system were utilized as the platform to fabricate soft-textured models.

### 2.1 Hardware

The new platform includes an Epson SCARA 4-axis robotic arm driven by Epson RC-700 controller, and a closed-loop-pressure-controlled hydrogel extrusion system (Figure 1). The hydrogel extrusion system consists of a custom stepper-motor-driven syringe pump, an end-effector adaptor incorporating a pressure sensor and a blunt-tip needle, and a Teflon tube connecting the syringe pump and the end-effector adaptor (Figure 2).

### 2.2 Software

The user interface and code for high-level coordination of robot and extrusion system were implemented in LabVIEW (National Instruments, Austin, TX). We use an open-source slicing engine (Slic3r) for 3D printing tool-path planning, and for setting parameters including layer thickness and material retraction on the hydrogel extrusion system.

### 2.3 Soft Matter Preparation

The supporting material and printing ink for soft matter 3D printing are prepared following the methods described in Bhattacharjee et al. [4,11]. To prepare the soft carbomer granular gel medium, the supporting material in soft matter 3D printing, 0.15 % (w/w) Ashland™ 980 Carbomer is suspended in ultrapure water and 0.01N NaOH. For the preparation of the printing ink, 25% (w/w) Polyethylene glycol 35000 is suspended in ultrapure water. Both were homogeneously mixed at 3500 rpm for 2 minutes in a FlackTek DAC 150 SpeedMixer before they were degassed.

### 2.4 Robotic Soft Matter 3D Printing Process

Complex-shaped models were used to demonstrate the system capability to fabricate complex anatomy and geometries. The 3D models were either designed and created using SolidWorks (Dassault Systèmes) or segmented from medical imaging using ITK-Snap. All the 3D models were exported in the STL file format, and were processed by Slic3r or CURA, open-source slicing engines, and sliced into layers with 0.25 mm thickness to generate G-code instructions for 3D printing. G-code files were then post-processed by MATLAB (MathWorks, Inc.), and sent to the LabVIEW Interface for printing (Figure 3).

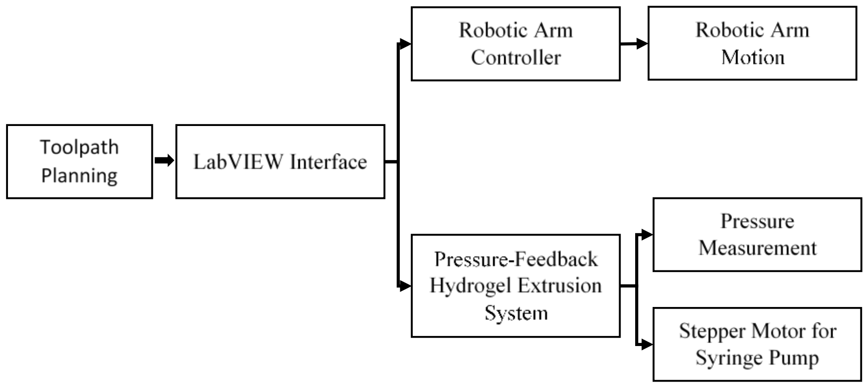


**Figure 3. System process**

Hydrogel printing inks were first drawn into a 30-ml disposable syringe. The syringe was then connected with the Teflon luer-lock connecting tube to the end-effector adaptor and mounted onto the stepper-motor-driven syringe pump. An open-top container to hold the printed part was filled with the carbomer granular gel supporting material, and manually placed on the build platform, which is a flat surface that is mechanically isolated from the soft matter 3D printing platform. The needle tip of the soft matter extruder was positioned at the center of the granular gel container in x and y and near the bottom of the container in z before printing.

### 2.5 Hydrogel Extrusion System

To achieve fast dynamic response and low vibration at the robotic arm end effector, an "off-the-end-effector" (Bowden-style) [12] soft matter extrusion system is used. In order to compensate for the mechanical compliance of the Teflon connecting tube and viscous hydrogel, and get high-quality soft matter 3D printing, closed-loop control of syringe pump pressure was implemented to provide consistent extrusion rate and eliminate general 3D printing issues, such as leaking nozzle/needle, stringing, and oozing [13]. Flow rate is proportional to the pressure measurement [14]:

$$Q = \frac{\Delta P \, \pi r^4}{8 \mu L}$$

where Q is the volumetric flow rate (mm3/s), ΔP is the pressure difference between the two ends of the needle (psig), r is the needle radius (mm), μ is the dynamic viscosity (centipoise (cP) = millipascal seconds (mPa·S) ), and L is the length of the needle (mm).

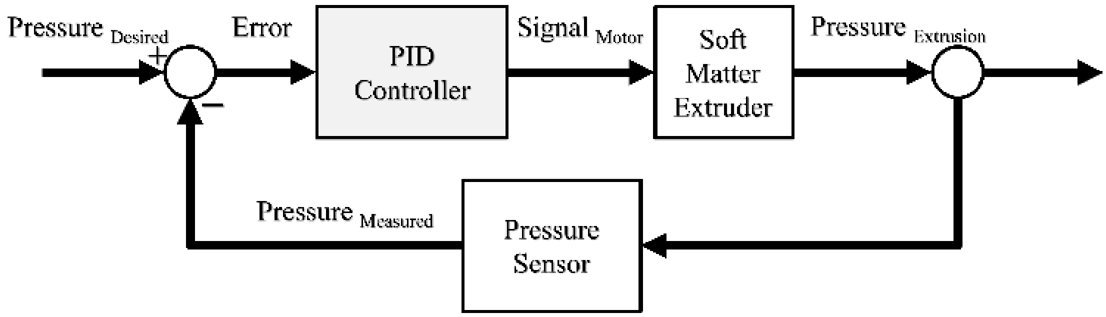


**Figure 4. Block diagram representation of the closed-loop control of pressure feedback soft matter extrusion**

A PID controller (Figure 4.) was employed as a highly responsive and stable pressure controller. The proportional, derivative and integral gains are tuned for particular setup (needle diameter, syringe size, hydrogel viscosity, length of the Teflon connecting tube, motor performance, etc.) for optimal performance. For characterizing the performance of the soft matter extrusion system, a well-characterized setup in Table 1 is used.

| | |
|---|---|
| Needle | a 2-inch blunt-tip needle with 0.5-mm-ID(inner diameter) |
| Syringe | 10 ~ 30 ml disposable syringe |
| Connecting tube | 2 feet |
| Hydrogel viscosity | ~200 CP |
| Motor holding torque | 22.6 N-cm / 32 oz-in |
| Lead screw | Diameter: 8mm, Lead: 8mm |
| Volumetric flow rate | ~3.6 $mm^3$ / sec @ 1 psig |
| Printing speed setup | 60 mm/s |

**Table 1. Parameters for system setup**

## 3 Results

To demonstrate the capability of fast soft matter 3D printing, a variety of hollow objects were printed using the platform (Figure 5). We show a variety of test objects fabricated using PEG hydrogel, which include a CAD model of double-helical tubes, a CAD-generated blood-vessel model, and a segmented blood-vessel model. These models were printed using a 0.5-mm blunt-tip needle with a layer of 0.25mm, using settings chosen to compromise between build rate and overall quality. Table 2 provides a summary of statistics of the above models including their volumes and average volumetric print rate. Objects where continuous paths predominate result in 4x faster volumetric build rates (Table 2).

| Part | Volume (mm3) | Layer resolution (mm) | Print time (s) | Average build rate ($cm^3$/hr) |
|---|---|---|---|---|
| (CAD) Helix | 951.35 | 0.25 | 1800 | 1.9 |
| (CAD) Blood vessel | 167.86 | 0.25 | 270 | 2.24 |
| (CAD) Alphabets | 491.27 | 0.25 | 450 | 3.93 |
| Segmented Blood vessel | 414.61 | 0.25 | 210 | 7.11 |

**Table 2. Summary of printing results**

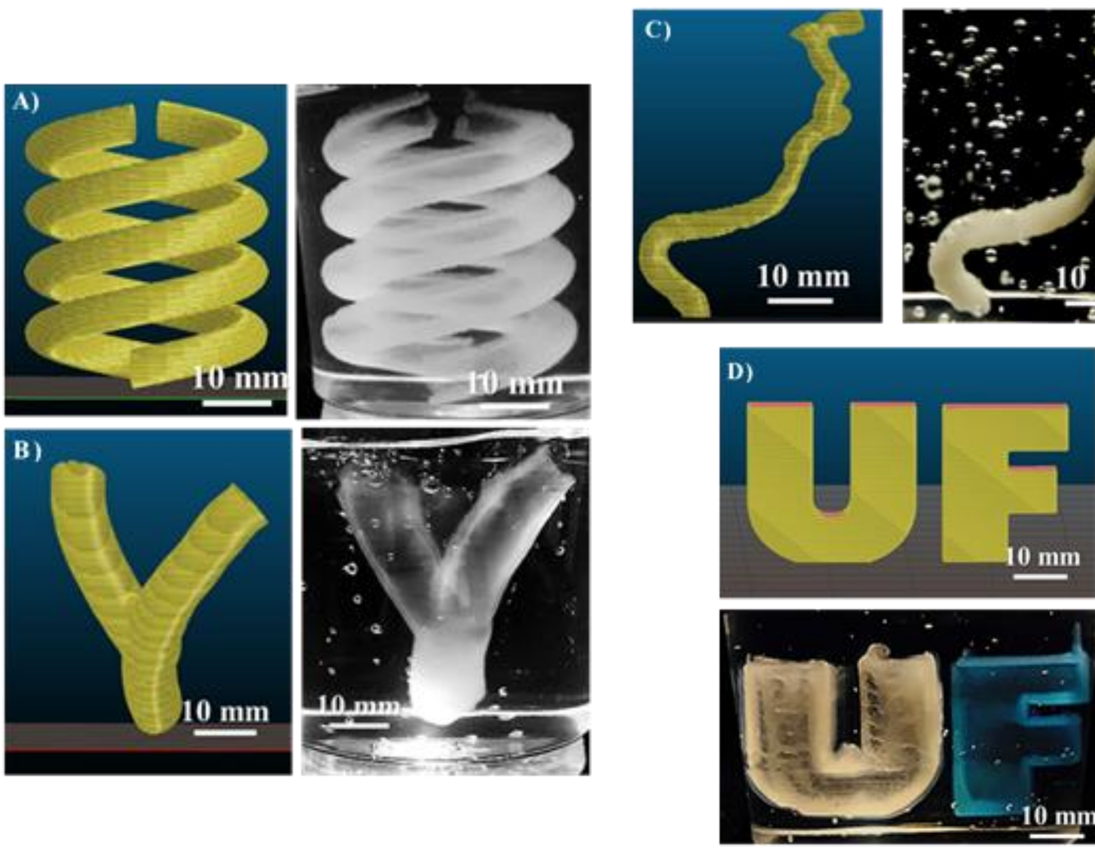


**Figure 5. Printing results for single material printing**

## 4 Discussion

This study was designed to investigate the capability of the new robotic soft matter 3D printing system for fabricating complex-shaped models in a timely manner. We found the use of the new robotic soft matter 3D printing platform, which consists of a SCARA robot arm and a pressure-controlled hydrogel extrusion system, enhanced the current capability for printing soft-textured objects. By implementing fast robotic motion and pressure-controlled soft matter extrusion, complex-shaped 3D geometries can be fabricated faster than the standard 3d printing platform for soft matter. These results suggest the new robotic soft matter 3D printing system has a great potential for fabricating patient-specific anatomical models in the near future.

Based on the printing results in Table 2, the segmented blood vessel model (Figure 5C) has the highest average printing rate, and the helix model (Figure 5A) has the lowest. Although the alphabets model (Figure 5D) has only a slightly larger volume than the segmented blood vessel model, it took more than twice the printing time. This shows that the printing time does not totally depend on the volume of the model, but might also depend on the complexity and path discontinuities of the model. Further research will address the relation between the model geometric complexity and the printing rate.

The major limitation for this study is the syringe volume and resolution by the “off-the-end-effector” hydrogel extrusion system. The former depends on the syringe size used in the syringe pump, and the latter depends on the diameter of the needle for hydrogel deposition. For the syringe volume, in this project we get good time response on the pressure feedback extrusion with the usage of a 30-mL disposable syringe. However, as the syringe size increases to 60 mL, it took longer to reach the steady state, and stepper motor slipping was observed. For printing higher resolution and fine-detailed objects, smaller diameter of needle should be used for material deposition. According to Hagen-Poiseuille’s equation [13], however, the force that is required to drive the syringe pump would dramatically increase as the needle diameter decreases and syringe diameter increases. This implies that either a higher torque stepper-motor is needed to drive the syringe extrusion, or an advanced design for the soft matter extrusion system is needed for achieving both large-volume extrusion and high-resolution soft matter 3D printing.

## 5 Conclusions

In summary, we have demonstrated a robotic soft matter 3D printing platform for fast fabricating soft-textured models using polymer hydrogel. This system will serve as an example of how soft matter 3D printing may be improved. To achieve the true potential of fast soft matter 3D printing for large volume objects, it will be necessary to develop an advanced large-volume hydrogel dispensing system, multi-material printing capability, improved toolpath planning algorithms, and further evaluate the coupling between the dynamics of fast robotic motion and hydrogel extrusion. Nevertheless, the capability to fabricate soft-textured and complex-shaped objects in 5–30 minutes allows us to conceptualize the ideas for fast fabrication of patient-specific anatomical models, and motivates future work on adaptation of the technology to large-volume hydrogel dispensing, and multi-material extrusion.

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