Rapid prototyping bacterial spore hygro-actuators for soft robotics and adaptive materials

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ABSTRACT

Over the past decade, rapid prototyping has migrated from research and industrial labs into the homes of consumers. However, these solid models are limited in demonstrating dynamic actuation. A large range of soft materials are readily available for sensing and structural applications, but soft actuators are still slow to manufacture and inefficient. One method of introducing strong, controllable actuation to devices with gentle stimulation is through hygroscopic actuators. Here, we present a platform that demonstrates the potential of printable soft actuators. We develop a spore suspension that resists sedimentation, improves ink jet performance, and optimizes surface wetting. We demonstrate control of the direction, speed, and magnitude of actuation. Extended work by the researchers demonstrate potential for both contractile and expansive actuation. Finally, stimuli-responsive folding architectures are presented as a possible tool for hierarchical design of humidity-responsive soft robots.

Keywords: water, bacteria, soft robotics, actuators, adaptive materials

1 INTRODUCTION

Additive manufacturing (3-D printing) is growing in popularity and are entering the homes of consumers. Many of these platforms allow users to manufacture solid models constructed from plastic parts and computer aided design (CAD) data. Some of these platforms have been modified for 4-D printing [1]. However, these models are limited in dynamic actuation options. A large range of soft materials are readily available for sensing and structural applications, but soft actuators are still relatively weak and inefficient [2]. The high voltages usually required to operate electroactive polymers can degrade some materials and can prove to be a user hazard, whereas lower voltage iconic polymer metal composites (IPMCs) are currently inefficient, slow, and weak. Pneumatic actuation requires extensive additional pressure infrastructure which can make these systems bulky. Finally, shape-memory wires have significant power requirements that make them unreasonable for smaller devices.

One method of introducing strong, controllable actuation to devices with gentle stimulation is through hygroscopic actuators [3, 4]. Hygroscopic actuators exhibit significant, and reversible, volume expansion resulting from the absorption/desorption of water vapor. One potential hygroscopic material is B. subtilis spores [5]. These spores have demonstrated high energy density (~10 MJ/m^3) due to the relatively gentle stimulus of water vapor. These spores have been imbedded in the semi-crystalline adhesive poly-vinyl alcohol to create composite materials that change shape due to changes in local relative humidity (Figure 1).

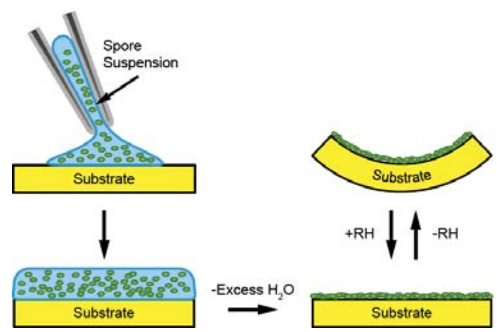

Figure1: Schematic of the micropipette drop coating process and the shape changes due to local relative humidity levels.

Inspired by the energy of these spores and the simplicity of fabricating these bio-composite materials, we manufacture a computer numerical control (CNC) platform combined with modified consumer inkjet cartridges to deposit a solution of spores onto flexible substrates in various geometries to achieve controlled shape actuation.

Here, we present the CNC platform and the potential toward developing printable actuators for soft robotic applications. We develop an improved spore suspension that resists sedimentation and improves ink jetting and surface wetting. We demonstrate that the vector of print direction can control the direction, speed, and magnitude of actuation. Extended work demonstrates the potential for both contractile and expansive actuation. Finally, stimuli-responsive folding architectures are presented as a possible tool for hierarchical design of humidity-responsive soft robots.

2 THE RAPID PROTOTYPE PLATFORM

Previously, these bio-composite materials were manufactured via manual, micropipette dispensed drop coating. To eliminate the manual labor involved, as well as enable higher resolution and unique geometries, we assembled a rapid prototype platform that merges the operation of a CNC router stage (ZenTool Works) with an open source inkjet controller (InkShield) that enables us to modify and control the operation of a commercial inkjet cartridge (HP C6602) (Figure 2) [6].

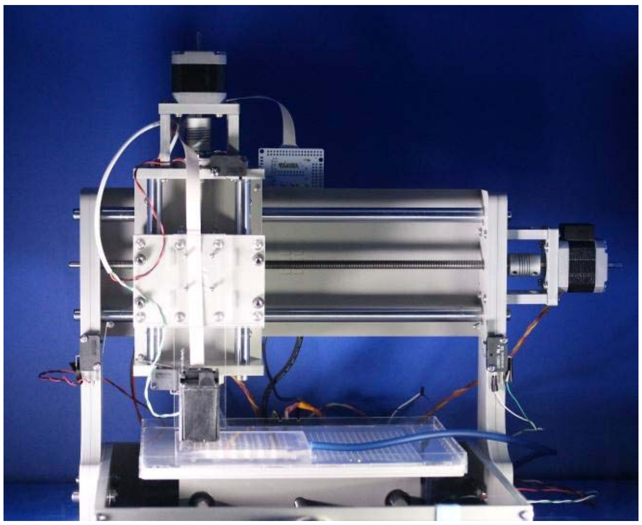

Figure 2: The Rapid Prototype Platform.

2.1 Hardware Setup

The CNC stage can move at a maximum of 2 mm/sec in any axial direction before the onset of mechanical instabilities. To maintain safe mechanical operation, the maximum operation speed was set at 1.67 mm/sec. The InkShield can fire the 12 nozzles of the HP C6602 cartridge at a maximum liquid feed rate of 199 nL per second per nozzle before burning out the heating elements that drive the thermal inkjet process.

2.2 Software Setup & Vector Design

After constructing and installing the necessary hardware components, several software packages need to be installed to render the system operational. First, the Arduino compiler needs to be installed along with additional InkShield and Grbl packages to facilitate the operation of the InkShield and CNC stage, respectively. Second, the appropriate parameters need to be calibrated for the CNC stage to allow for an accurate conversation of vector print image to G-Code to final printed product. Finally, vector graphics are converted to G-code via the online software package MakerCam.

3 INK: SEDIMENTATION & WETTING

A critical component of this rapid prototyping platform is the ink composition. The final composition will have an impact on its ability to jet (print), to remain homogeneous (resist sedimentation), and to appropriately coat the surface (wetting) while maintaining functionality.

3.1 Ink Preparation

While previous experiments have demonstrated the appropriate ink compositions for micropipette drop coating of bio-composite materials, inkjet technology has a limited operating window [7]. This can be illustrated by a relationship of two dimensionless parameters: the Reynolds Number and the Ohnesorge Number (Figure 3). To adjust our ink to be in the printable fluid regime, we introduced thixotropic methylcellulose and an ethanol co-solvent.

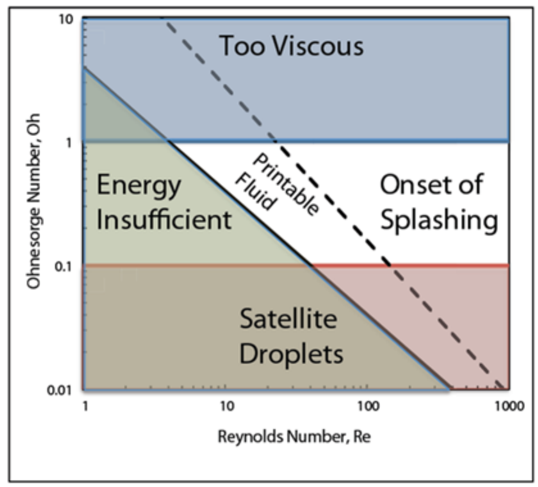

Figure 3: Illustration of the regimes encountered in inkjet systems at different Re and Oh. Adapted from [7]

3.2 Sedimentation Control

One concern during an extended print run is the need to limit inhomogeneity in the ink suspension. One phenomena that can be controlled to limit homogeneity is sedimentation. The force balance of sedimentation can be simplified as Equation 1.

$$v_t = \frac{F_{net}}{6\pi r_0 \eta} \tag{1}$$

The terminal velocity can be controlled by appropriately modifying the viscosity of the ink in the cartridge, as long as the size of the spores and specific gravity of the solution is not significantly altered. By introducing methylcellulose into the ink solution, we reduced sedimentation by nearly 50%, enabling print sequences that last up to 3 hours with minimal ink composition changes (Figure 4).

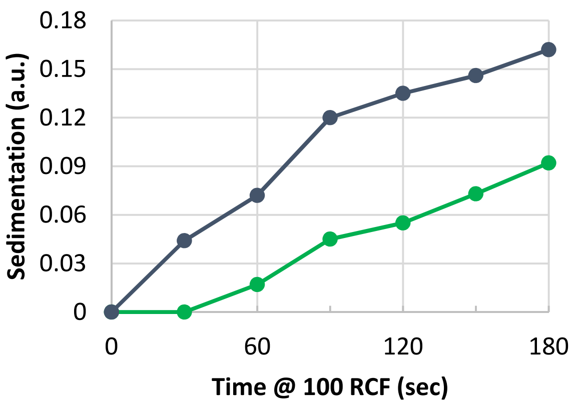

Figure 4: Sedimentation of the original spore/PVA solution (blue) vs. the spore/PVA/methylcellulose solution (green) sampled at various times of centrifugation.

3.3 12 Nozzle Horizontal Sweeps

After formulating our ink appropriately, we tested the ability of our new ink composition to wet a 9 by 3 cm area (27 square mm) on the surface of three different plastic substrates, Kapton (polyimide), Mylar (PET), and Polypropylene. Our results are illustrated in Figure 5. We are able to observe the desired print area on the Kapton and Mylar substrates with acceptable variance, while the polypropylene substrate exhibits significant dewetting, resulting in smaller contact patches. Due to this effect, our following work focused on using Kapton and Mylar.

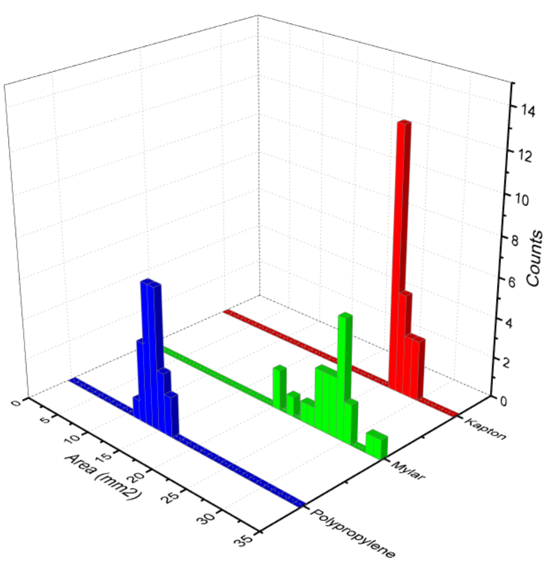

Figure 5: Histograms of 12 Nozzle Test Results on Kapton (red), Mylar (green), and Polypropylene (blue). Note the Kapton and Mylar distribution around 27 mm^2, while Polypropylene is around 15 mm^2.

3.4 Single Nozzle Resolution

After observing that Kapton and Mylar are appropriate substrates for large scale actuator printing, we continued our tests to determine the narrowest lines we can produce as a function of inkjet nozzle frequency at a fixed transverse velocity of 1.67 mm/sec along with recoating to dispense the same volume of ink on each test. Figure 6 illustrates the trend that lowering our printing frequency results in smaller feature sizes (~300 micrometers) along with lower variability in line width.

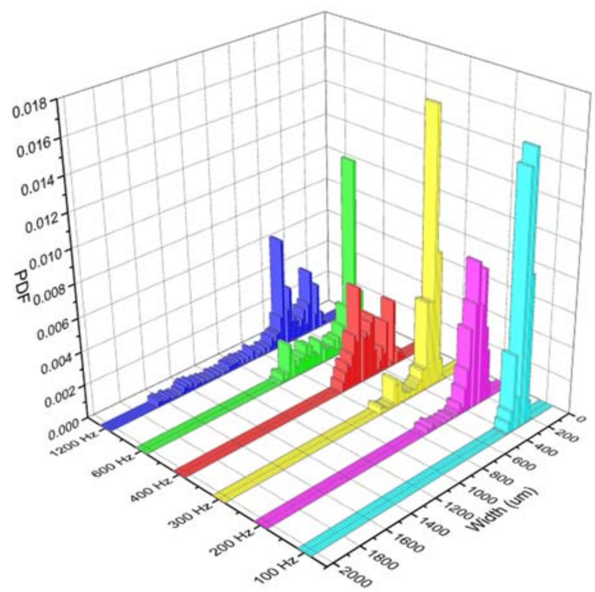

Figure 6: Histogram of our single nozzle test on Kapton for a range print frequencies of 100 – 1200 Hz. Note the narrow width distribution for samples from 100 – 300 Hz.

4 DESIGN & APPLICATIONS

This rapid prototyping platform now enables controlled fabrication of bio-composite actuators with features below 400 microns in size. The following section now details the results of various actuators designed and controlled by the method of fabrication

4.1 Curling Actuators

Previous experiments with this bio-composite actuator focused on curling, or contractile, composites. These actuators are flat at high relative humidity and curl as the relative humidity decreases.

One difficulty with this class of actuator is in controlling the direction of bending. Due to the complicated energy landscape of the relatively large surfaces being coated by the manual micropipette method, the curling actuators would occasionally bend in directions that were not beneficial for device fabrication because of lower energy barriers for these bending modes.

To impose control on our system, we fabricate our curling actuators on Mylar via our single nozzle printing method. On a 60 mm by 20 mm surface of Mylar, we printed 10 parallel lines, each 60 mm long and 0.3 mm wide (a 15% surface coverage). As the relative humidity decreases, we observe that the direction of curling is orthogonal to the direction of printing and that these actuators curl to a width 75% of the starting width (Figure 7). This is confirmed on several different Mylar samples with various orientations of rolling stress.

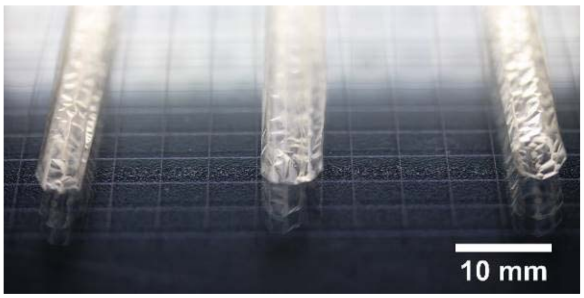

Figure 7: Dry Mylar Based Curling Actuators (25% RH).

4.2 Expanding Actuators

We further explored using this method of actuation to develop expanding actuators that remain flat at low relative humidity and expand at higher humidity levels. We repeated our printing method of section 4.1 on a Kapton substrate and observed that this structure exhibits both curling and expanding modes of actuation (Figure 8).

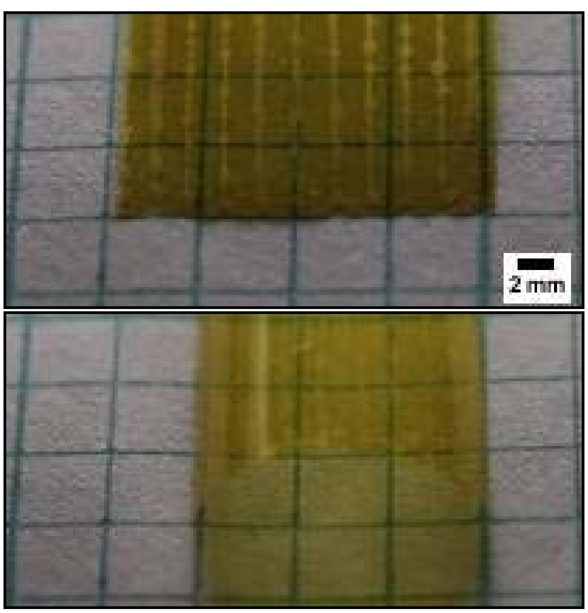

Figure 8: Expanding Actuator. (T: 25% RH, B: 90% RH)

5 CONCLUSION

Here, we presented a CNC platform and the potential toward developing printable actuators for soft robotic applications. We developed an improved spore suspension that resists sedimentation and improves ink jetting and surface wetting and demonstrate that ink vectors control the direction, speed, and magnitude of actuation, both contractile and expansive. We believe that these stimuli-responsive folding architectures will be a possible tool for hierarchical design of humidity-responsive soft robots.

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