Freeform 3D Printing: Towards a Sustainable Approach to Additive Manufacturing

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ABSTRACT: Most additive manufacturing technologies, such as 3D printing, utilize support materials in the fabrication process. Beyond the technical challenges of support removal, these materials are wasteful – increasing fabrication and processing time while impacting quality. This paper presents “Freeform Printing”, a novel design approach for 3D printing without additional auxiliary structures. A 6-axis KUKA robotic arm is repurposed as a 3D printing platform onto which custom-designed thermoplastic extruders are attached. We demonstrate freeform extrusion using a round nozzle attached to an active air-cooling unit, which solidifies the material upon extrusion. In addition, we present a method for printing geometrically complex structures using a multi-strand extrusion nozzle. The experiments presented in this paper, combined with their evaluation and analysis, provide proof-of-concept for Freeform Printing without support materials. They represent a sustainable approach to additive manufacturing and digital fabrication at large, and point towards new possible directions in sustainable manufacturing.

1 INTRODUCTION

1.1 *Biological Systems*

Material systems in Nature are typically composed of graded composites grown and adapted from a single material system rather than an assembly of parts (Oxman et al. 2011). More so, growth in the plant and animal kingdoms rarely follows rectilinear paths confined to single planes but instead spreads through space in response to various factors and stimuli (Braam 2004). Identical systems and matching fabrication processes can result in substantially different structures depending on external environmental constraints. Such is the case with *Cecropia* silkworms, which can produce silk cylinders and sheets in addition to the canonical silk cocoon (Van der Kloot & Williams 1953).

In Nature, form typically follows function such that the composition and properties of a material system vary locally as part of the fabrication process. *Bombyx mori* silkworms vary the porosity and amount of sericin – a bonding agent between fibers found throughout the layers of their cocoons producing a highly bonded network in inner layers compared with outer layers (Chen et al. 2012). Orb-weaving *Araneus diadematus* spiders spin a wide variety of different silks, ranging from the incredibly stiff and strong dragline-silk to the glue-coated and highly extensible viscid silks (Guerette et al. 1996).

In all of Nature’s systems, the optimization of material usage and hence metabolic cost plays a necessary role. In tensile systems such as spider webs, there is little material waste as structural support is an integral part of the web design (Gosline et al. 2004).

2 BACKGROUND

Additive manufacturing technologies emerged in the 1980s as a promising method for fabrication and construction automation (Jacobs 1992). Today, these additive fabrication technologies operate across a wide variety of materials and are used in applications ranging from medical implants to large-scale prototyping. Fused deposition modeling (FDM) systems in particular are found in both hobbyist and professional 3d printing platforms such as the MakerBot Stepstruder, and more professional grade systems such as the Stratasys Dimension 3d printer. Consistent to all of these systems is the need to use support materials to fabricate certain thin-walled or particularly complex geometries (Levy et al. 2003).

3 GOALS AND OBJECTIVES

Interest in Freeform Printing was inspired by the concept of self-supporting fiber-based construction in contrast to the scaffold-based robotic weaving and wrapping explored previously (Tsai et al. 2012). Here, various natural examples were examined, including silk producing bi-valves, spiders, and silkworms both wild and domesticated (Fig. 1a). One of the guiding principles observed among the different natural systems was the concept of producing a continuous fiber based construction method. (Fig. 1b).

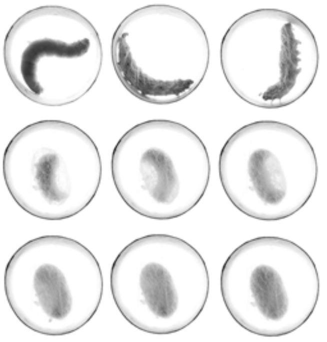
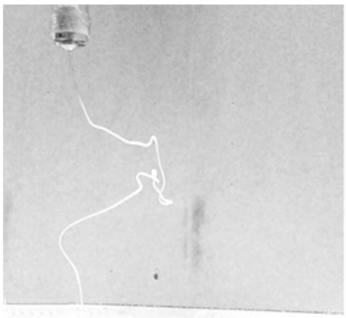


Figure 1a. (L.) *Bombyx Mori* silkworm cocoon sequence.
Figure 1b. (R.) *B. Mori.* Silkworm spinning in half-sphere.

Initial extrusion of a mono-material was pursued through the employment of a 6-axis KUKA KR5 sixx R850 robotic arm as a means to increase the scale capacity (build volume) of the final result (Fig. 2). The ability to create knitted or woven structures requires high levels of robotic dexterity or multiple agents, otherwise resulting in the process being rate limited by fiber component length and splicing or tangling of the material.



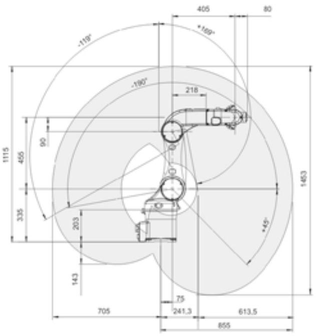


Figure 2a. (L.) Single strand of High-Density Polyethylene (HDPE) freeform print.
Figure 2b. (R.) KR5 sixx R850 robotic work envelope.

4 METHODOLOGY

4.1 *Initial Exploration*

Preliminary tests explored the use of a Stepstruder tool-head with MakerBot Acrylonitrile Butadiene Styrene (ABS) filaments to test the concept of drawing a fluid plastic material through space (Fig. 3a). As a departure from small-scale ABS tests, a custom extrusion tool for attachment to a robotic arm was developed. The design of the tool was based on research into current extrusion devices in industrial applications. The core of the tool is a large 20.6 mm diameter auger-type masonry drill bit cut to a length of 184.5 mm. The goal was to make the housing as compact as possible in order to achieve a high degree of control over the maneuverability of the tool in the robot workspace. (Fig. 3b).

Figure 3a. (L.) ABS Filament freeform extrusion.
Figure 3b. (R.) Custom HDPE extruder mounted on KUKA.

4.2 *Tool Development*

A 3d model of the tool was developed in Rhinoceros 5 for design development, visualization and fabrication (Fig. 4a). The housing for the extrusion chamber was constructed out of 50 mm diameter aluminum round stock.

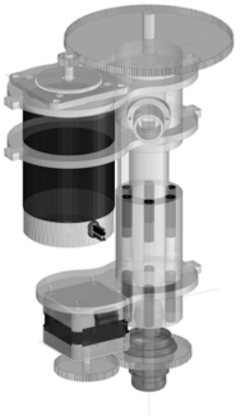


Figure 4a. (L.) Digital model of extrusion tool
Figure 4b. (R.) Extrusion tool with variable tip.

The body and other cylindrical parts of the extruder were turned from round stock on a CNC lathe. The housing was bored to accept the auger bit and then machined from the other end to allow the extruder to accept various interchangeable extrusion tips via three setscrews. The output end of the tool also retained a substantial wall thickness between the bore and the exterior to allow for the placement of up to twelve cartridge-heating elements. Near the top of the tool, the auger bit was machined with an indexed shank to accept a series of water jet cut aluminum spur gears. Near the top of the housing at the furthest point from the heater elements an opening was created to feed plastic pellets. Aluminum motor mounts were created using a flexural design to carry the NEMA 23 stepper motor. The motor is controlled by a Gecko G201X Digital step driver to drive the gears turning the auger bit. When the auger bit is turned by the gears, a steady supply of plastic pellets is fed from a hopper through flexible tubing via a venturi for material advancement (Fig. 4b). As the pellets are transferred down through the housing, the heater cartridges heat the pellets to about 130^{o} C as regulated by an Arduino-controlled thermistor, while the downward pressure advances the molten material out through the selected tip.

4.3 *Material Tests*

For the proof-of-principle experiments, we chose high-density Polyethylene (HDPE), commonly used today for a variety of applications, ranging from storage containers and furniture products to professional lenses and pipes. In contrast to low-density Polyethylene (LDPE), the HDPE polymer backbone has no branches, yielding stronger intermolecular forces and denser packing. It is therefore more crystalline and exhibits a higher ratio of tensile strength to density – a property crucial to its ability to support itself during printing. In addition, its relatively low melting temperature of 130^{o} C allowed us to melt, extrude, and harden it in the air using a compact setup that is easily mountable on the robotic arm.

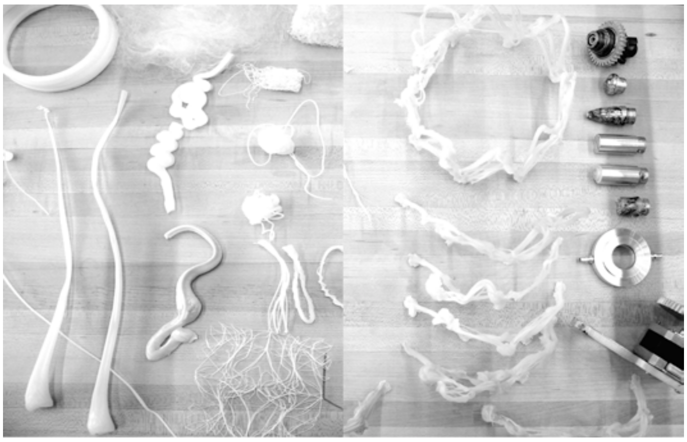


Figure 5a. (L.) Tubular and triangular cross-section extrusions.
Figure 5b. (R.) Custom extrusion tips & freeform tests.

4.4 *Tip development*

A variety of tips were explored and developed based on material properties and deposition processing constraints. The initial tip was developed as a variable diameter and cross section tip (Fig. 5a.). With an additional stepper motor mounted near the bottom of the extruder this tip is able to vary between a 10 mm round extrusion to an 8 mm triangulated extrusion profile.

Following initial experiments with the variable tip (Fig. 5b), a series of interchangeable tips were developed, including two tapered single diameter extrusion tips of different length. The diameter of these single extrusion tips consisted of a 3 mm extrusion hole resulting in a 3.5 mm final extrusion.

Additional tips were developed to enable more complex extrusion profiles. For example, one of the tips was designed with a flat ‘ribbon-type’ extrusion cross-section. The extrusion clearance measurements were 3 mm by 16 mm and resulted in a ribbon extrusion of 3.5 mm by 16.25 mm. Another tip enabled the generation of a hollow tube-like extrusion with a series of internal fins allowing the molten plastic to flow around and reconnect between the interior walls of the tip and a cylinder shaped interior wall. Advanced versions of this tip incorporated a multi-strand approach. Two multi-strand tips were developed, one with a variety of self-similar holes and another with varying holes. The holes of the second tip contained larger diameter strands on the interior retaining heat for reconnection; and thinner strands to cool more quickly to support the printing in 3D space (Fig.6a).

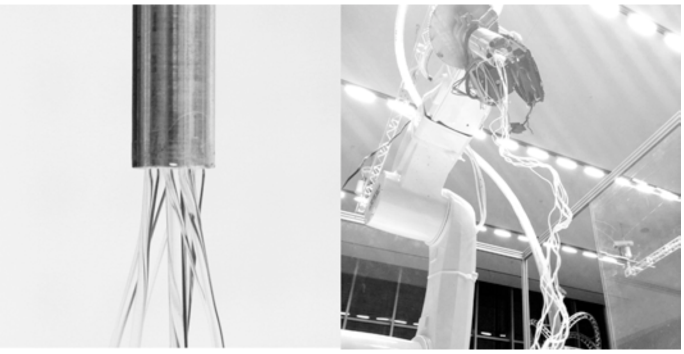


Figure 6a. (L.) Multi-strand HDPE extrusion close up.
Figure 6b. (R.) Multi-strand HDPE extrusion in space.

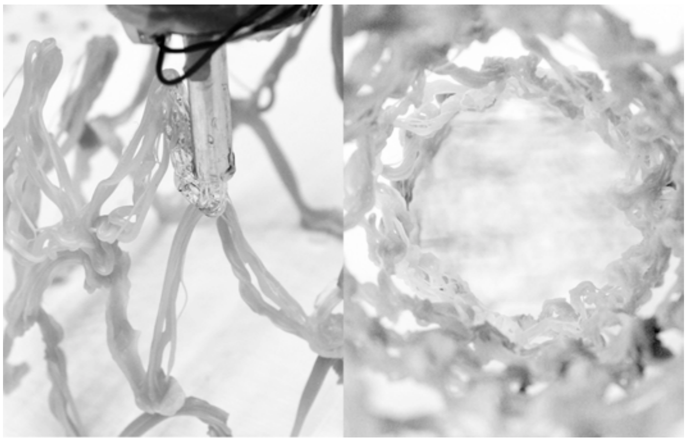


Figure 7a. (L.) Close-up of HDPE freeform prototype.
Figure 7b. (R.) Detail of finished HDPE freeform prototype.

5 RESULTS AND DISCUSSION

5.1 *Testing*

The initial variable extrusion was found to be promising in modulating the extrusion profile from a complete round strand to a triangulated tapered design. The single strand extrusion profile proved to be the best balance of both heat and rapid cooling for initial print in-space experiments. The first of the multi-strand extrusion experiments proved to be a success and allowed for a quicker vertical extrusion test with the fibers cooling in air. The multiple-strands have the potential for multiple-strand bundling as a way of providing additional support (as the structure progresses in vertical space) and self-alignment due to the forces of gravity.

The final multi-strand printing nozzle was modified for the original design to be both longer and thinner for increased agility when printing more complex structures. One of the challenges in many of the freeform printing tests was to provide for material connectivity to plastic parts previously cooled and hardened. The revised multi-strand tip utilizes five thicker diameter holes at the center and along the outer perimeter, allowing for a balance between quickly cooling strands for structural support as the path is extruded and thicker slower cooling stands, which retain more heat and allow for better reconnection to existing cooled extrusions (Fig.7a).

It was also found upon attempting more complex path planning and part printing exercises that a longer extrusion tip length allowed for much greater flexibility in the maneuverability of the extruder while attached to the six axis robotic arm (Fig.7b).

5.2 *Future Development*

While initial tests were highly dependent on developing custom tooling, future work may explore the further development of active heating and cooling at the tooltip, allowing for greater freedom of possible print geometries. Larger printed systems may be explored through leveraging the strand-like nature of larger printed ‘cells’ that utilize fibrous interfaces at their edges to assemble a larger fibrous aggregate system.

Future tests could also benefit from substantially expanding the working envelope of the machine. This could, for instance, be a larger scale industrial robotic arm or an autonomous robotic system capable of transporting deposition material to the final desired location(s).

6 CONCLUSION

As of yet additive manufacturing methods typically rely on the use of support materials in the fabrication of certain geometries. These materials are used to support overhanging features and undercuts during the construction process, and are typically removed or dissolved upon completion of the print. In powder-based selective laser sintering (SLS) processes the excess material acts as the support of the printed structure, whereas thermoplastic deposition and resin curing processes require additional support structures that are themselves printed.

The research and experiments presented in this paper focus on the intersection of biologically inspired design, fibrous construction, mono-material construction and the development of free-form printing. Applications for this novel process are varied and range from product fabrication to furniture and architectural scale construction. With the elimination of support material in the printing process, printing speeds are increased, and waste is eliminated. The experiments presented in this paper provide proof-of-concept for Freeform Printing without support materials. They represent a sustainable approach to additive manufacturing and digital fabrication at large, and point towards new possible directions in sustainable manufacturing.

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