SUSTAINABLE RAPID PROTOTYPING WITH FUNGUS-LIKE ADHESIVE MATERIALS

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Abstract. The purpose of the research work presented in this paper is to develop a sustainable rapid prototyping technology. Fused filament fabrication using synthetic polymers is today the most popular method of rapid prototyping. This has environmental repercussions because the short-lived artifacts produced using rapid prototyping contribute to the problem of plastic waste. Natural biological materials, namely Fungus-Like Adhesive Materials (FLAM) investigated here, offer a sustainable alternative. FLAM are cellulose and chitin composites with renewable sourcing and naturally biodegradable characteristics. The 3D printing process developed for FLAM in the past, targeted large-scale additive manufacturing applications. Here we assess the feasibility of increasing its resolution such that it can be used for rapid prototyping. Challenges and solutions related to material, mechanical and environmental control parameters are presented as well as experimental prototypes aimed at evaluating the proposed process characteristics.

Keywords. Rapid Prototyping; Sustainable Manufacturing; Digital Fabrication; Robotic Fabrication; SDG 12.

1. Introduction

Ensuring responsible consumption and production is a grand challenge part of the Sustainable Development Goals (SDG #12) by the United Nations (UN, 2015). It calls for considering the utilization of natural resources from the extraction of raw materials to the design of products, the energy intensive manufacturing processes involved and their end-of-life disposal. The example used by UN to illustrate the idea of the "global material footprint" is that of plastic waste; a problem its magnitude we recently begun to appreciate (Geyer et al, 2017).

Additive manufacturing (Chua and Leong, 2014) is a technology for the design and fabrication of products using material resources in a highly efficient manner (Thomson et al. 2016), unlike conventional techniques which often produce substantial amounts

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of waste (Tofail et al, 2018). Rapid prototyping (Chua and Leong, 1997) is the earliest and still most popular use of additive manufacturing. With long history in architecture (Kvan et al, 2001, 2002; Burry, 2003; Sass and Oxman, 2006); most prototyping in both academia and practice is performed today using 3D printing (Agirbas, 2015).

Despite its popularity, there is a growing concern regarding the negative effects of rapid prototyping on health (Short et al, 2015) and the environment (Drizo and Pegna, 2006; Ford and Despeisse, 2016). The dominant use of plastics for creating short-lived artifacts is at the heart of the problem (Wang et al, 2018). While certain plastics can be recycled, in practice it is highly uneconomic and energy intensive to perform (Baechler et al, 2013). Advances in polymers gave rise to renewable and biodegradable plastics such as polylactic acid. While bioplastics are more sustainable compared to petroleum polymers, they are often produced from food sources, such as corn starch and sugar cane, and require industrial composting for recovery (Tokiwa and Calbia, 2006).

The objective of this work is to overcome the over-use of plastics by developing a new sustainable rapid prototyping technology. Our approach employs renewable, abundant, locally available, and naturally biodegradable materials, deposited, and cured using a low energy additive manufacturing process.

2. Background Work

In the past, we presented the design of Fungus-Like Adhesive Materials (FLAM); a family of natural biological composites comprised exclusively of environmentally benign ingredients, namely cellulose and chitin (Sanandyia et al, 2018). Those are two of the most abundant and ubiquitous natural components, available in nearly every ecosystem on earth. FLAM resemble high-density synthetic foams and low-density natural timbers (Figure 1). Synthesis of FLAM is performed without modifying their raw natural form, avoiding both health and safety as well as environmentally harmful chemicals. Exactly because they are not modified to behave like conventional plastics, FLAM they retain their property of natural recovery.

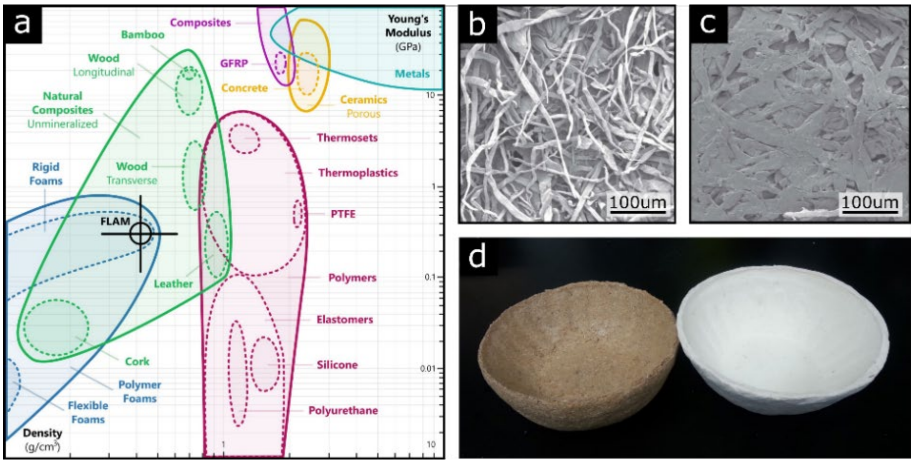

Figure 1. (a) Ashby plot of FLAM properties, (b) Scanning electron microscopy of pure cellulose fibre and (c) FLAM, (d) Objects produced with FLAM using wood waste and pure cellulose

Cellulose and chitin used in FLAM are sourced from by-products of the timber and fishing industries, namely saw dust and shrimp shells. Use of waste streams aims at keeping cost low and competitive with commodity synthetic polymers. In addition, FLAM do not require use of agricultural land or food sources for their production. To assess the potential for regionalized manufacturing, we performed a study using urban waste to synthesize FLAM (Sanandyia et al, 2020). Production thus does not need to rely on forestry or coastal regions, because the material can be synthesised at the place of its consumption, which may be even highly urbanized environments (Fernandez and Dritsas, 2020). This does not merely eliminate a substantial amount of energy for transportation (Ng, Song and Fernandez, 2021), but it also provides a new paradigm for circular manufacturing and urban ecology.

The 3D printing process created for FLAM (Dritsas et al, 2018a; 2018b) is based on material extrusion (ISO/ASTM 52900, 2015). The system is comprised of a robotic positioner and a volumetric dispensing system (Figure 2). The material is deposited in the form of a viscous paste which hardens by evaporation of its water content overtime. Unlike fused filament fabrication (FFF), which relies on energy input for melting and fusing thermoplastics, FLAM are deposited and cured at ambient temperature. Thus, apart from requiring lower energy, cold extrusion enables increased speed of printing using large nozzle diameters, exactly because the material does not need to transition phase at the point and time of its extrusion. The system developed for 3D printing initially targeted large-scale artefacts to demonstrate those unique process features (Dritsas et al, 2019). In this study we modified the system to assess the potential for using FLAM in smaller scale rapid prototyping applications.

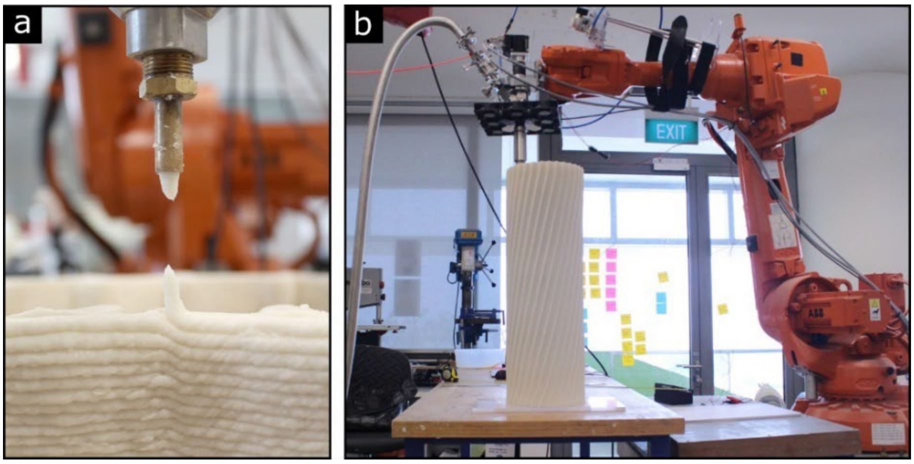

Figure 2. (a) Large-scale FLAM 3D printing using 7mm diameter nozzle. (b) Industrial robot positioner and extrusion dispensing system printing prototype using 1.5mm nozzle

3. Challenges and Solutions

There are different types of challenges when 3D printing large-scale artifacts, using nozzle diameters of a few millimetres, versus 3D printing at rapid prototyping scales, situated at a few hundred microns. Process parameters previously calibrated for large-scale artifacts (Vijay et al, 2018), turned out to be scale dependent. The challenges, result of the change of scale, may be categorized as being related to: (a) the material properties, (b) the mechanical system, and (c) the environment conditions.

Material challenges are in ensuring that the FLAM paste is fine enough to flow through a small diameter nozzle such that 3D printing is uninterrupted. Cellulose and chitosan are sourced in the form of powders. Pure cellulose has nominal fibre length of 200μm, but over 500μm if raw wood waste is used. Chitosan crystals are dissolved into an adhesive paste with no discernible particles, in theory. However, there are often traces of unground shells, as we are using low-cost fertilizer-grade chitosan. Without additional material processing, compared to large-scale printing, we managed to reduce the nozzle used down to 1.0-1.5mm. Smaller nozzles, such as the typical 200-400μm used for fused filament fabrication, were unsuitable.

The mechanical system developed for large-scale 3D printing was unideal for rapid prototyping, with challenges including: (a) the robot's positional accuracy, (b) the controller's inability to process machine code files containing hundreds of thousands of instructions, and (c) the dispensing system, designed for high flow rates, whereas precise micro-dosing is required. To address those problems, we updated our slicing software forcing for interpolated motions, such that the robot could synchronize with the dispenser, and developed a new binary file format for progressively downloading machine code for very large 3D prints.

The amount of material extruded in the large-scale 3D printing setup, is large enough that environmental parameters, such as temperature and humidity, have no discernible effects during the extrusion process. At ambient conditions, objects dry overtime, with the most rapid phase of water mass loss taking place within the first 24 hours. Hardening is mainly related with the surface and cross-sectional area of the objects printed. Therefore, with finer nozzle sizes, aiming at rapid prototyping, curing takes place much faster and most importantly during 3D printing. Change of mass however is accompanied with change of volume; shrinkage of FLAM is anisotropic (Vijay et al, 2019). Geometric change during 3D printing is a problem that requires control, because otherwise consecutive runs and layers of material may not be spatially located where they should be. The solution was to integrate a fan array to control drying (Figure 2b). Not only this solved the problem but also allowed for printing and curing concurrently.

4. Calibration and Experiments

Key process parameters for extrusion-based 3D printing are: (a) the motion speed of the positioner, (b) the flow rate of material deposited, (c) the vertical offset between consecutive layers, and (d) the nozzle diameter. Those require calibration such that the material deposited is consistent. Problems are encountered, such as over-extrusion, if motion speed is too low in relation to the flow rate, or under-extrusion, where material continuity is interrupted, in the extreme opposite scenario.

We approached this task experimentally by varying the motion speed and flow rate, while retaining the layer offset and nozzle size constant (Figure 3). We then measured the width of the runs and identified settings with the lowest variation. While there are multiple feasible feed-and-flow rate combinations, we used 1.5mm nozzle diameter, 0.75mm layer offset, 3.8cc/min flow and 36mm/sec feed rates.

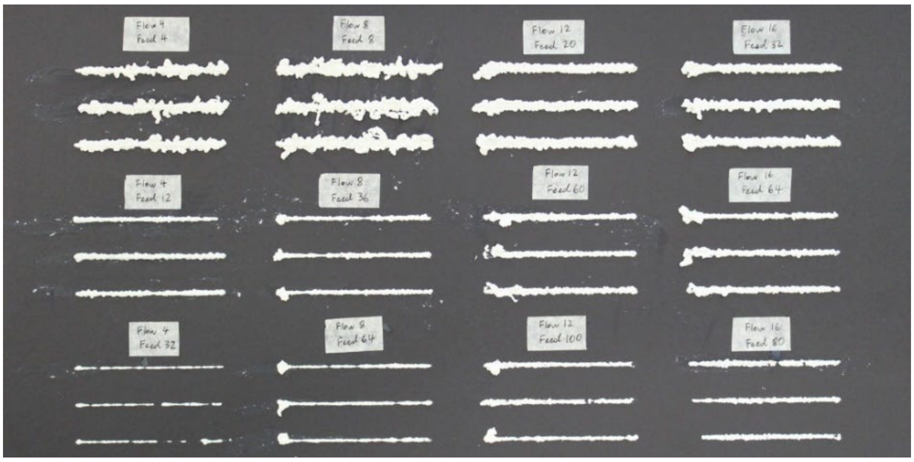

Figure 3. Experiments using various feed and flow rate combinations. The top right cases demonstrate over-extrusion, while the bottom right under-extrusion problems

Several prototypes were produced to evaluate the process including variations of both material composition, namely FLAM from pure cellulose and wood waste, and geometry, such as vertical, twisting, and cantilevered forms. Early results of successful prints (Figure 4) illustrate overall satisfactory layer consistency with minute diametral fluctuation. An important result from early prototypes is in that even though the layer height was 0.75mm at print time, after the material was cured completely, its apparent resolution increased. This is because the vertical shrinkage of 3D printed FLAM is circa 67%. Cured layer height therefore reduced to about 0.5mm. This layer height is thus comparable to conventional rapid prototyping systems.

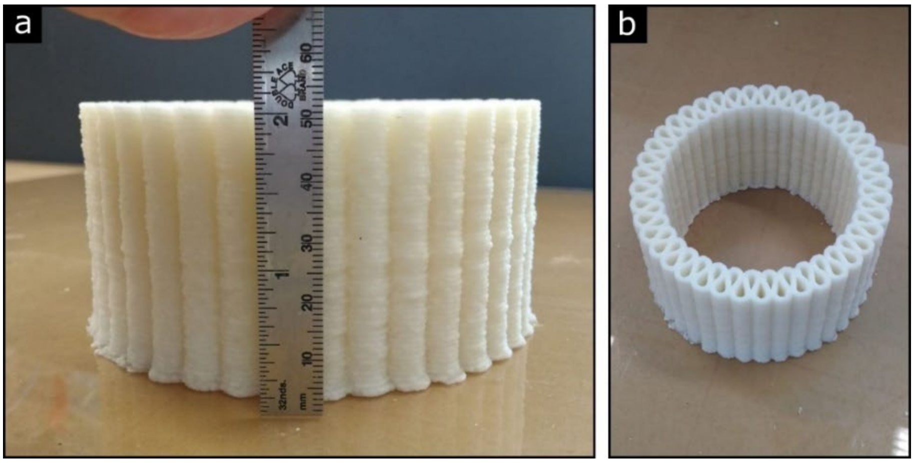

Figure 4. (a) Extruded cylindrical prototype using 1.5mm nozzle and 0.75mm layer height. (b) View of the same prototype where the corrugated wall pattern can be seen

Concurrent curing, using convective airflow, enabled 3D printing prototypes with significant taper angles, approximately 45deg. This was also an important achievement because the FLAM paste has poor mechanical properties before curing, even though it is highly viscous. This allowed for 3D printing prototypes without temporary support structures. To demonstrate this capability, we designed and 3D printed several complex geometry prototypes. The entangled element pillar prototype (Figure 5a) for instance, cantilevered for several layers before being supported by a cross-bracing member.

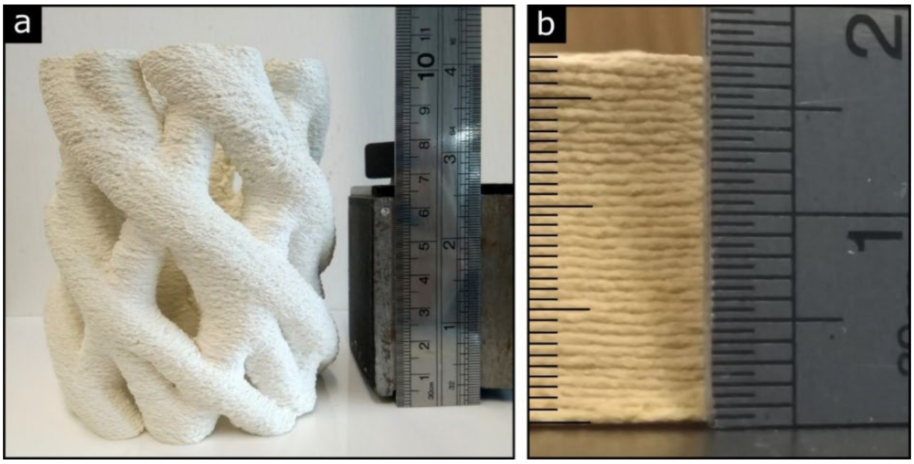

Figure 5. (a) Composite pillar prototype demonstrating the ability of layer tapering and cantilevering. (b) Detail of dry prototype with 20 layers per centimetre or 0.5mm per layer

The last experiment aimed at answering how tall we could possibly 3D print before the prototype collapsed under its own weight. It was a test of the material's mechanical properties and the reliability of the system, as those prototypes required 12 hours of printing each. We printed two fluted columns featuring a corrugated wall profile for structural stability. The first column (Figure 6) was vertically extruded while in the second prototype each layer was rotated minutely creating a spiral form (Figure 7). Both reached approximately 500mm at which point the material supply hose became a limiting factor. From the surface texture of the prototypes, namely several punctuated points of over-extrusion, we infer that the dispenser's nozzle clogged multiple times during the long printing process, but the pumping pressure was sufficient to recover and continue the print without loss of tracking between layers.

While we do not know what the limit is for how tall we can 3D print FLAM, due to technical difficulties, the experiments demonstrated that: (a) tracking between the previous and current layer is retained even after several hundred layers, (b) the material hardens sufficiently to support itself without discernible deflection such bulging as due to buckling effects, (c) the process is both robust and resilient after performing several hours of continuous printing, and (d) it is compatible with rapid prototyping equipment which feature work envelopes of typically 300mm in vertical range.

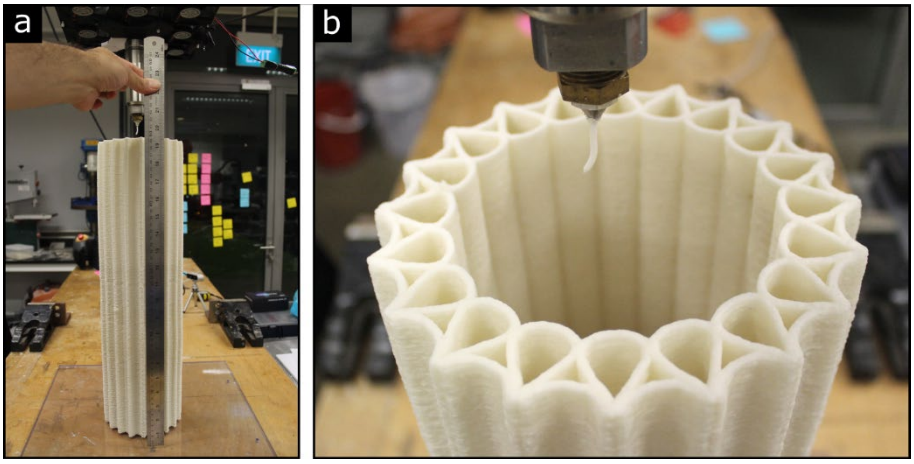

Figure 6. (a) Straight extruded fluted column prototype measuring vertically approximately 500mm. (b) Detail of 3D printing using a 1.5mm diameter nozzle

5. Conclusions

We presented research progress, including the challenges, solutions, and results, in adapting a large-scale additive manufacturing technology to resolutions relevant for rapid-prototyping applications. The objective of the project is to develop a sustainable general-purpose alternative to the currently available commercial rapid prototyping systems that 3D print synthetic plastics. Rapid prototyping became an essential part of the design process from architecture to consumer products in the last decades. Today desktop 3D printing is both highly popular and widely available, not only to design professionals and students but general audiences for educational as well as recreational purposes. With such rapid adoption, the predominant use of plastics for making objects which are rarely recycled and most often disposed is a problem with environmental implications we need to consider.

Natural biological materials offer a profoundly sustainable alternative as far as they are renewably sourced and can be recovered without human intervention. However, because they do not behave like synthetic polymers, where control of temperature and pressure is of main interest, they require new methods for spatial assembly effected by water content and pH levels. In this study we aimed to demonstrate that Fungus-Like Adhesive Materials can be used for rapid prototyping reaching similar resolutions. We discovered and presented several new insights, namely (a) the vertical shrinkage can be exploited to create a form of super-resolution, (b) finer nozzle sizes and environment control enable concurrent 3D printing and curing, and (c) the material's mechanical properties can support large cantilevers and quite substantially tall prototypes.

The hiatus between 0.1 to 0.4mm layer height of a typical fused filament fabrication plastic 3D printer versus 0.5mm achieved here, can be closed with improvements in material preparation regimes and optimization of the mechanical system. This requires re-formulation of the material in terms of reducing the fibre length of the cellulose used to allow for finer nozzle sizes and higher resolutions. Change of fibre size however affects critical rheological material properties such as viscosity which are relevant to extrudability and requires further investigation. In addition, the robotic system while it offered motion flexibility and an extended work envelope, it also introduced positional errors due to its cantilevered structure supporting a heavy dispensing system. Moving forward, a conventional Cartesian positioning system may be thus more relevant for rapid prototyping in terms of positional accuracy and overall stiffness. Development of a miniaturized high-precision volumetric metering system for high-viscosity materials is also a design and development challenge we are looking forward to investigating.

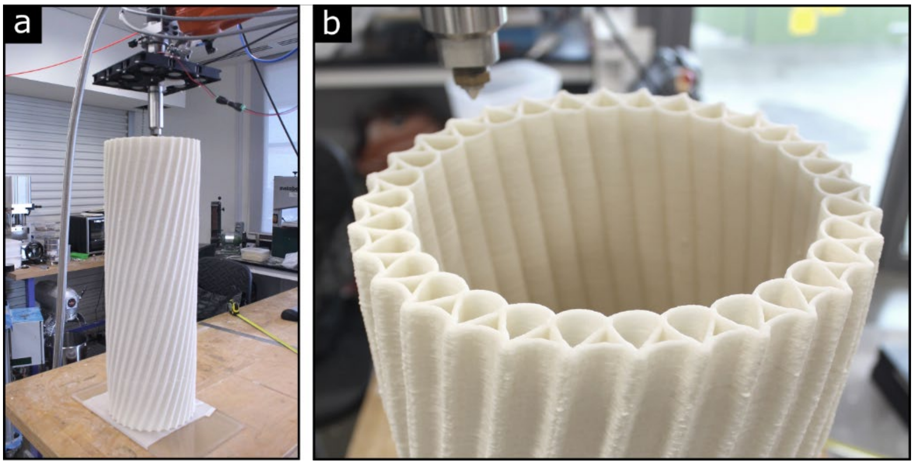

Figure 7. (a) Twisting fluted column prototype showing fan array mounter on dispenser and material supply hose. (b) Detail of 3D printing and corrugated wall pattern for structural stability

In conclusion, we consider the results of this study successful as they support the possibility for rapid prototyping using natural biological materials. We hope our work will assist in addressing the problem of plastic waste as per of the UN's sustainable development goals and motivate further research in environmentally considerate digital design and fabrication.

Acknowledgements

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