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ORIGINAL PAPER

Digital fabrication with natural composites

Design and development towards sustainable manufacturing

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Abstract

The purpose of the research work, an overview thereof presented here, is to create a new digital manufacturing technology with an emphasis on its sustainability characteristics. We designed a family of natural composite materials comprised of exclusively renewable, widely available, biodegradable, and low-cost components. Their physical and mechanical properties closely resemble those of high-density synthetic foams and low-density natural timbers. They are produced without inclusion of petrochemical products or harmful solvents and adhesives, often associated with adverse human and environmental effects. We designed a material extrusion system based on additive manufacturing principles similar to the Fused Deposition Modeling and the Direct Ink Writing methods. The mechanical system used is comprised of a mobile industrial robotic unit, a viscous liquid transport, and dispensing sub-system and programmable control logic. We performed extensive modeling and testing of material properties with the objective of tightly integrating material behavior with manufacturing. We developed design software for direct transition from design to production, including support scaffold generation for accelerated curing by evaporation and predictive models for process parameter control. To address the challenge of scale, we approached the fabrication process from a hybrid perspective including additive, net-zero-change, and subtractive operations. Early proof-of-concept demonstrators offers encouraging results towards manufacturing with two of the most abundant and widely distributed natural materials on earth. We believe that, with persistent effort of controlling the innate variability of natural materials and tighter integration with contemporary fabrication methods through predictive computational modeling, this process has very strong potential for a significant impact on product design, general manufacturing, and the building construction industry.

Keywords Additive manufacturing · Natural composite materials · Industrial robotics

1 Introduction

Additive manufacturing (AM) technologies saw rapid advancements over the past few decades. Methods such as Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS), originally developed for rapid prototyping applications, are progressively considered as the future for general manufacturing (Manyika et al. 2013) and the building construction industry (Khoshnevis 2004; Lim et al. 2012). While great leaps in the development of AM actively take place, fundamental challenges such as materials, design software, sustainability, affordability, speed, and reliability, still persist (Royal Academy of Engineering 2013). It is merely not possible to directly translate technologies created for the production of small-scale disposable plastic artifacts to manufacture properly designed and engineered products of higher complexity and/or larger scale. Even though our research work is fundamentally motivated by material considerations, such as investigating the implications of prioritizing sustainability in AM, using environmentally benign bio-inspired materials, we also present an approach for

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achieving larger scale artifacts which may be used for construction applications.

2 Sustainable biological materials

Popular materials for 3D printing, notably those used for rapid prototyping (3D Systems In 2018, Materialise 2016), such as thermoset and thermoplastic polymers, are primarily derived from petroleum products. Not all plastics, however, are equal from a sustainability point of view, as thermoplastics such as ABS can be recycled and PLA derived from starch is compostable in special conditions (Martin and Averous 2001). Thermoset resins, on the other hand, coupled with the notion of disposability innate to rapid prototyping are rather problematic. Natural inorganic materials for additive manufacturing such as plaster (Bard et al. 2012), clay (Friedman et al. 2014; Dunn et al. 2016), or sand (Gramazio et al. 2018) as well as organics such as wax (Gardinger et al. 2014), if unmodified by unsustainable chemical processes, may be considered environmentally friendly due to modest embodied energy, natural and/or renewable sourcing. In addition, metal alloys and glasses can be considered eco-efficient for their high recyclability content. Unadulterated biological composites offer a profoundly different value proposition when the entire life cycle impact is considered.

Cellulose, for instance, the main component of plant matter, is notorious for being difficult to dissolve and bond, requiring strong solvents and adhesives such as phenolic and formaldehyde resins (Lu et al. 2000) which are often used for the production of plywood, fiber boards, cross-laminated timber, and even additive manufacturing wood-plastic composites (3DSystems Inc. 2016). Introduction of those chemicals results in the transformation of an otherwise highly sustainable material into products which can no longer be easily recovered (Franke and Roffael 1998). Unlike general wood-plastic composites, fully biological materials present a sustainable alternative with active history in material research. Relevant work includes wood bio-composites fused by glutinous (Lei et al. 2010) or ligneous (Pizzi 2006) organic adhesives from agricultural sources and additive manufacturing with organic composites such as starch (Lam et al. 2002), protein-based adhesives from animal by-products (Tan et al. 2017), and gelatinous bio-composites (Mogas-Soldevilla et al. 2014) with chitinous matrices.

The material used here originates in prior work on bio-inspired composites (Fernandez et al. 2009; Fernandez and Ingber 2012, 2014). Its composition was derived from the study of the cell wall of oomycetes, a family of fungus-like microorganism comprised of a cellulose-chitin organic composite (Bartnicki-Garcia 1968). Its components, first and second most abundant natural polymers on earth (Reiterer et al. 1999), are sourced in either industrial grades or from waste by-products of timber and food processing. The physical and mechanical properties of the 1:8 chitosan to cellulose composite currently used, such as bulk density and tensile strength, are 0.37 ± 0.02 kg/m^3 and 6.12 ± 0.37 MPa, which are between the range of high-density synthetic foams and low-density timbers. Its appearance, when wood particles are used, is similar to that of fiberboard products, while, in pure cellulosic form, it resembles compressed paper (Fig. 1). Additional details on the material design and properties of the family of the fungus-like adhesive materials (FLAM) are available by Sanandiya et al. (2018).

The fundamental challenge of this project is in the concurrent design development of the material and its fabrication process. Variation of ingredients and ratios thereof produce changes in material properties associated with process parameters such as flow, due to viscosity, dimensional stability, due to shrinkage, phase separation, due to grain size, and even mold growth, due to contamination.

3 Robotic fabrication system

The fabrication process resembles fused deposition modeling (FDM) for its progressive linear filament material extrusion (ME) (ISO/ASTM 52900:2015 2015), but it is also similar to the direct ink writing (DIW) method (Stuecker et al. 2004; Lewis 2006). Unlike FDM where linear filament is sourced from a spool, the process uses a viscous colloid transported hydraulically by a pump. As the material cures at ambient conditions, the process does not require temperature control for thermoformed dispensing and fusion. Convective air flow accelerates drying and various modes such as robot mount air supply or external fans are used. The developed 3D printing system is comprised of several integrated hardware and software sub-systems (Fig. 2):

1. *Spatial positioning* The system is based on an industrial articulated robot, namely a six-axis robot with 20 kg payload and 1.65 m horizontal reach unit. The machine is mounted on a hydraulic scissor-lift mobile platform. The platform can travel vertically, between 0.8 and 1.6 m from the ground, and the combined maximum vertical reach is 3.7 m. Horizontally, with an additional calibration effort for registration after relocation, the range can be expanded almost indefinitely. Additional information for the robotics design is available by Dritsas and Soh (2018).
2. *Material transport:* The material supply system is composed of two units, namely a stationary material unloading pump and a precision dispensing unit mounted on the robot. The bulk material unloading system is designed to transport viscous materials, with up to 20 bar internal pressure, without pulsation or shear arti-

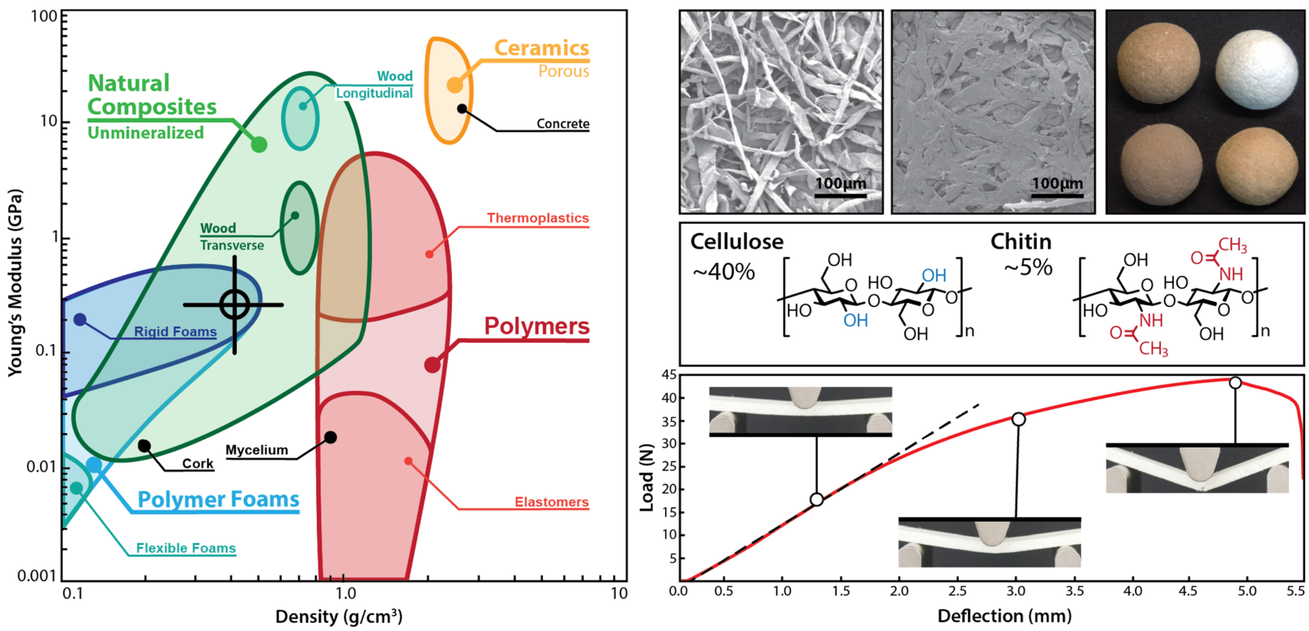

Fig. 1 Left: Ashby plot of physical and mechanical material properties. Top right: electron microscope photography and samples with various wood flour and pure cellulose. Middle right: molecular composition of composite. Bottom right: three-point bending test measurements

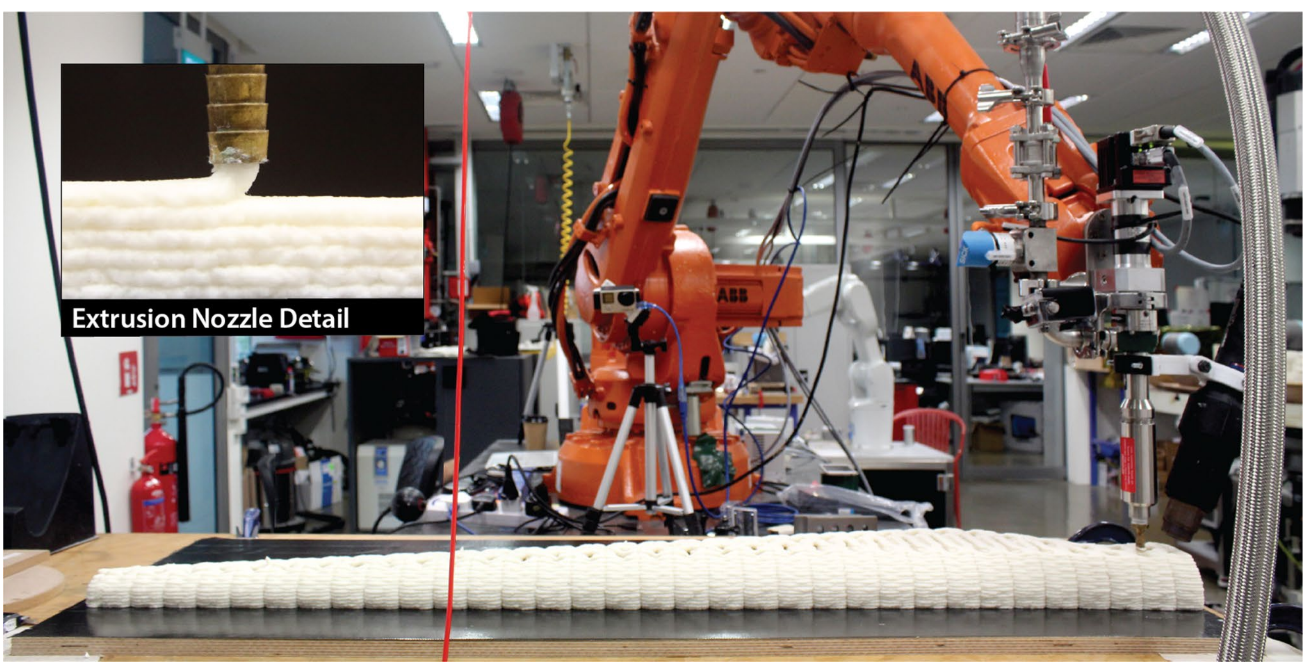

Fig. 2 Industrial robotic system configured for additive manufacturing with natural composites while printing of the airfoil prototype

facts. The dispensing unit, also using auger screw cavity transport, allows for precise flow control enabling drip and tail prevention. The inner diameter of the nozzle may be at maximum 12 mm, currently using 7 mm orifice, while flow rate can be as high as 3.5 ml/s, currently, using approximate 2.5 ml/s. For shaping operations, we use a PTFE-coated nozzle jacket to reduce surface friction against the material, and for subtractive operations, we use a pneumatic die grinder mounted at 90°, about the extrusion nozzle.

3. *Hardware–software integration* Communication between the material transport and positioning systems

is performed via programmable logic control (PLC). The firmware design is minimal, namely comprised of digital-to-analog conversion for dispensing flow control and digital switching for peripherals such as the die grinder. Control logic is pushed upstream on the design-to-production software, based on modern programming principles.

4. *Design-to-fabrication CAD/CAM* The Jeneratiff Digital Fabrication library (Dritsas 2016), within the Rhinoceros/Grasshopper parametric environment, is used for kinematic simulation, machine code generation, and communications. Additional software components developed include algorithms for preprocessing of design geometry, generation of support scaffold structures, and integration of predictive models of process parameters.

4 Process parameters

A critical challenge for any new AM process is in achieving dimensional predictability. It is more acute with biological materials because of their pliability and variability of source components. The material can be classified as thixotropic, where its viscosity depends on shear forces applied, and viscoelastic, where mechanical properties, such as stiffness change over time. Indicatively, from the wet state at dispensing time to the fully cured state, a 3D printed object may lose as much as 4/5ths of its weight, by evaporation of water, with vertical shrinkage as high as 1/3rd of its height. To approach the combined material and geometric behavior, we performed a series of experiments and developed predictive experimental models:

1. *Shrinkage anisotropy* The objective of this study was the characterization of shrinkage in the longitudinal, i.e., along the extrusion path, and transverse and vertical directions. A series of profiles were printed and oven-dried. Thereafter, their sizes were compared against the respective wet dimensions. The shrinkage rate measured is approximately 5% in the longitudinal, 12% in the transverse, and 32% in the vertical directions.
2. *Extrusion control* The objective of this design of experiment (DOE) is to understand and control ME operating parameters, namely motion speed (v), the extrusion flow rate (f), and vertical distance between layers (z). We measured the wet and dry width and height (w, h) of the filament as well as its tensile strength (t). Process parameter control was approached through the development of a 2^3 face-centered Central Composite Design (CCD) experiment model (Montgomery 2008, 2012). Response surfaces (S) of the form (Eq. 1) were fitted and validated, enabling multi-response optimization (Derringer and Suich 1980) where desired effects are reverse-mapped onto operating parameters. Additional information pertaining process parameter control modeling effort is available, by Vijay et al. (2018):

$$\begin{aligned} S(v,f,z) = {} & b_0 + b_1 v + b_4 v^2 + b_7 v^2 f + b_{10} v^2 z + b_{13} vf \\ & + b_2 f + b_5 f^2 + b_8 f^2 z + b_{11} f^2 v + b_{14} fz \\ & + b_3 z + b_6 z^2 + b_9 z^2 v + b_{12} z^2 f + b_{15} zv \\ & + b_{16} vfz, \end{aligned} \tag{1}$$

where $v, f, z \in [-1, 1]$, $b_i \in \mathbb{R}$
and $S : \{w_{\text{wet}}, h_{\text{wet}}, w_{\text{dry}}, h_{\text{dry}}, t\}$.

3. *Filament adhesion* The objective of this study was to determine the distance, or step-over in numerical control terminology, between adjacent filaments in plane, to ensure sufficient adhesion after drying. We deposited a series of filaments at various overlap distances and measured the average shear force required to separate them using universal testing instruments. We examined the point of failure of specimens and defined fusion adequacy if breakage occurred outside the filament overlap region, as opposed to delamination at the interface. Overlap of approximately 40–50% between filaments was determined as sufficient for adhesion among co-planar filaments.
4. *Preset modeling* The objective of this study was to construct a predictive model to counter dimensional changes due to shrinkage. Preset models are used in the building industry to provision for the shrinkage of steel members during construction, by progressive accumulation of dead loads. As FLAM properties are non-linear, we are unable to use statics Finite-Element Analysis (FEA) to account for displacements. Instead, we used statistical machine learning techniques, namely deep neural network (DNN) regression (Haykin 2009), motivated by the ease of printing and measuring objects to collect data. A series of conical surfaces were printed and their displacements were measured using 3D scanning equipment. Measurements were split into training and validation sets and the DNN was trained to predict deflections. The input is comprised of 40 vertically ordered positions, expressing a section of the original surface, and its output is a set of 40 displacement vectors. Predicted displacements are applied in reverse, producing the preset models. The approach demonstrated promising results (Fig. 3), but additional training data of composite surfaces, including, perhaps, horizontal curvature features, are required for expanding its applicability to a broader range of geometries than composite conics. Additional

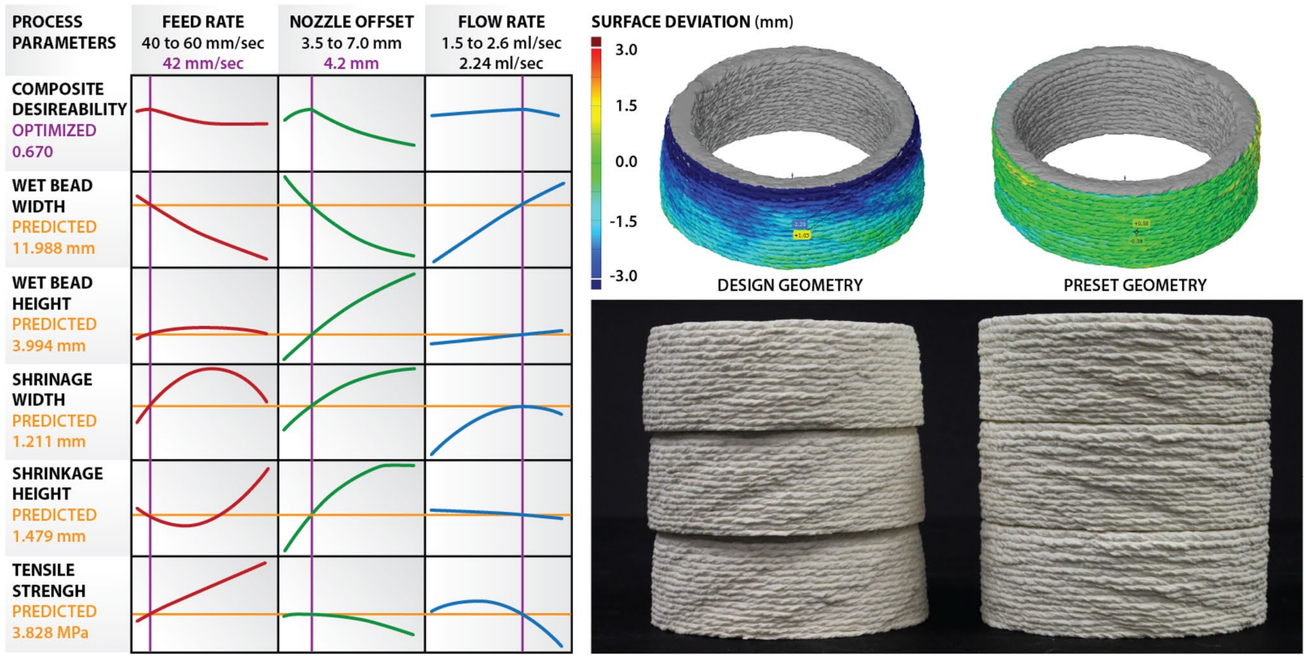

Fig. 3 Left: multi-response optimization results of design of experiment process parameter model. Right: point-set deviation between design geometry of cylindrical surfaces printed directly from model without compensation versus corrected via deep neural network preset model

information on machine learning for preset model estimation is available, by Vijay (2018).

5 Process fusion

For generating machine paths from design geometry, we developed several segmentation and motion-planning algorithms. The initial implementations followed conceptually FDM principles, where a solid is decomposed into layers by slicing, exterior contours are printed first to achieve continuous surface finish, and the interior is fractionally filled with structural support patterns. However, as the filament sizes used here are substantial in size, the exterior surface is bound to a rather rough-layered finish. In addition, the material in its wet state is highly pliable preventing significant spanning and cantilevering between layers. Therefore, we had to rethink the process to respond to the inherent material opportunities and limitations.

The interior structure of a solid is first constructed, preferably with minimal infill and wall thicknesses to accelerate drying. Then, exploiting the self-adhesive characteristics of the material, we first coat the support structure and then shape it to improve finish using the nozzle as a forming tool (Fig. 4). We also investigated deposition and forming in overlapped mode, where forming occurs every few layers deposited. Benefits of such approach are: (a) the ability shape geometries, externally and internally, that cannot be shaped or machined after the build is complete, due to physical access constraints; (b) improve dimensional accuracy and/or relax extrusion process parameters, as the secondary process can enforce surface boundaries by conforming actions. Furthermore, by integrating a die grinder tool with the dispenser, we are able to also improve surface finish, dimensional accuracy, and even add details using the conventional computer numerical control (CNC) machining techniques. Overall, the process concept fuses ideas from additive, forming (net-zero material change operations) and subtractive manufacturing.

To translate support structures into motion planning, the first family of algorithms developed was based on reduction from solid to horizontal closed contours, also known as slicing, and then scan-lines by segmenting contours by vertical planes. Scan-line stacks, seen from the section, were patterned by top–down injection of cavities followed by incremental expansion vertically into protruding arches (Fig. 5). The fractal heuristic, inspired by false-arches, produced vault-like structures hollowing out most of the interior. Unfortunately, abrupt flow modulation required to achieve discrete stripping was detrimental to geometric accuracy which informed the development of a new method aiming at fixed flow rate. The second family of algorithms was based on a parallel sweep-line method, where each contour slice is scan-converted into a serpentine path without flow changes. In principle, this is also one of the most common motion-planning strategies for CNC roughing and finishing, known as parallel machining. Modifications of this approach catering

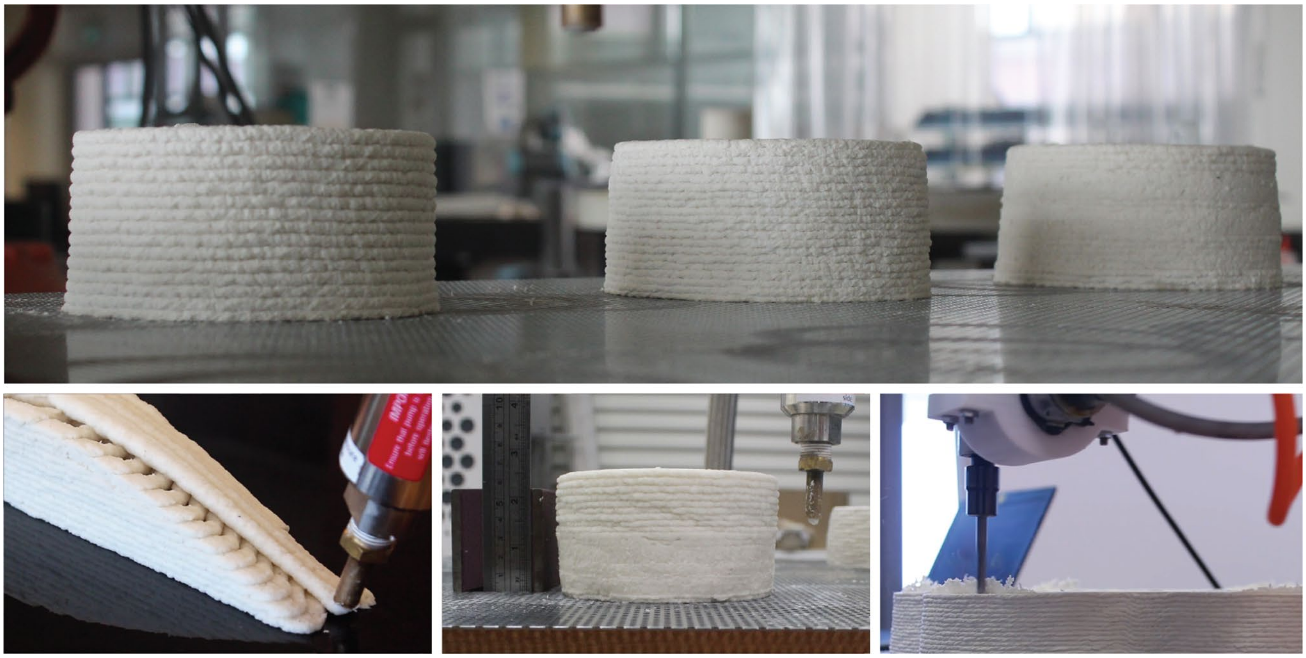

Fig. 4 Top left: raw surface with 4 mm layers. Top middle: raw surface with 3 mm layers. Top right: smoothed surface with 3 mm layers. Bottom left: additive pass over supports. Bottom middle: net-zero-change forming pass. Bottom right: subtractive finishing pass

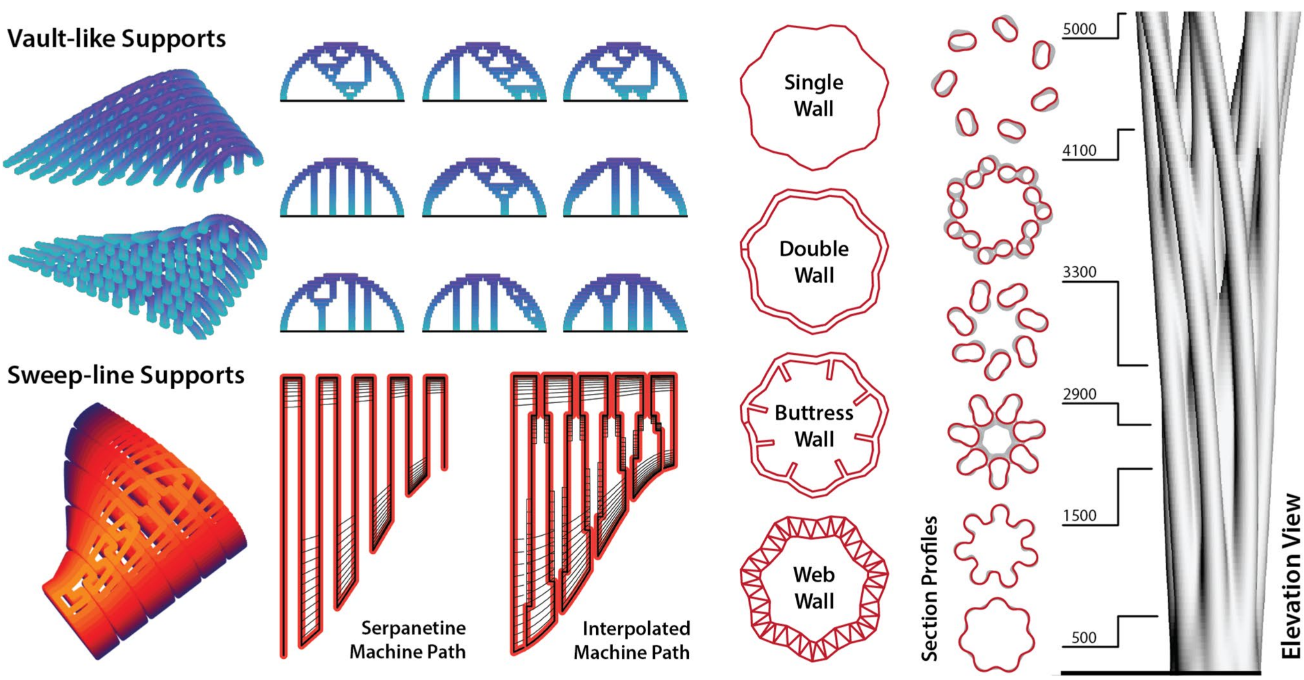

Fig. 5 Left: computer simulation of vault-like and continuous sweep-line support structures. Middle: single, double, buttress, and interior web wall designs for pillar segments. Right: composite pillar design elevation and indicative section profiles at various level above ground

to material and fabrication process include interpolated edge-smoothing and fusion of the scan-line boundaries for achieving consistent exterior finish and patterned inter-scan-line overlapping for stiffening and control of shrinkage. This approach also enables fractional volume filling, typically about 50% rate, which improves air circulation for faster drying.

6 Experiments, fabrication, and evaluation

Numerous parts were printed during the development of the process. Evaluation prototypes include mainly linear and circular primitives to allow measuring dimensional accuracy, layer compaction, shrinkage, tensile, and bending performance. Even if the material is still medium in viscosity, it is possible to build single walls of up to 250 mm high. To demonstrate the versatility of the material, we produced an airfoil measuring 1.2 by 0.3 by 0.1 m. The blade is comprised of two printed halves which required 1.5 h each. After drying by convection at 50 °C, they were fused and coated using a thin layer of the material. The surface was finished using sanding. The blade weights approximately 5 kg, and remarkably, it is comprised of one material which can be 3D printed, used as an adhesive and also processed using the conventional wood-working techniques.

To understand the scalability, segmentation strategies, process efficiency/limitations, and assembly logistics, we designed a composite pillar (Fig. 6). Its geometry is expressed as an implicit tubular surface with sufficiently complex topological features. Nevertheless, locally, it is within the domain of composite conic surfaces for which our models are trained. It is an object that would have been very difficult to fabricate with any other conventional method. The pillar measures 5 m in height and between 0.6 and 1.0 m in diameter. While it is a proof-of-concept demonstration artifact, it also hints towards construction applications of free-form concrete formworks. Timber, particle boards, and cardboard materials are already used for such applications.

Various wall patterns were evaluated for 3D printing including: single, double, interior web, and buttress-like designs (Fig. 7). Single-wall objects were structurally insufficient as well as too refined for corrective postprocessing. While both the buttress-like and interior web wall designs were structurally superior, they both tripled and quadrupled material consumption and production time, respectively, compared to the single-wall design. The conservative middle ground of double-wall design, measuring 20 mm in thickness, was thus selected for the final production.

Segmentation of the pillar in 50 vertical parts was informed by the constraints of material supply per batch, due to laboratory equipment setting; the weight of each part for ease of handling; the increase of risk for potential part collapse due to buckling as a function of its height; the faster rate of production as opposed to the time required for curing. In an industrial setting, it would also made more sense to print continuously, as it is the fastest and most automated part of the process, rack printed parts, and kiln dry them in large batches. In the laboratory setting, we deployed a few dozen computer fans to shorten drying time at ambient temperature. There exist chemical methods to achieve accelerated curing, but we avoided compromising the sustainability characteristics of the process.

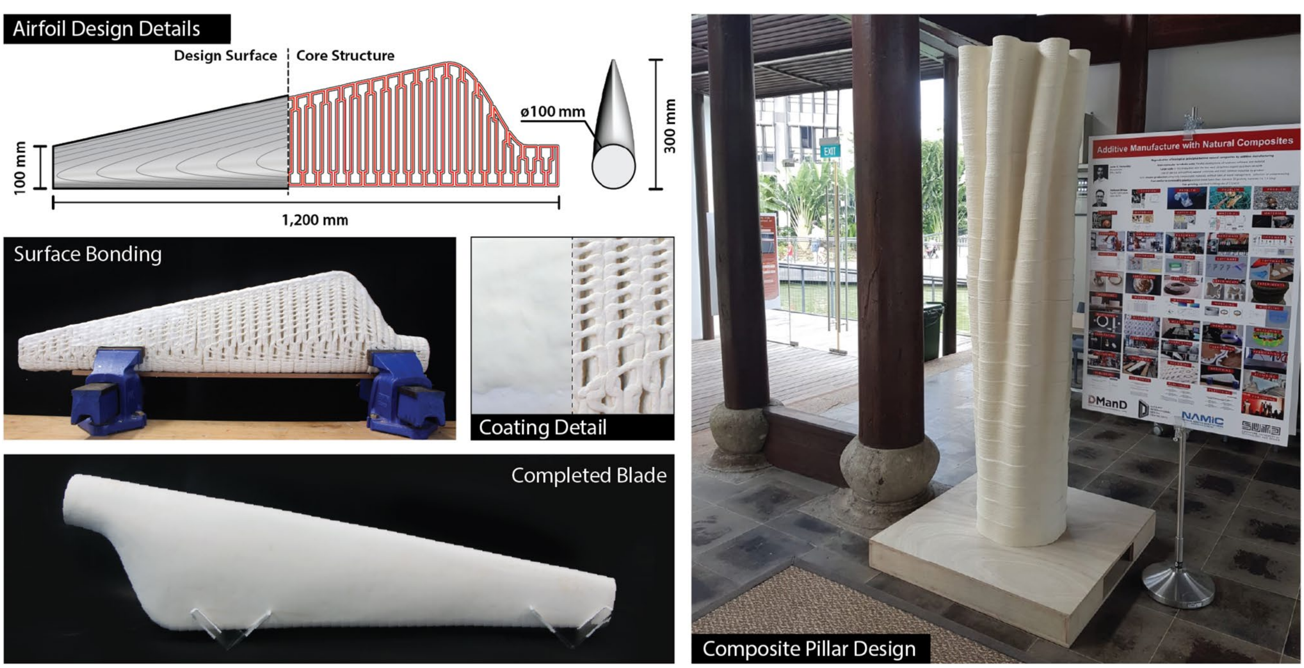

Fig. 6 Left: wind blade airfoil design evaluating hybrid fabrication combining additive manufacturing as well as conventional wood-working techniques. Right: composite pillar design work-in-progress currently 100% printed but only approximately 50% assembled

Fig. 7 Left: double, internal web, and buttress wall designs. Middle: dry cylinder and wet capsule cement casting prototypes. Cement did not penetrate the walls. Right: two buttress wall segments fused with FLAM, half sanded, half rendered, and cast with concrete

The pillar is comprised of total 2000 layers, with 3.5 mm wet and circa 2.5 mm dry height per layer. The total aggregate run length of filament printed was slightly over 10.6 km with average of 213 m per segment. At 50 mm/s motion speed, the time required per segment varied within 0.5–2.0 h with total net print time of approximately 60 h, or about 2.5 days. The material consumption in wet form reached about 480 kg, 375 kg thereof being water, which in dry state resulted to approximately 105 kg total. The approximate cost of raw materials was about 275 USD or equivalently 0.57 USD/kg wet and 2.04 USD/kg dry.

Reliability-wise, we had two fault incidents, namely a miscalculation of one preset model and a crashed part by the nozzle, both due to operator error. The fabrication process was uninterrupted signaling that the electromechanical and design-to-production systems are robust. The predictive models require further developed as we experienced vertical and horizontal deviations. While the effect is less noticeable in the vertical direction, the DNN overcompensated the tool paths resulting into protrusions between segments. The assembly involved applying a thin layer of FLAM between segments as an adhesive and stacking every ten into blocks. A comprehensive study including a model for logistics optimization is within the horizon.

Preliminary experiments for 3D printed formworks for reinforced concrete construction show promising results. Samples, wet and dry, were poured with high water-to-cement ratio 1:1 (*w*/*c*) to access the interaction between materials. The molds showed no adverse chemical reaction between the alkaline cement and mildly acidic FLAM components. The molds also did not leak through the layers despite the low viscosity mixture. Predictably, the wet mold conformed better to the cement but also deformed and shrunk uncontrollably. In another experimental prototype, two segments from the composite pillar's buttress-like wall design were fused with FLAM, a conventional tubular-welded rebar steel reinforcement cage was inserted in the cavity and cast with concrete. Again, we observed no concrete penetration through the segment interfaces. After the concrete set, the exterior surface was finished using sanding, rendering with FLAM, and painting. Envisioned opportunities of using FLAM 3D printing for precast building component construction include:

- Use of conventional concrete mixes without need for specialty accelerants and superplastisizers required for direct concrete AM setting time and flow control.
- Use of industry standard steel reinforcement strategies which is also a major challenge for direct concrete AM.
- Digitally prefabricated prefinished volumetric construction (PPVC) as FLAM has pleasant appearance and/or it is easier to finish compared to exposed concrete.
- Insulated component fabrication as FLAM is a biofoam material at its lower density formulations. Nevertheless, this requires measurement with guarded hot-plate apparatus for thermal conductivity determination.

- Services and functional features integration as, for instance, electrical junction box and conduit cavities embedded in the design at the time of 3D printing.

Before moving towards this direction, we first need to understand the hydrostatic behavior of concrete casted into taller 3D printed molds. We aim to use the pillar and proof of concept for large-scale free-form 3D concrete fabrication. While this may not substitute all construction processes, it may expand the realm of formal and functional integration opportunities.

7 Conclusions

We presented an overview of the ongoing development efforts for a manufacturing process using natural composite materials. While there is a lot more work to understand and control its parameters, we hope that there is good evidence that it can produce large-scale artifacts with highly sustainable characteristics. We do not yet know the limits of such scaling, but it would be naive to assume that no assembly, or no other materials, will be required to span the orders of magnitude and systemic complexity covered by architectural artifacts. It may thus make more sense to try minimizing production time to leverage increases in scale of physical dimensions. Fusing aspects from the conventional and contemporary manufacturing processes, additive, forming, and subtractive, may be a reasonable way forward. Translating the problem to the domain of programmability, where development and production can take place efficiently, is a way to counter the increase of overall process complexity.

A collateral benefit of focusing on the time domain, as a handle to physical scale, had the unforeseen ability to improve the overall quality of produced objects. If the process is rapid enough, then discarding parts that do not fit quality requirements is more affordable, because reprinting becomes more viable than performing manual rework or lowering acceptance quality standards. We discarded numerous parts that failed or did not meet expectations by merely placing the still wet material back in the supply end. A unique characteristic of FLAM is their high recyclability; even after fully cured, parts can be ground and the material reused without determent to their properties.

For a new digital fabrication process to move outside the laboratory and enter industrial production, its cost is a critical parameter that we cannot afford to overlook. Scaling in this sense becomes a function of availability and intensity of resource extraction and use. All material components used here are literally present in nearly every natural ecosystem on earth, that is as long as plants and critters exist. Availability thus is not only not a fundamental problem, but, instead, there is also potential for the reduction of environmental impacts related with transport of resources around the globe. Consider, for example, the waste for transporting fiber board products from developing countries, where manufacturing often takes place, to the developed world. In addition, both key components can be obtained from waste by-products of manufacturing processes such as timber and food processing, and thus, resource intensity is also low. At already a modest material cost of approximately 2 USD/kg, we foresee that the economy of scales will further lower production costs to the point of being able to compete with commodity industrial material products.

As this is a fundamental technology research project, a little time was devoted on the development of specific target applications. We expect those to come directly from the industry. However, there are foreseeable uses that spring from the unique properties of the material and fabrication process in the domains of interior design, such as furniture and fittings; industrial applications such as recyclable packaging beyond composting; perhaps naval and aerospace applications where light-weight materials are important; products where non-toxic materials are required including medical; applications where synthetic foams are used for impact energy absorption such as automotive; even architecture and construction.

The mechanical properties of the produced objects so far do not suggest directly for structural applications, in the building industry sense, if the material remains unmodified. Infusing polymers would allow us to immediately compete with engineered wood plastics, but it would nullify all efforts on sustainability. While the material is non-porous, it is susceptible to natural elements including oxygen and water. Only plastic polymers have such ability to resist nature so persistently, which is the key contributor to their ecological impact and what we aim to overcome with this research in the first place.

In the interim, we may approach building applications such as interior light-weight partitions, acoustic, and insulating panels in replacement of synthetic foams, engineered wood composites taking advantage of the adhesive properties of FLAM, and production of recyclable formworks for the conventional casting processes. Sequestration of construction waste is also possible as composites tested with contaminated saw dust from plywood and fiber boards were often stronger because of the presence of the existing polymer adhesives. Overall, using digital fabrication with natural composites towards prefinished prefabricated volumetric construction applications may both improve the efficiency and sustainability of building production processes in the near term horizon.

Nevertheless, the strength of natural timber and water resistance of natural lacquers is not because of the innate properties of the ingredients alone but because of their hierarchical design and assembly that takes place through "natural manufacturing" processes. Digital fabrication methods may enable us to replicate such multi-scale spatial material synthesis, but this requires long-term research effort on materials and methods. Perhaps, more interestingly, the opportunity of reflecting on how natural processes actually work suggests that we may have to question our deeply ingrained concepts pertaining resisting the elements by any means, and orienting, instead, our thinking and methods of production towards embedding within ecological cycles. Again, digital technologies may assist us moving our design artifacts towards this embedded aptitude for perpetual fabrication and assembly required to arrive there.

We envision that success in digital manufacturing with two of the most globally abundant and locally available biomaterial components in the world, positive steps towards presented here, may impact significantly downstream general manufacturing, upstream design thinking, and move us closer towards a more sustainable society.

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