From material intelligence to informed digital fabrication

Abstract. We present results on the development of a sustainable digital manufacturing technology, discuss the challenges associated with additive manufacturing with natural materials, how statistical modelling techniques enabled understanding the intricate relationship between material and fabrication and allowed to control material extrusion. We present a prototype created to assess the ability of the process to create large-scale artifacts. We believe steps towards advancing methods for environmentally-aware digital fabrication may pave the way in transforming the industry and society towards more sustainable production and consumption paradigms.

Keywords. Digital Fabrication; Bioinspired Materials.

1. Introduction

Additive manufacturing (AM) has been at the centre of research across disciplines for the past decades (Thompson et al, 2016). Potential of AM includes rapid design to production, innate ability for customization, functional integration and improved resource utilization (Tofail et al, 2018). Several shortcomings including materials, design software, sustainability, reliability and production speed, prevent its advancement (Royal Academy of Engineers, 2013). Research work presented here aims to address challenges in AM primarily from the perspective of its sustainability characteristics. The environmental impact of AM is a domain only recently has come to research attention (Ford and Despeisse, 2016). Indicative work includes comparative study between subtractive and additive manufacturing (Faludi et al 2015), life cycle analysis of AM products (Da Silva Barros, Zwolinski and Mansur, 2017), energy consumption studies (Hao et al, 2010; Baumers et al 2011; Kerbrat et al, 2016) and broader analysis of AM and sustainability (Huang et al, 2013; Gebler et al, 2014). Our work begins from the first principles of AM, namely its material domain.
2. Bioinspired Materials

Biological materials and processes have been a source of design inspiration for architecture in the past (Hensel, Menges and Weistock, 2010; Mazzoleni, 2017). Nevertheless, difficulties in their synthesis and control in fabrication has prevented their wide adoption often resulting in morphological replication of their outcome or replication of their functional characteristics by synthetic polymers to suit manufacturing objectives. We developed Fungus-like adhesive materials (FLAM), a family of natural composites result of bioinspired design along a fabrication process to overcome some of those barriers (Author, 2018). They are composed of cellulose, a biopolymer common in plant matter, and chitin, a biomolecule often associated with the exoskeleton of arthropods and insects (Author, 2012). Study of the cell wall of oomycota, a fungus-like microorganism that combines those molecules, gave rise to FLAM. While arbitrary composition of the ingredients results to composites either too weak or uncontrollable, replication of the composition encountered on oomycota produced materials with strong and well-behaved properties. What makes them highly sustainable is their original components: cellulose is the most abundant bio-material on the surface of the earth (Reireter, 1999) and chitin may be the second most common natural material. Both originate from renewable sources and they are biodegradable outside special composting environments (Author, 2014). Moreover, both are obtained as by-products of industrial timber and food processing at low prices. We investigated various cellulose sources including laboratory-grade cellulose, industrial wood flour fillers and waste saw dust from timber processing. The physical and mechanical properties of FLAM composites are in the range of high density synthetic foams and low-density timbers. Visually, when pure cellulose is used the material resembles paper while using wood flour, its appearance is closer to fibreboard products (Figure 1).

Figure 1. Left: Ashby plot of physical and mechanical material properties. Middle: Electron microscope photography. Right: Samples of FLAM with saw dust and pure cellulose.
3. Digital Fabrication

Robotic fabrication with natural materials has been a topic gaining acceptance in the past years in the architectural community with materials including clay (Friedman, Kim and Mesa, 2014; Dunn et al, 2016; Al Othman et al 2019), sand (Grammazio and Kohler, 2015) and wax (Gardinger and Janssen, 2014). Digital fabrication with FLAM composites is based on Material Extrusion (ME) principles (ISO/ASTM, 2015). The materials components are combined in an aqueous solution forming a viscous colloid deposited in linear filaments alike Fused Deposition Modelling (FDM) techniques familiar from rapid prototyping. As the material state is closer to liquid than solid, the process can be also considered as variation of the Direct Ink Writing (DIW) method. The process does not require temperature control during extrusion and the material dries overtime, as water evaporates, to form solid objects. The digital fabrication system developed for FLAM 3D fabrication is comprised of an industrial robotic arm, a high-pressure bulk material unloading pump, the associated volumetric dispenser attached to the robot’s flange, various peripheral devices, such as an air drier and a die grinder, and integration components such as programmable logic controllers. To investigate how to improve the speed of production and product quality, the method combines three modes of operation including mainly additive (3d printing) but also net-zero (forming) and subtractive (machining) operations (Author, 2018).

![Digital Fabrication Process](image)

Figure 2. Left-to-Right: The digital fabrication process fuses 2D and 3D additive manufacturing with net-zero material change and subtractive principles.

4. Challenges

Using natural materials in additive manufacturing is challenging because of their innate variability. Insofar as no two pieces of wood are ever the same, FLAM composite fabrication needs to account for similar kind of variation. This is unlike standardized industrial products such as metal alloys and synthetic polymers,
developed exactly to avoid the unpredictability of raw natural material sources. We thus faced, and still do, significant difficulties before being able to 3D print with a certain level of confidence. Those include:

1. Material viscosity is proportional to the pressure required for extrusion. If too low the material extrudes easily but it cannot support itself. High viscosities are preferred but require high-pressure systems. There is a limit of how much pressure can be applied on a material in suspension before its phases separate, the lower viscosity matrix pumps out first leaving behind a starved cellulose.

2. Particle size affects the pressure requirements due to interparticle friction. Waste saw dust requires higher pressures because of presence of a variety of other material components such as lignin and oils and contaminants.

3. While cellulose and chitin have low caloric value for most organisms, use of waste produced on occasions fungal growth. Using waste for sequestration is tolerated by the material but care is required to prevent such contamination.

4. The material cures at ambient temperature and humidity by water evaporation. If left to do so naturally, it takes several hours for parts to stabilize and several days before they fully harden. To accelerate curing, we tested oven baking and convective drying. Increasing the temperature rapidly yielded poor results as the exterior formed a crust trapping moisture or caused filament delamination.

5. The rate of moisture removal is related to wall thickness and surface area as parts dry outside-in. Thinner walls and larger surface areas exposed to air result to faster drying parts but too thin walls are also structurally weak.

6. Extrusion is dependent on motion speed and flow rate. If motion is too fast, filaments tend to break apart, detach from the base plate or one another. If flow rate is too fast, the shape of the filament becomes highly non-linear. Overall, the dimensions of the filament are highly sensitive to both velocity components.

7. Filament adhesion was approached by decoupling in vertical and in-plane directions. Vertically, it is insufficient to place beads on top of another as they do not adequately fuse. Instead, they are compressed to ensure a form of mixture. Care though is required because dynamic normal pressure applied affects shape, surface finish and overall stability.

8. In-plane fusion is also critical otherwise adjacent filaments delaminate while drying. Adjacent beads require approximately 40-50% overlap to bond. We printed several pairs at various overlap rates and mechanically sheared them.
When failure occurred outside the overlap we determined fusion was sufficient.

9. Wet FLAM is highly pliable and mechanically viscoelastic as is its stiffness is time dependent. It is difficult to model and simulate how an object will deflect overtime, as the behaviour is both dynamic and non-linear.

10. The most challenging aspect of 3D printing is in the transformation that takes place between wet and dry states. The material shrinks by as much as 5% along the direction of extrusion, 12% in the transverse and up to 32% vertically. Thus for achieving a specific geometry after curing, design geometry needs to be preset against anisotropic shrinkage.

5. Experimental Design

The process depends on numerous parameters, some identified and many still unknown. While their impact is observable their interactions are opaque. Attempting to model and drive the process analytically is as task of insurmountable complexity. It is possible however to perform experiments, observe results and instead of a mechanistic, develop an empirical model to systematize the problem and take steps forward. The method used, namely design of experiment (DOE), originates in statistical analysis and quality control (Montgomery, 1997). Its key idea is that a process can be approached as black box influenced by controllable and uncontrollable inputs. Varying controllable factors and measuring their effects, may explain statistically the source of variation and allows for control (Montgomery, 2009). We thus constructed a factorial DOE model. A unique aspect of the method is in varying multiple factors together, instead of one at a time. This reduces the number of tests performed while producing a picture across the process domain. Data collected were used to fit a polynomial model that accounts not only for the influence of the main factors but also their interactions.

![Figure 4. Left: Design of experiment main factors, effects and response surfaces. Right: Filament uniformity achieved using multi-response optimization for 3 and 4 mm heights.](image)

Parameters used include the motion speed ($v$), flow rate ($f$) and vertical nozzle offset ($z$). We measured the filament width ($w$) and height ($h$) in wet and dry states and their tensile strength ($t$). For each factor we established three test levels, low, medium and high, and constructed a face-centred central composite design (CCD) model to account for non-linearity (Author 2018). The model is expressed as a set
second order relationships between controllable parameters to expected outcomes. Analysis of variation, assisted in understanding which parameters and interactions affected results and those with low significance were purged. Graphically the model is represented by response surfaces where input parameters map to response outcomes. To confirm that the model was not merely statistically sound but it produced desirable results we printed several prototypes. The operating settings used, were result of multi-response optimization using composite desirability to mediate between responses (Derringer and Suich, 1980). Results were successful (Figure 4) as both 3 and 4 mm of layer heights produced consistent filament dimensions.

6. Prototyping

As a demonstration for being able to print large-scale objects we designed and built a pillar prototype. It measures 5 m vertically with diameter ranging between 0.6 and 1.0 m (Figure 5). The design was developed using implicit surfaces whereby a distance-field was loaded with seven pairs of parabolic arcs arrayed radially and level-set profiles were extracted by polygonization. This produced 14 tubular sections which fuse and detach from one another vertically, creating a geometrically and topologically a complex shape that cannot be fabricated easily by conventional processes. To 3D print the pillar efficiently, we segmented it into 50 vertical parts. Those were fused after partially drying with FLAM adhesive into larger blocks. Blocks were mechanically fastened for ease of transporting and assembling the pillar.

Figure 5. Left: Diagrams of the pillar at various levels. Right: Wall design properties.
Using single filament thick walls, circa 12 mm, was questionable because of structural considerations for supporting its total weight and because we expected dimensional errors due to shrinkage for which thin walled segments would leave little room for post-processing. An alternative wall profile design used an internal web, offset 40 mm inwards, to increase the sectional area (Figure 5). While the design was reasonable, it was abandoned because of increased material consumption as high as four times of a single wall case. Another alternative, incorporated 50 mm vertical fin stiffeners. The fins were radially arranged from the center of the pillar and beyond structural improvement, they aided registration and fixing between consecutive segments. This design also required triple the amount of material compared to single wall design and eventually the simpler double filament wall design, circa 20 mm, was used as it required only twice as much material per segment.

The pillar is comprised of 2,000 layers, 40 layers per segment, with each layer measuring 20 by 2.5 mm in cross-sectional width and height after curing. To measure material consumption, we use the travel distance of print for which we printed about 10.6 km of material total with 213 m per segment on average. With extrusion rate of approximately 0.045 kg/m, the total weight at wet state was circa 480 kg of which 370 kg was water. The pillar, without accounting for segment to segment adhesive and hardware, weights approximately 105 kg after drying. With motion speed of circa 50 mm/s the total print time was about 60 hours with the smallest segment requiring 30 min and the largest 2 hours. The cost in raw materials was approximately 275USD or about 2 USD/kg.
Beyond a segment for which we printed without the correct surface to machine path offset and had to recycle the material and reprint; and another case of crashing the robot on a printed part due to registration error, the process was interrupted. It is encouraging that in terms of robustness the process seems already to perform very well and both incidents were due to human error. In terms of dimensional accuracy, even though the overall geometry was successfully reproduced, there is a lot more work to be done for improvement. We are not far from a few millimeters away though, something that is visually observable by the protrusions between consecutive segments. The cause of this is the anisotropic shrinkage between the bottom layers of a part which adhere to the printing base in conjunction with the top layers which are not compress fused and they dry faster as more surface is exposed to air compared to interim layers.

7. Conclusions

We presented part of the development for a digital fabrication technology aiming to approach additive manufacturing from a sustainable perspective. We highlighted the challenges of working natural materials and their highly complex behaviours. This explains why despite offering the most environmentally benign option for production, they have been largely rendered obsolete and displaced by standard industrial material products.

In architecture we rely on representations and mechanistic models aiming to prescriptively predict the future. It is impossible to perform comprehensive experimental design due to scale, time and cost. However, experimental methods are not absent as computer simulations cannot yet model intricate physical phenomena. Those include mechanical evaluation using tensile and bending tests, impact tests on cladding units and quality control procedures such as concrete slump tests. Statistical methods of experimental design are valuable for developing understanding of complex physical phenomena, extracting material intelligence, informing design thinking and eventually allowing for process control. As the barrier from design to production lowered by programmable design and production systems over the past few decades, it is now easier to perform physical experiments and also measure results. We believe the use of empirical predictive modelling techniques will progressively become an invaluable tool in the domain of digital design and fabrication. Computational experimental design techniques may exactly what eventually will allow us to understand natural materials and perhaps bring them back in manufacturing and construction.

The bulk of the research effort so far has been devoted in basic technology development including material and fabrication systems design. We have not investigated concrete applications for additive manufacturing with natural composites. We can only speculate of potential applications based on material and fabrication properties and initial interest expressed by the industry parties. Applications in product design include recyclable packaging, customized furniture, lightweight components for naval, automotive and aerospace, products that non-toxic materials properties are important, upcycling or sequestration of industrial waste. In construction, if unmodified by synthetic polymers which may deteriorate its sustainability aspects, the material is not yet structural in the
building sense nor weather resistant in the sense of plastics. As such we can foresee applications related to interior design such as fittings and partitions, reusable molds for cast building components, perhaps acoustic or insulating products, restorative applications for historical timber architecture. In any case a lot more additional work is required to assess its suitability for building applications.

In conclusion, we demonstrated positive steps towards creating large-scale artifacts with two of the most abundant natural material on earth. There is a lot more research work required to fully understand and control the process, but early results are encouraging. We believe that continued effort on integrating natural materials and digital fabrication will pave the way towards environmentally-aware paradigms of production and a more sustainable society.

References
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