Integrative Green Building Envelope

Large Scale Robotic Additive Manufacturing

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1 Image of the full-scale IGBE system prototype.

ABSTRACT

The Urban Heat Island (UHI) effect, corresponding pollution, and a lack of biodiversity in urban areas pose serious threats to human health that will significantly increase with the rapid urbanization predicted in the next several decades. Green building envelope systems that incorporate plants and vegetation on the building exterior offer one solution to reduce UHI effect and air pollutants while increasing building performance through passive cooling, wind buffering and added insulation.

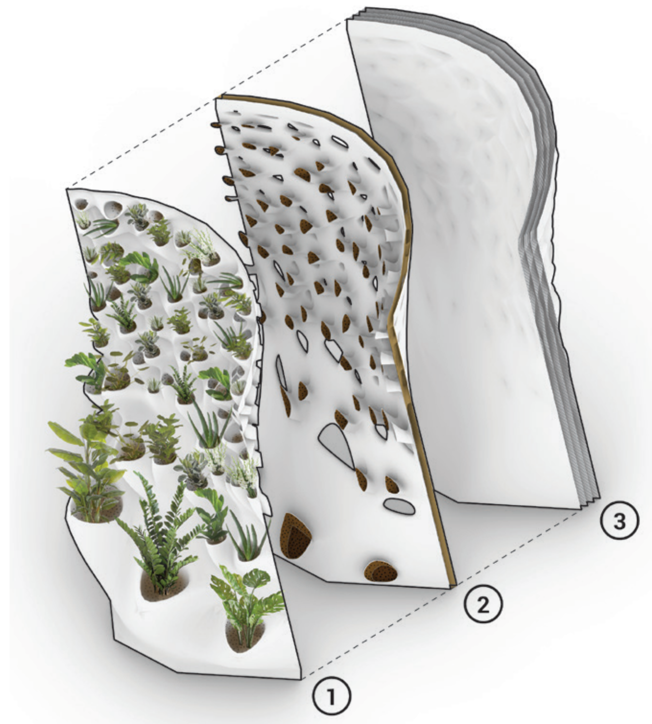
While conventional green wall systems are often materially inefficient due to a lack of integration with functional building envelope layers, this research investigates the potential of large-scale 3D printing with robotic pellet extrusion (RPE) to produce a novel integrative green building envelope system. The developed envelope system fosters the growth of a self-watering, diverse plant ecology to passively cool buildings, filter contaminants from polluted air, and attract diverse forms of wildlife. This paper presents the conceptualization, design, and prototypes of the Integrative Green Building Envelope (IGBE) system. The fabrication and computational methods developed through this research resulted in the successful 3D print of a geometrically-complex full-scale prototype with multiple layers that can be adapted and applied to many different architectural typologies and locations.

INTRODUCTION

Urban areas face a host of existential environmental crises brought on by anthropogenic climate change. Urban Heat Island (UHI) effect and corresponding pollution pose serious threats to human health and well-being that will only magnify with the increasing frequency and intensity of extreme weather events (Masson-Delmotte et al. 2021). UHI effect is a phenomenon by which urban areas experience elevated temperatures in comparison with rural surroundings. This difference in atmospheric temperature can reach 12°C at night while surface temperatures are found to be 15°C higher during the day (U.S. Environmental Protection Agency 2008). Caused by the high thermal absorption of construction materials, heat entrapment from urban canyon effect, heat generation from human activities, and a lack of green space in cities, UHI adversely affects urban communities through increased energy demand, thermal pollution of sensitive ecosystems, the formation of ground-level ozone and other air pollutants, as well as heat-related illness and mortality (U.S. Environmental Protection Agency 2008). UHI is estimated to cause an additional 1.1 million heat-related deaths in the United States each year while ambient air pollution is responsible for an additional 4.2 million deaths globally (Lowe 2015; World Health Organization 2018). The impact of these problems will be exacerbated by the rapid urbanization needed to accommodate two-thirds of the world's population by 2050. There will be a significant increase in UHI effect as more buildings are constructed and urban areas densify (United Nations Publications 2019).

Green building envelope systems that comprise vegetation on the building exterior offer one solution to reduce UHI effect and its negative impact on human health (Lehmann 2021). Plants cool their surrounding environments through evapotranspiration and shading, reducing ambient temperatures during extreme heat events and improving building performance. Green envelope systems also filter harmful pollutants and contaminants from the air, absorb carbon, increase building longevity, and provide insulation and wind protection to further reduce energy consumption (Perini and Rosasco 2013). In addition, urban ecosystems can benefit from the habitat and sources of food such envelope systems provide for birds and various invertebrates (Mayrand et al. 2018).

In cities, building facades offer expansive areas to cultivate plant life with green wall systems. Conventional green wall systems, however, are typically designed as superimposed structures that lack integration with building systems, resulting in material inefficiencies that increase their life cycle global warming potential (Ottele et al. 2011). These systems comprise mats (often non-recyclable felt) or modular planters with a uniform depth of growing substrate that limits plant size, variety, and support of biodiversity (Convertino, Vox, and Schettini 2021).



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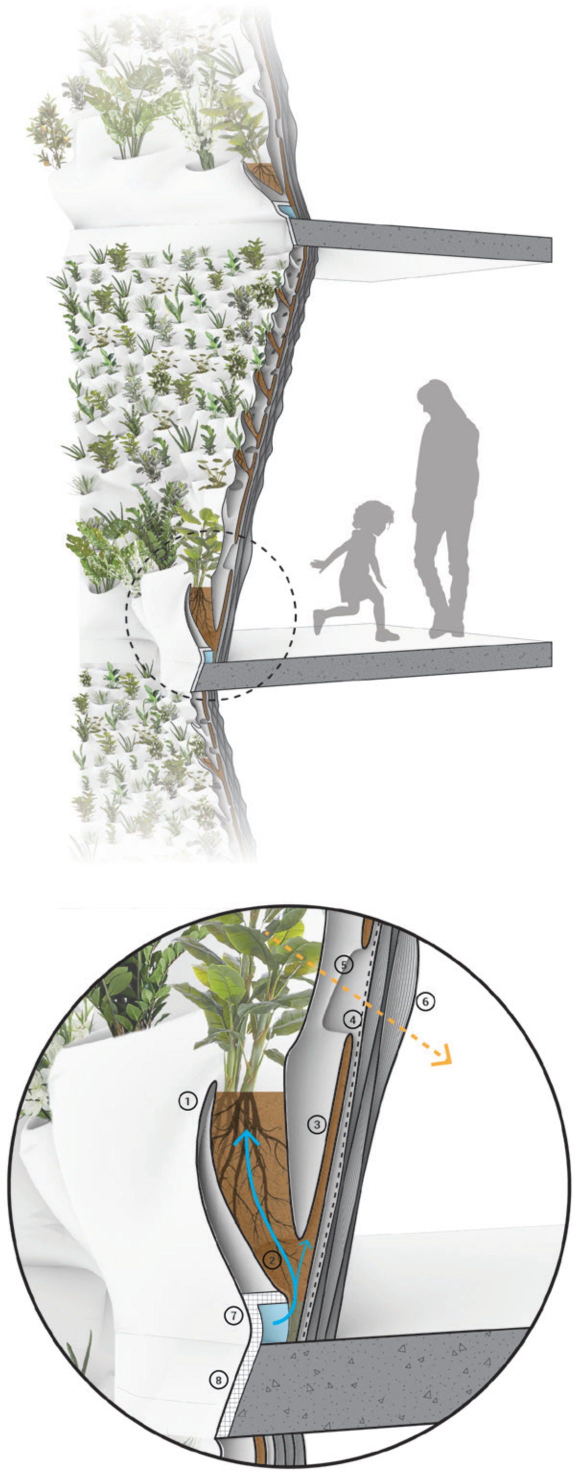
2 Multi-functional layers of the IGBE system include: 1. the exterior shell comprising plant pods of various sizes, 2. the capillary irrigation layer, 3. multiple interior air layers.

The environmental burden and high cost of mat systems in particular, are largely impacted by the high installation cost of pre-vegetated panels and annual maintenance requirements, including frequent panel, plant and irrigation pipe replacement (Perini and Rosasco 2013).

Large-scale 3D printing through fused filament fabrication (FFF) and fused granulate fabrication (FGF) has the potential to profoundly change the way we conceptualize, design, and build envelope systems by allowing for the seamless integration of many functions. FFF and FGF are additive manufacturing (AM) processes through which material is heated, extruded through a nozzle, and deposited to form objects layer by layer. FFF uses filament, while FGF uses granular material as feedstock. These fabrication methods allow for the fast manufacturing of complex components. Printing with thermoplastics in particular, which are lightweight and versatile, enables the invention of high-performance envelope solutions with energy saving benefits. Material research of thermoplastics, especially bio-based plastics, is a rapidly expanding field that promises to greatly reduce the carbon footprint of the construction industry (Bhatnagar 2019). Together, AM and thermoplastics can radically transform the production and performance of building envelope systems.



3 Schematic section perspective and detail of the IGBE system. 3

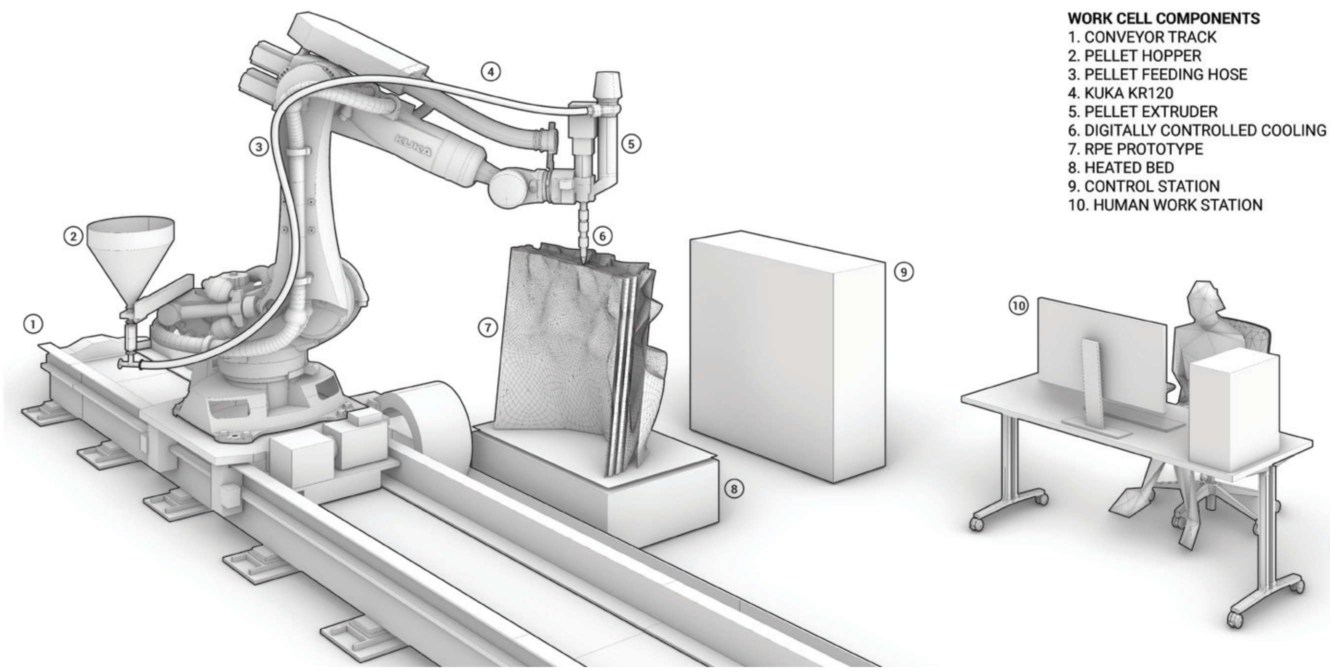
Recent research has demonstrated the interest of the Architectural Engineering and Construction industry in the thermoplastic 3D printing of building envelopes. For example, the Additive Manufacturing and Integrated Technology (AMIE) project, a research collaboration between Skidmore Owings and Merrill, LLP and The U.S. Department of Energy's Oak Ridge National Laboratory demonstrates the use of Big Area Additive Manufacturing (BAAM) technology to design and fabricate a high-performance building enclosure that integrates vacuum insulated panels, self shading windows, structural and electrical systems, photovoltaic panels and an innovative energy sharing platform (Guerguis et al. 2017). Students at ETH have 3D printed a functionally graded facade system with non-orthogonal discretization, gradient infill structures, and integrated snap-fit connectors (Taseva et al. 2020). Branch Technology, a Tennessee-based fabrication company, uses spatial 3D printing of ABS plastic and carbon fiber, a process they have patented as "Cellular Fabrication" (C-Fab), to build mass-customized rain-screen panels in addition to other bespoke building elements (Shelton 2017). The full potential of polymer 3D printing, however, remains unexplored. The application of novel 3D printing technologies will require a complete reimagining of construction practices, design processes, and the entire conceptualization of building envelope systems.

STATE OF THE ART

A new alliance between nature and construction is proposed to address the growing environmental issues that humans and urban ecosystems face. This research presents a novel green wall typology designed as an integral component of a multi-layer 3D printed building envelope system. Such a system combines the many functions of conventional building systems including structure, insulation, air and vapor barriers, and exterior cladding with components that support the cultivation of plant life. The proposed envelope system is composed of a) an exterior shell entailing plant pods that vary in size, b) a capillary irrigation layer (CIL), c) channels that connect each plant pod to the CIL, and d) multiple, separate interior layers that provide thermal insulation (Figure 2).

This research advances the existing research on 3D printing thermoplastic envelopes and green building infrastructure by:

1. developing 3D printing methods based on Robotic Pellet Extrusion (RPE) for large-scale geometrically-complex parts,
2. conceptualizing an integrative green building envelope (IGBE) system,
3. developing a computational design method for the seamless integration of diverse plant species within a building envelope system, and
4. developing tool pathing methods and control systems that improve the speed and efficiency of RPE 3D printing for construction.



4 The construction scale RPE work cell.

Achieving holistic integration of various envelope functions results in geometric complexity that can only be produced through 3D printing. A computational model based on Voronoi logic is developed to partition the exterior layer of the envelope into many unique plant pods with channels that connect each plant pod to the CIL.

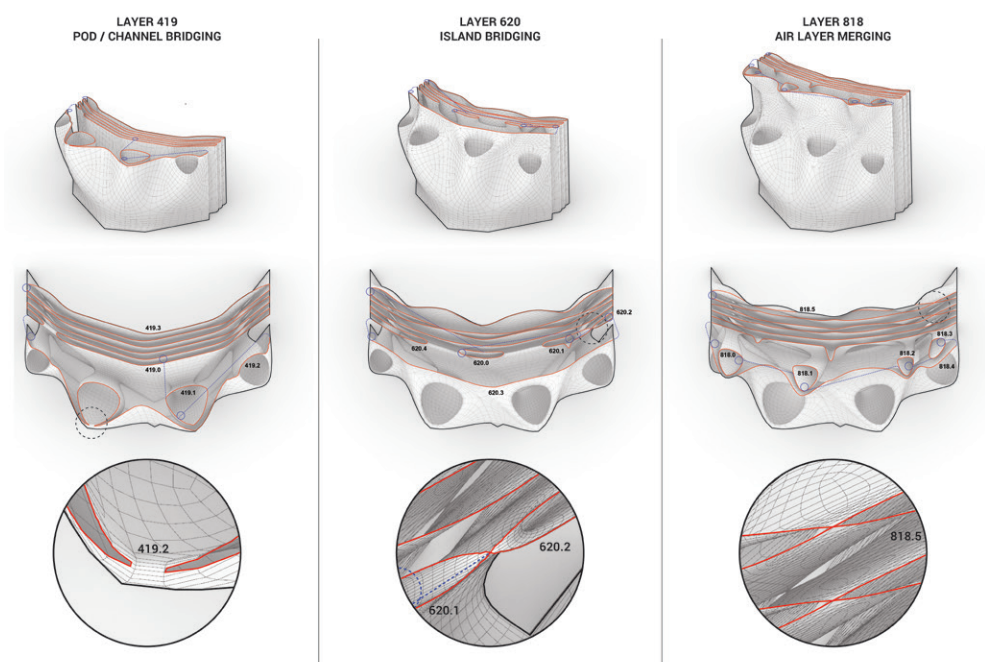
Production of complex topologies through robotic extrusion demands toolpath strategies that account for shallow overhangs, minimizing or eliminating support material, and optimizing the route between discontinuous polylines both within a single layer and between successive layers. The toolpath is defined by contour curves that outline the designed form. A complex geometry with interior porosity and voids, as in this research, demands outlines of the form in the exterior and interior of the designed part. Therefore, contouring the overall mesh geometry to generate 3D printing data results in sets of open and closed polylines (with connected start and endpoints) per layer. These polylines are the source for the toolpath generation process and they contain all of the information needed to generate tool paths.

PETG is used as the 3D printing feedstock. While PETG is an affordable material that can produce durable and hard-wearing components, it is derived from non-renewable resources and causes environmental harm at various points along its supply chain. For this project, PETG is proposed as a proxy for an alternative, renewable thermoplastic. Numerous types of non-petroleum-based plastics are being utilized in architectural 3D printing applications. Projects such as the 3D Printed Urban Cabin, located in Amsterdam, and the temporary facade of Europe Building designed by DUS Architects for the Dutch EU presidency in 2016 are printed with materials from renewable biomass sources (DUS Architects). Technical advancements to the fabrication setup can allow future exploration of alternative materials. Through prototyping, the toolpath strategies, fabrication settings, computational model and the geometry of the components were adjusted and refined. The developed envelope system, computational and fabrication methods in this research are generalizable and scalable.

METHODS

CONCEPTUALIZATION

The exterior cladding is devised for plants to inhabit pods in an upright orientation as they would inhabit the earth's ground (Figure 3). This approach is similar to conventional modular living wall systems that provide greater soil depth than mat systems and allow for more diverse plant habitation, greater plant longevity, and easier maintenance (Dover 2015; Jim 2015). Unlike conventional modular green walls, however, these integral plant pods vary in size. Proper container size is critical to the survival and growth of cultivated plants; containers either too small or too large can harm plant health, leading plants to become root-bound or develop root rot. Additionally, root depth and morphology vary among plant species, necessitating a variety of pod sizes to foster plant diversity. Support of diverse flora allows a unique tailoring of species specific environmental performance; for instance, plant species with small leaves and high foliage density have been found to exhibit greater cooling effects, woody plants have been found to store carbon more



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5 Englarged tool paths generated at critical bridging and merging layers.

6 Early prototypes testing plant pod geometry and print settings for speed and print quality.

effectively, and leaf morphology has been found to affect the capture of airborne particulate matter (Charoenkit and Yiemwattana 2017; Ysebaert et al. 2021).

Here, pod size is parametrically adjustable through the computational design of the enclosure system. Each computationally generated pod is unique in its form and volume. In the proposed IGBE system, pods are largest in scale at the base of the envelope and decrease in size with height, giving clearance to plants for vertical growth and access to sunlight.

The plant pods are connected by interior channels to the CIL which contains a substrate to transport water upwards through capillary action. These channels act as a pathway for plant roots to absorb water. A capillary irrigation system is proposed as an alternative to complex drip irrigation networks that are costly to maintain and prone to failure (Jim 2015). At each building floor, a perimeter water channel supplies water at the base of the CIL. This water channel can provide plants with water that has been collected from rainwater or supplied from the building's water system. Voids for light and ventilation perforate the CIL at each plant pod. While in summer these voids would be shaded by foliage, winter sun could passively heat buildings in temperate climate zones if perennial plants are used.

In the IGBE system, sand is proposed as the capillary substrate given its relatively large particle size. Rudimentary tests were conducted to prove the sand filled irrigation layer holds water. Plastic is hydrophobic and a PETG test cylinder did not wick water. When the test cylinder was filled with sand, water wicked all the way to the top of the cylinder, and the sand was fully saturated. Capillary rise depends on the porosity of the infill material. Sand has the potential to rise 1-8 feet; silt 12-16 feet; and clay 12-20 feet (Thomas 2020).

Adjacent to the CIL are sandwiched layers that provide thermal insulation. The close proximity of the layers creates air pockets, and air is a heat insulator. Previous research in 3D printed insulation has demonstrated that more pockets result in a higher thermal resistance and smaller pockets reduce the thermal conductivity of encapsulated air (Grabowska and Kasperski 2020). 30 air-filled layers would be necessary to achieve the required R-20 value for Climate Zone 4A (Lars Junghans (Associate Professor of Architecture) in conversation with authors, November 18, 2021). Argon and other noble gasses such as krypton and xenon could be used in place of air to improve the thermal resistance of these layers. Because vegetation has been found to increase the thermal insulation capacity of exterior wall systems, the R-value of the proposed enclosure system could also grow as the density and foliage of cultivated plants increases (Pötz 2016).

In the proposed IGBE system, 3 layers are sandwiched at a spacing of 25mm. The extruder end-effector as well as the fabrication speed are factors that influenced the number of layers in the full-scale prototype. A future challenge is to achieve 30 layers without increasing the thickness of the overall facade, which can be achieved with advancements to the fabrication setup, most importantly designing an end-effector nozzle to print at various resolutions.

CONSTRUCTION SCALE RPE SET UP AND CHALLENGES

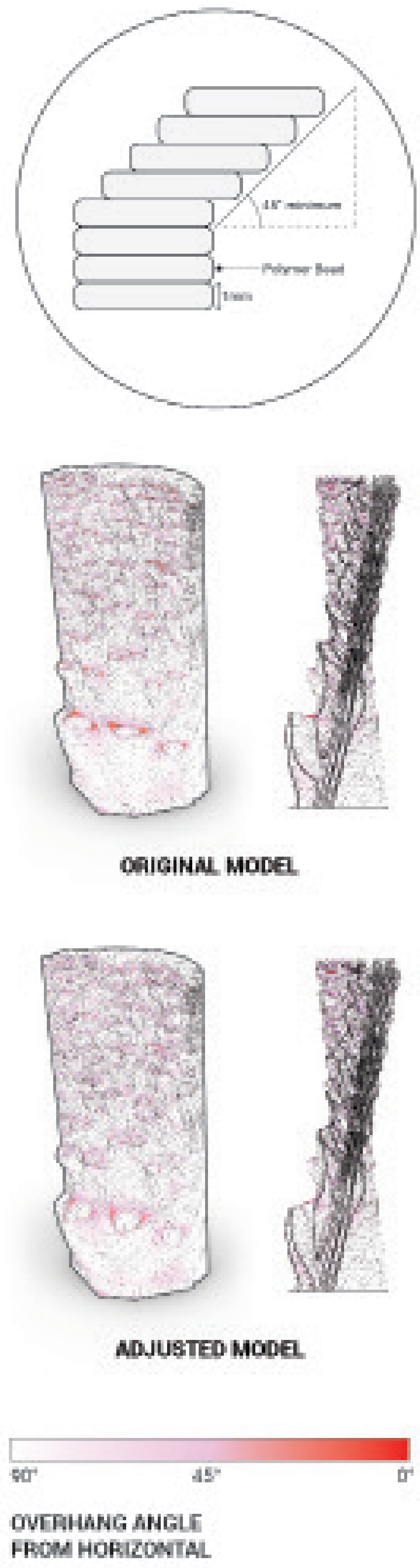
A construction scale Robotic Pellet Extrusion (RPE) refers to a method of FGF using a pellet extruder conveyed by an industrial robotic arm. The fabrication set up for this research includes an industrial robotic arm with payload of 120Kg and a 2.5m maximum reach, accommodated with an inhouse built pellet extruder, automatic pellet feeding system, digitally controlled cooling systems, and a (1236 mm x 762 mm) heated bed (Figure 4).

The RPE process comes with certain challenges and limitations including: a) limited overhangs without support material, b) bridging islands without support material, c) adhesion between the first printed layer and the heated bed, d) layer adhesion and print stability as the height of the print increases, and e) unintended material deposition during traversal of the extruder. In this project these challenges were addressed respectively through computational modeling and fabrication setups that: a) integrate parameters to limit overhang angles; b) provide cooling and air flow at bridging moments; c) generate a dense raft beneath the first printed layer and increase extrusion rates of the first several layers to facilitate adhesion; d) tangentially merge internal layers to add stability; and e) optimize traversal path while refining traversal settings. At shallow cantilevers and moments of unsupported horizontal printing, manual techniques were also employed to ensure the success of the print such as manual reduction of print speed and addition of external support.

FORM GENERATION FROM FABRICATION CRITERIA

The generation of toolpaths for FGF processes always utilizes polyline geometries. Through planar slicing of a 3D geometry, each slice, or layer, contains a collection of 2D open and closed polylines, or islands. In this project, toolpaths are generated at 1 mm increments. The complex topology of the building envelope entails continuous internal cavities and passages for functional integration which produce collections of islands per layer. Islands each require starting and stopping the print with lead in and lead out motion parameters that affect fabrication time. While sufficient time for cooling can reduce sagging at overhangs and bridging moments, an overall reduction in fabrication time is desirable for efficiency and improved layer adhesion (Roschli et al. 2018). To reduce the number of islands and shorten fabrication time with toolpath continuity, alternating edges of the interior air layers were enclosed prior to slicing (Figure 5).

As islands increase in size in successive layers, they merge with each other. At the moment of merging, each island toolpath must intersect tangentially. This is considered the lamination layer. A perfect tangent in the lamination layer is critical to the



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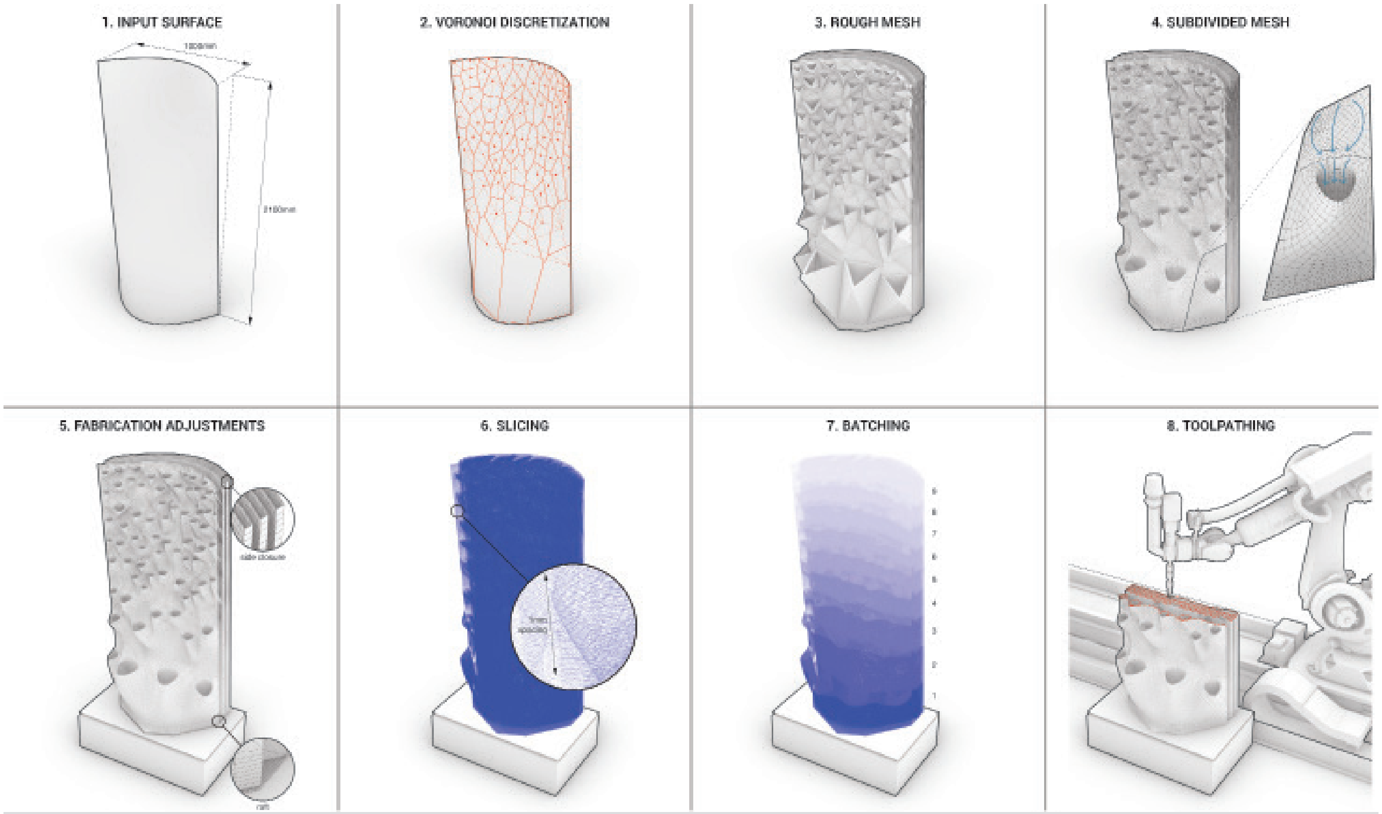
7 The minimum cantilever angle from horizontal is shown above. The angle of each mesh face in an earlier version is compared with the printed version of the full-scale prototype.



8 Steps of the omputational design methodology.

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watertightness and stability of the 3D printed part. A successful build-up of the printed part is determined by the overhang angle of islands in successive layers, as well as the amount of cooling delivered by the fan. Minimal unsupported distance between islands and high cooling decreases the chance of sagging in the lamination layer. Through prototyping, it was found that a minimum overhang angle of 45 from horizontal was required to reduce sagging and delamination between layers. This data was integrated in the computational model to guide the geometric design of the enclosure system (Figure 6).

The full adhesion of the printed geometry to the heated bed during the fabrication process is critical to the success of the print. Vibration of the robotic arm increases with height, which can lead to shaking of the print. Proper bed adhesion and the design of tangentially merging interior layers ensure the stability of the print as it grows in height. The temperature of the heated bed and surface area of the first several print layers contribute to the print adhesion. To prevent detachment of the printed part from the heated bed throughout the printing process, the temperature of the bed was set to 105°C and a zig-zag raft with 4mm thickness was introduced at the base of the prototype geometry.

COMPUTATIONAL DESIGN

The computational methodology of the IGBE system is designed as an adaptable framework to enable site-specific design strategies and involves the generation of design geometry and fabrication data. The computational design stages include: 1. inputting a given freeform surface, 2. discretizing the surface via a Voronoi algorithm, 3. generating a rough mesh of interconnected geometry from Voronoi cells, 4. subdividing the rough mesh with the Catmull-Clark algorithm, 5. modifying the mesh for fabrication constraints including: a) a raft for bed adhesion and b) layer enclosure for toolpath continuity, 6. slicing the mesh to generate contours, 7. batching the contours, and 8. generating and simulating toolpaths with printing parameters per batch (Figure 8).

To best accommodate a diversity of plant species within the building enclosure system, a computational model based on the Voronoi diagram is developed. This model allows parametric partitioning of any given exterior surface into regions close to the size required for a given set of diverse plants. For each plant, there is a corresponding region, the Voronoi cell. The bottom portions of these cells form the plant pods and their connection to the CIL, resulting in one continuous mesh. The top portions of the Voronoi cells are articulated as concave surfaces that are designed to direct precipitation to plants.

To integrate thermal performance, the developed computational model generates interior layers that can be controlled parametrically. The overall thickness of the envelope, spacing between layers, and tangential merging of layers can be computationally adjusted in response to design and fabrication considerations such as thermal resistance, daylighting, material efficiency, and print speed. The reduction in spacing between layers as they merge allows for variation in translucency and patterning across the facade. This merging between layers also provides structural stability during the fabrication process so that the full height prototype can be produced without the need for infill support, reducing the overall weight of the 3D printed part, material used, and printing time.

The computational design of the envelope was refined multiple times in response to a number of fabrication constraints after prototyping. For example, the geometries of plant pod rims were angled downward at a sufficiently steep angle to allow for successive layer deposition based on the observed minimum overhang angle. Plant pod and channel geometries were steepened and elongated as well. Interior voids were rescaled and shaped to limit the unsupported distance at bridging moments.

TOOLPATH GENERATION

The tool path generation is developed as an automated process. The complex and interconnected geometry of the envelope entails islands that require turning on and off the extruder as well as the unique naming of separate toolpaths on each layer. An algorithm was developed to automatically name these islands based on K-Nearest Neighbor (KNN) to optimize the travel path of the robot, and therefore minimize the time needed to fabricate a piece.

Besides toolpath generation, print settings for material deposition were developed and refined through prototyping. These print settings include: lead-in and lead-out path and parameters, material extrusion rate, robotic toolhead velocity, traversal velocity, extruder activation and deactivation locations, and cooling activation and deactivation locations (Table 1). Lead in and lead out settings were refined to minimize excess material deposition at the end of toolpaths and during traversal, while also balancing the reduction in speed necessary for such quality control measures. The introduction of helical lead ins/outs resulted in neat and watertight seams with high resolution. Print speed, extrusion rate, and cooling settings were refined as well.

FABRICATION AND PROTOTYPING

A series of prototypes at multiple scales were printed to investigate the relation between the geometric properties of the envelope design and the fabrication settings, constraints, and criteria (Figure 6). Based on the prototypes across these scales, strategies for computational design and fabrication methods were refined.

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9 Fabrication images of the full-scale prototype highlighting the seamless connection of channels and interior layers.

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RESULTS

TThe resulting 1:1 scale prototype (1018 mm x 678 mm x 1022 mm) demonstrates the advantages of FGF 3D printing thermoplastic for integrative and green building envelopes. The 3D printed building envelope prototype entails a highly complex topology with an array of unique plant pods that form interconnected channels and multiple interior layers. The prototype weighs 58.9 kg and was 3D printed over the course of 64 hours (Table 2). The size of plant pods vary in several domains; here the largest pod (174mm x 181mm x 488mm) measured 7,845 cm3 and the smallest (70mm x 67mm x 295mm) measured 710 cm3. The prototype plant pods were filled with plants of various species and sizes to qualitatively evaluate the utility and design of the IGBE system. The planted envelope attracted pollinators as shown in Figure 12. Layers of translucent polymer shaded by plants and growing substrate allow diffuse light to permeate the envelope prototype.

Design and development of a robust raft was necessary to ensure the stability of the prototype throughout the 3D printing process. The 4-layer thick raft effectively secured the print to the heated bed throughout the entire printing time. The interconnected geometry and merging layers also provided adequate stability and support for a successful print. No additional support was required. The toolpath was refined to allow excess extrusion material to collect outside the printed geometry rather than along the toolpath. While early prototypes required manual care throughout printing to monitor excess material deposition, these changes to the toolpath made such observation unnecessary.

The limits of both the angle and the height were pushed while prototyping. Portions of the envelope with overhang angles shallower than the 45-degree minimum managed to print effectively, though minor sagging and delamination occurred at these moments (Figure 9). Human robot collaboration to support these shallow areas was the cheapest and most time efficient method to ensure a successful print without any 3D printed support. In future prototypes, shallow cantilever limitations could be resolved through further geometric adjustments in the computational model. The full-scale prototype and earlier experiments established rulesets for the design geometries and toolpath settings, which will be useful to future advancement of this research.

CONCLUSION

This project successively demonstrates that RPE of thermoplastic can be used to establish a hybrid approach to architectural design and construction, integrating natural and building systems within a 3D printed building enclosure. The proposed IGBE system offers a strategy to remediate UHI effects and atmospheric pollution in urban areas

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10 Photgraph of the full-scale planted IGBE prototype.

11 Top view of the prototype revealing the inter-connected interior geometry.

12 Photograph of a pollinator drawn to the planted prototype when brought outdoors.

13 Photograph of the full-scale IGBE prootoype.

Print Settings		
Lead In	Style	Arc Tan Ramp
	Distance (mm)	10
	Overlap Distance (mm)	100
	Speed (m/s)	0.08
Lead Out	Style	Arc Tan Ramp
	Distance (mm)	10
	Overlap Distance (mm)	100
	Speed (m/s)	0.01
Extrusion	Rate	1.1
Path	Speed (m/s)	0.08
Traverse	Speed (m/s)	0.4
Extrusion	Activation Delay (mm)	0
	Activation Distance (mm)	-3
	Deactivation Delay (mm)	0
	Deactivation Distance (mm)	-3
Cooling	Activation Delay (mm)	0
	Activation Distance	20
	Deactivation Delay (mm)	0
	Deactivation Distance (mm)	0

Table 1

Results	Printed Portion (Segments 1-3)	Full Height (Segments 1-9)
Material	Thermoplastic PETG	Thermoplastic PETG
Dimensions (L x W x H)	1018 mm x 678 mm x 1022 mm	1018 mm x 745 mm x 2175 mm
Total Tool Path Length	9,427 m	19,842 m
Volume	47,135 cm^3	99,210 cm^3
Weight (using 1.25 g/cm3)	58.9 kg	124.3 kg
Printing Time	64 hours	135 hours
No. Mesh Faces	62,347	381,370
No. Curves	5,106	17,320

Table 2

while supporting an increase in biodiversity and contributing to the development of resilient urban ecologies. The fabrication and computational methods developed through this research resulted in the successful 3D print of a geometrically-complex full-scale prototype with multiple layers that can be applied and adapted to many different architectural typologies and locations. Speed and material efficiency of the RPE fabrication method have been studied through this research, though further research is needed to calculate and optimize energy use of the entire process and to apply such optimization at an industrial scale.

This research will continue in the following areas to advance the study of integrative green building envelope systems: development of the fabrication system to allow for the high speed production of thinner plastic layers; performance modeling and testing of the IGBE system for passive cooling effect, thermal resistance, air filtration, daylighting, and longevity; performance testing of the capillary irrigation layer to investigate the feasibility of a self-watering irrigation system; a thorough study of specific plant species, their unique performance profiles and habitation requirements; further study on the circular economic model of thermoplastic and bio-plastic building envelopes; and further study on bio-plastic 3D printing and its performance in the context of building envelope fabrication.

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IMAGE CREDITS

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