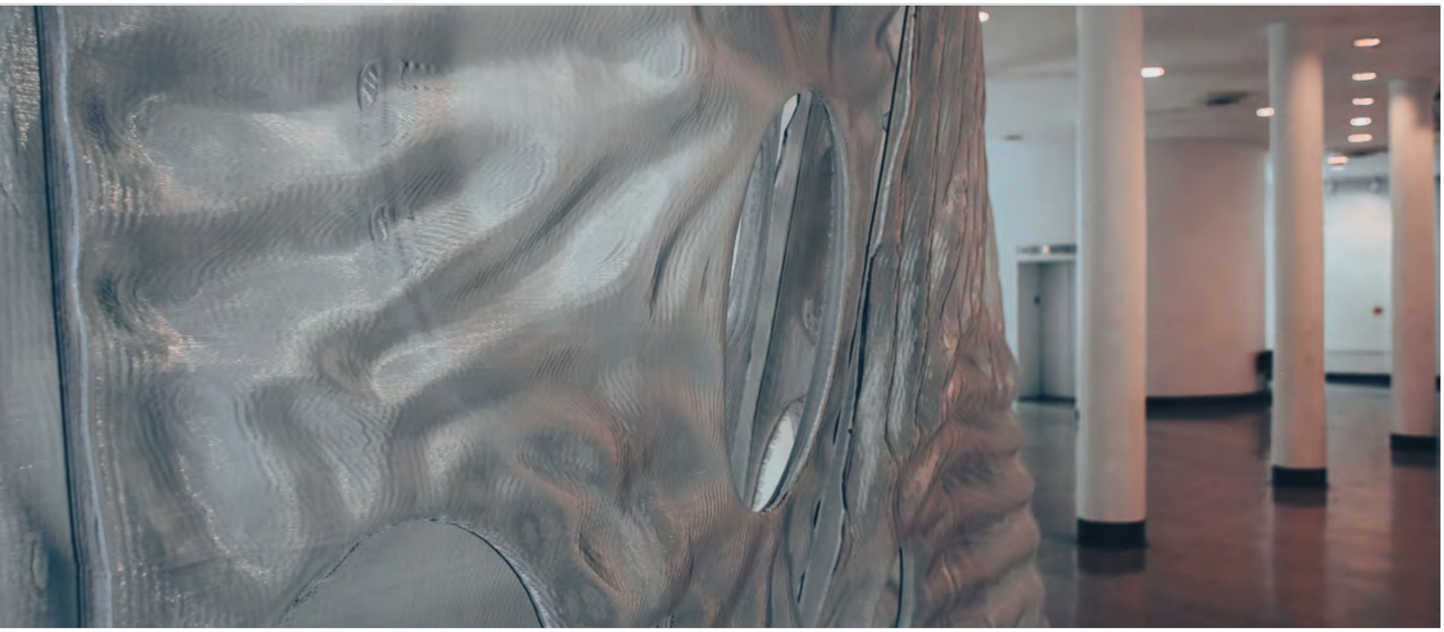
Robotic 3D Printing Multilayer Building Envelope

Geometric Design and Robotic Control Strategies

Mania Aghaei Meibodi
DART, University of Michigan

Wes McGee
University of Michigan

Alireza Bayramvand
DART, University of Michigan



1 Multilayer thermoplastic building envelope, Plastic Architecture Exhibition, Cooper Union, New York, 2021

ABSTRACT

This research explores the use of robotic pellet extrusion 3d printing (3DP) in the production of a multifunctional thermoplastic building envelope. A computational design method was developed to generate multi-layered systems of interconnected volumes using minimal surfaces, combined with a rib-stiffening approach that accommodates fabrication constraints. The investigation highlights the development of an integrated system that includes robotic end-effector tooling, programming/control methods to allow “endless” prints, as well as specific toolpath strategies to improve print speed and quality. These developments are then demonstrated through the design and fabrication of two 2.2m by 1.1m building envelope panels, and the results are discussed along with specific details of the printing process. The innovations of this research are 1) A computational design tool that allows intuitive generation and adaptation of multilayer building envelopes to site criteria; 2) A robust robotic control system allowing continuous, uninterrupted printing at architectural scale with minimal supervision and high-quality surface finish.

INTRODUCTION

Energy-efficient building design is one solution combating global warming that reduces energy consumption while utilizing renewable energy for building operations (Torcellini et al. 2006; Li et al. 2013). Building envelope design significantly affects a building's energy performance as the mediator between interior and exterior climatic control. Building envelopes account for 70% of a building's energy performance (Yang and Choi 2015). They are site-specific, and they're geometry depends on various climate conditions and the surrounding natural or urban context. Envelope geometry influences a building's operational energy, and affects structural performance and material efficiency (Fang and Cho 2019). Designing envelopes for improved energy efficiency often results in geometrically complex forms, with complicated exterior surfaces and internal topologies. However, due to higher construction costs, the industry has adopted elementary shapes (Hemsath and Alagheband Bandhosseini 2015). Innovations in the design, material, and construction process of building envelopes are critical to reduce embodied and operational carbon and enhance building life spans. ,

3DP technologies allow for the fabrication of topologically-complex building envelopes with intricate geometric features at multiple scales. This is demonstrated in binder jet 3DP of sand mold for casting lightweight freeform aluminum facades (Aghaei Meibodi et al. 2018; Aghaei Meibodi et al. 2019), binder jet 3DP for doubly curved glass fiber reinforced concrete facades(Aghaei Meibodi et al. 2021), robotic 3DP of mineral foam for lightweight facades (Bedarf et al. 2021), robotic extrusion 3DP of fiber reinforced concrete facade panels (McGee et al. 2022), and 3DP with different kinds of clay and ceramics (Rael and San Fratello 2017, 2018; Cruz et al. 2020; Peters 2013; Lekka Angelopoulou 2022).

3DP thermoplastic is an emerging field of research with radical innovations in facades and building envelopes.Thermoplastics are lightweight, recyclable, durable, versatile, watertight, can withstand severe weather conditions, and take nearly any shape 3DP thermoplastic for envelope often has been investigated using one of the two extrusion-based 3DP process: Fused Filament Fabrication (FFF) where thermoplastic filament is melted through a heated nozzle, or Fused Granular Fabrication (FGF) where thermoplastic granules are fed from a hopper into a barrel containing a motor-driven screw along multiple heat zones. This research focuses on FGF as a more viable method for scaling to real-world construction.

Robotic 3DP further offers higher geometric degrees of freedom and scalability than traditional 3-axis gantry 3DP. Research in Robotic FGF, herein referred to as Robotic Pellet Extrusion (RPE), is increasingly being used in construction scale 3DP and has already been applied in projects related to building envelopes such as SensiLab and B515 Studios projects (Burry et al. 2020), thermoplastic concrete formwork from carbon fiber PETG and translucent PETG (Aghaei Meibodi et al. 2021), and well known projects by commercial fabricators like Nagami and Branch Technology. However, several key challenges such as low print speed, poor surface finish, and difficulty in starting and stopping the extrusion bead currently limit achieving the full potential of PRE for large scale building envelopes.

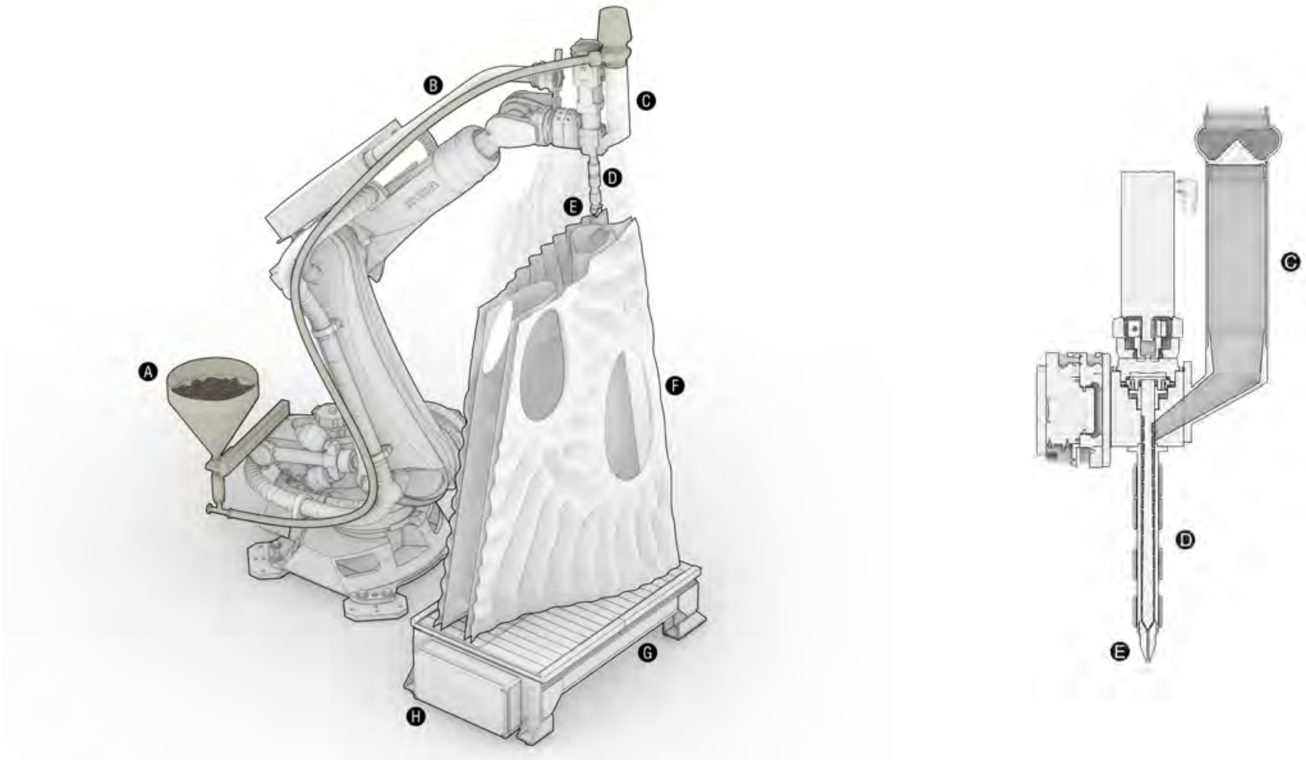
3DP thermoplastic has immense potential for integrating multiple functions within building envelope designs particularly with respect to thermal energy efficiency (Mungenast 2017) . Integration of cavities for air or phase-changing materials (PCM) have been shown to retard thermal conduction for better performance and energy efficiency of buildings. Notable precedents are "The Double Face 2.0" project integrating PCM in facades to store and delay thermal transmission (Tenpierik et al. 2018), and "The SPONG3D" integrating air cavities for thermal insulation along with a motile liquid for thermal storage and exchange (Sarakinioti et al. 2017).

However, what is most notably missing from most studies on 3DP of thermoplastic building envelopes is a comprehensive design tool developed in the context of fabrication methods to enable innovative multifunctional design solutions. This research contributes to the emerging field 3DP Thermoplastic by focussing on novel computational design strategies and large scale RPE of multifunctional integrative thermoplastic building envelopes.

APPROACH

This research advances existing research on 3DP thermoplastic envelopes by (1) developing a non-interrupted RPE system compatible with the scale of construction and geometrically-complex envelope components, (2) developing toolpathing approaches and control systems that improve the speed and efficiency of RPE, and (3) developing a novel computational design method for intuitive and automatic generation of multilayer building envelope systems with partitioned interiors based on minimal surfaces that is also adaptable to site-specific criteria. Minimal surfaces are a useful design medium for generating partitioned volumes and the ideal geometry for achieving complex topology while eliminating any need for building supports during 3DP. This research utilizes minimal surfaces to conceptualize a speculative multilayer building envelope system made of only thermoplastic for improved energy and thermal performance. We present and discuss a 1:1 scale prototype and case study for understanding and exploring the geometric complexities achievable and their fabrication.

Fabrication System: Non-Interrupted Robotic Pellet Extrusion



2 Diagram of the robotic Pellet extrusion system with a continuous feeding system. The automated pellet feeding system transfers pellets from a 30L hopper (a) via a pipe (b) to a smaller hopper (c). The end effector consists of a servo-driven extrusion screw and three zone heated barrel (d) and nozzle (e). The heated bed (h) is constructed of aluminum slats attached to a thick aluminum plate needed to ease the dismounting of the 3d printed part after 3d printing (g). 2

PETG is used as the 3D printing feedstock as it is a semi-rigid material with good impact resistance yet lightweight, enabling the production of durable and hard-wearing components that are easy to handle in the assembly process. It is highly water-resistant and enables 3D printing of a waterproof enclosure system with cladding and an integral vapor barrier made of the same material. Moreover, PETG can be recovered at the end of the building's life and cycled in both open and closed-loop systems , and 3DP of building envelopes using one thermoplastic enables the potential of melting, processing, and recycling back to pellets at the end of its lifetime.

This research develops a customized robotic pellet extrusion system entailing a continuous feeding system to enable the large-scale production of geometrically complex plastic parts (Fig. 2). The current version of the system is based on a 22mm diameter extrusion screw with a 2:1 compression ratio and a 15:1 length to diameter ratio (Fig. 2). It is driven by a synchronous servo motor which is positionally controlled as an external robot axis. To enable continuous 3D printing on a construction scale, the system has been upgraded to include an automated pellet feeding system that transfers pellets from a 30L hopper on the robot's base to a smaller hopper mounted directly to the end effector (Fig. 2). The system also utilizes an annular cooling nozzle fed from a passive refrigeration unit to solidify the deposited material rapidly. This improves production speed and the ability to print overhanging geometries without the need for 3D printing support (McGee and Peller 2020). The printing is performed on a heated bed constructed of precision aluminum slats attached to a thick aluminum platen. These slats allow for the removal of parts which include large "raft" areas while restraining the part during cooling (Fig. 2).

Extrusion Control And Toolpathing Strategies

Extrusion-based 3DP requires controllable, steady material flow rates to produce constant thickness walls at a given layer height. In the case where the travel velocity of the end effector is constant, this behavior is well-characterized and relatively simple to control. However, in this project where there are multiple closed contours per layer, as well as combinations of both large and small toolpath radii, the end effector travel speed and the extrusion rate need to vary significantly and synchronously. In the case of FFF processes, the dynamics of the extruder are generally fast and well modeled. It is significantly more complex to model and predict the behavior of pellet extruders, and most literature focuses on the steady-state as opposed to dynamic behavior. The high output rate (corresponding to higher end-effector travel speeds) coupled with the relatively small orifice diameter leads to higher back pressure and a significant time lag between the motion of the extruder screw and the response of the output. Several techniques have been tested to compensate for this time lag in the system, discussed below.

Lead-In and Lead-Out Geometry

For the extrusion setup and travel speeds used in this research, an iterative approach was used to identify the "excess flow" that occurs at the end of an extrusion path. A decision was made to utilize a "wipe" motion on the inside of each contour, depositing the excess material within the 3DP cavity. During the toolpath generation stage, a "winding number" technique is used to determine inside from outside, which allows for multilayer systems, and avoids the material being deposited on the outside surface. The toolpath generation step allows for a parametric "lead in" and "lead out" behavior, providing control over the shape and speed of the path. The ideal path, in this case, was a balance between the extra time required to "bleed" the extrusion pressure and the desire to maintain the speed of the process. The target travel speed of the extruder along the path was 50 mm/s, to account for the necessary layer-to-layer cooling time and the speed that the end effector could maintain at this level of geometric complexity. During the "lead out" motion, the speed was reduced to 12 mm/s resulting in a lead out path which traversed a 15mm diameter circle in approximately 4 seconds before "wiping" the excess material on the completed layer and ramping away from the layer tangentially followed by a rapid traverse to the next contour or layer.

Online Control Methods and Innovations to Improve Extrusion Synchronization

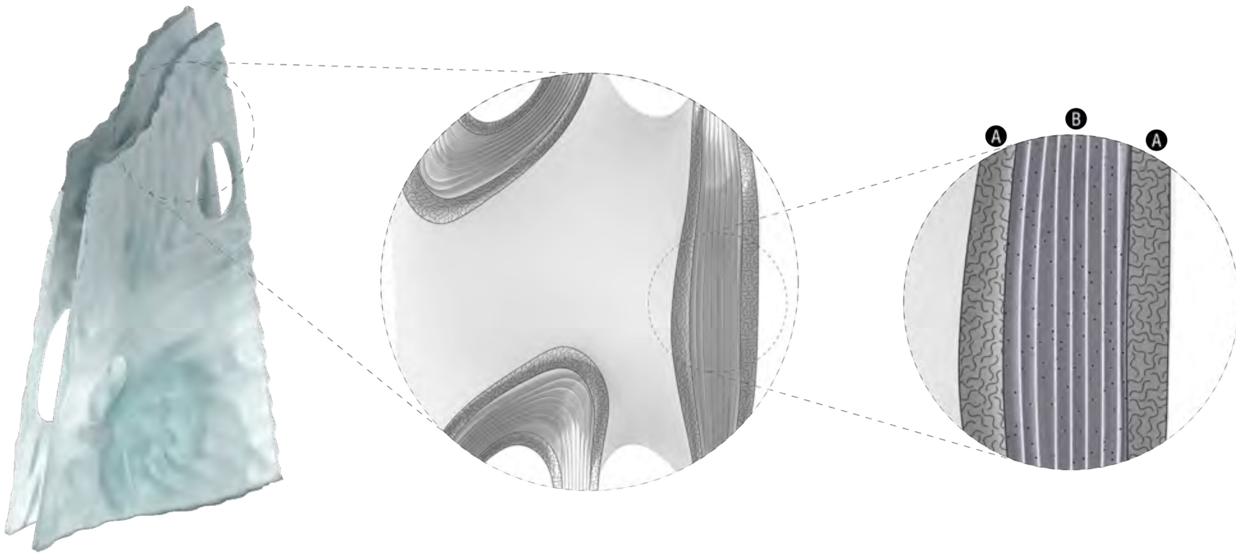
While CNC machine controllers have developed significantly in their processing power and memory over the last few decades, industrial robots have not experience the same demands, with primary use in repetitive motion applications with limited geometric complexity With the overall accuracy of a large 6 axis robot typically being in the range of 0.5 -1.0 mm spherical error, it is important to use geometric filtering methods to reduce the size of toolpaths, particularly in the case of large-scale AM toolpaths. A geometrically complex, multi-layered facade panel sliced at heights of 1 – 2 mm might require over 1 million motion commands. This is well beyond what is supported by a robot controller such as the Kuka KRC4. Some manufacturers provide the ability to receive streamed robot instructions in a buffer (ABB, UR), and the research community has provided plugins to support this (HAL, ExMachina, COMPAS, et al). The KRC4 controller does not support this functionality, however, it does support data streaming at a lower level through the Kuka Robot Sensor Interface (RSI). RSI allows an external motion server to stream cartesian or joint (servo) positions at either a 4 or 12 ms update rate. This technique has been used in prior research to enable adaptive fabrication methods.

In this research, an industrial CNC motion controller is used to decode and plan the synchronous cartesian motion trajectory (6 degree of freedom + extruder feed) while accommodating joint velocity limits. To accomplish this, the motion controller must perform the kinematic transformation to joint space in real-time (~1ms) during the lookahead phase of planning, then adapt the overall motion profile of the cartesian motion; this is particularly important in the vicinity of robot singularities. In this case, the motion controller is modeled as a "virtual" robot. The joint positions of the planned trajectory are then streamed to the KRC4 controller via the EtherCAT fieldbus where they are interpreted by the RSI interface. One advantage of using a "virtual" robot is the ability to time delay the robot servo positions relative to the extruder positions. This allows for partial compensation of the substantial physical lag between extruder motion and actual material extrusion. This research utilizes Beckhoff's TwinCAT, developed as a "digital twin" allowing bidirectional communication between external software such as Rhino or ROS (Liang et al. 2022). The TwinCAT CNC controller additionally provides an external streaming interface that buffers g-code instructions, allowing near real-time streaming of motion commands and eliminating memory limitations on the robot program while also opening up extensive possibilities for adaptive and responsive fabrication processes.

Computational Design

3DP enables production of the entire building envelope as one single component for integrating multiple functions such as insulation voids, vapor barriers, and exterior cladding. Design tools are needed that allow design exploration of envelope elements that can intricately separate interior and exterior zones, with multiple functional internal layers. A computational model is developed that enables designers to generate: a) envelope architecture with interior layers designed for the potential integration of different fluids such as air and phase changing material (PCM) that increase thermal insulation (Fig. 3), and b) an exterior shell with undulated detailing that can vary in size for structural stability. This computational design model is composed of the following algorithms:

- An algorithm that generates the topology of the envelope through a Minimal Surface with intertwined networks of channels and interconnected regions, then parametrically offsets the form inward to provide for separate zones or volumes.
- An algorithm that adapts the generated geometry to required functions then translates the resulted topology to rough mesh, then to high-resolution mesh
- An algorithm that generates a Rib-Stiffened Surface through a Reaction-Diffusion model



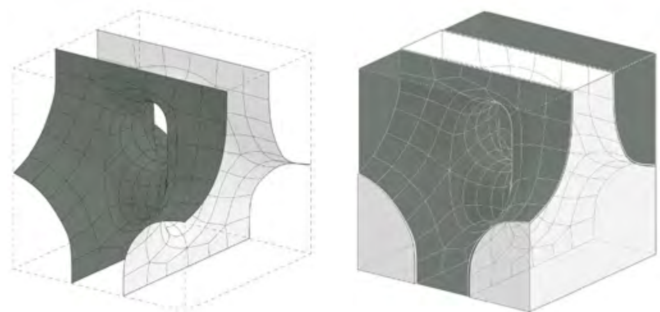
3

Minimal Surface To Generate Multifunctional Topologies

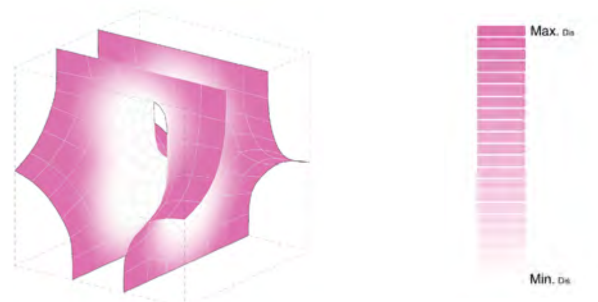
Minimal surfaces are a useful design medium for creating multi-layered building envelopes because they bisect space into two separate yet interwoven volumes (Fig. 4). This geometric property is particularly useful for applications where two volumes interface across a plane, such as that with PCM and air space for thermal insulation. Instead of only containing one fluid, the inner volume (V1) can be offset inward to create multiple separate interior air layers providing designers flexibility in adjusting thermal resistance. The result is sandwiched layers where PCM may occupy the outer peripheral volume while air pockets occupy interior volumes. This putative model would result in greater thermal resistance as the number of air filled interior layers is increased (Fig. 3).

In contrast to FFF 3DP of complex topology that requires printing of support structures for cantilever areas, minimal surfaces do not require support structures as they are Zero mean curvature, meaning every point in the print is supported by a doubly curved surrounding (Fig. 6). This significantly improves production speed, reduces material waste, as well as ensures printability without deformation. Finally, the interconnected channels of the minimal surface provide structural stability and furthermore maintain stability as the height of the print increases during fabrication.

The integration of multifunctional behavior in an envelope system results in working with complex topologies. In this research, minimal surfaces are utilized as a geometric medium that generates a topology with two separate volumes at the interface of inside and outside climate zones. There are different ways to generate and visualize minimal surfaces digitally. Most methods use mathematical expressions or computational physics simulation with mesh relaxation to generate minimal surfaces in 3D design space, which can be difficult to use when a high degree of formal control and articulation is needed. In this research, we use a newly developed approach named "Minimal Surfaces through Skeletal Graphs" (MSSG) at Digital Architecture Research Technologies (DART) (Aghaei Meibodi et al. 2022), which uses the skeletal graphs to



4

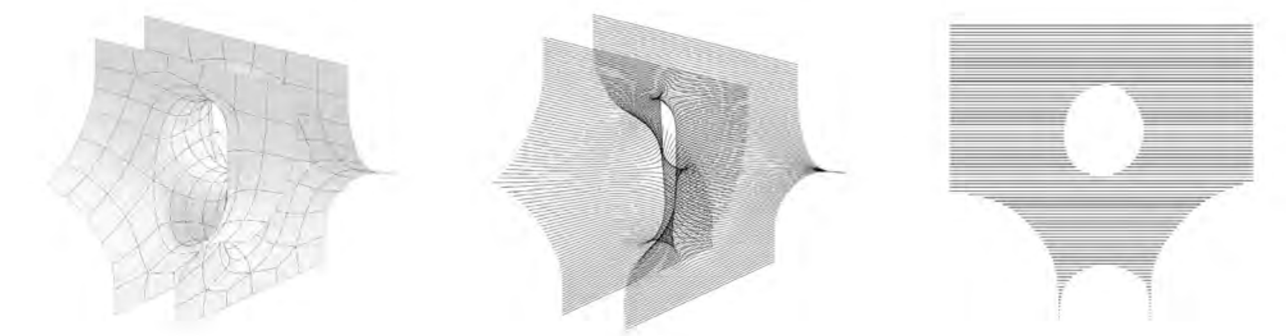


5

3 The left image shows how a minimal surface divided the inside and outside climate but also provides for two interconnected regions and two separate volumes in the envelope, the middle image is a zoom in to a region with sandwiched layers, right image is sandwiched layers detail drawing showing PCM occupying the outer periphery volume (A) and air pockets occupying the interior (B).

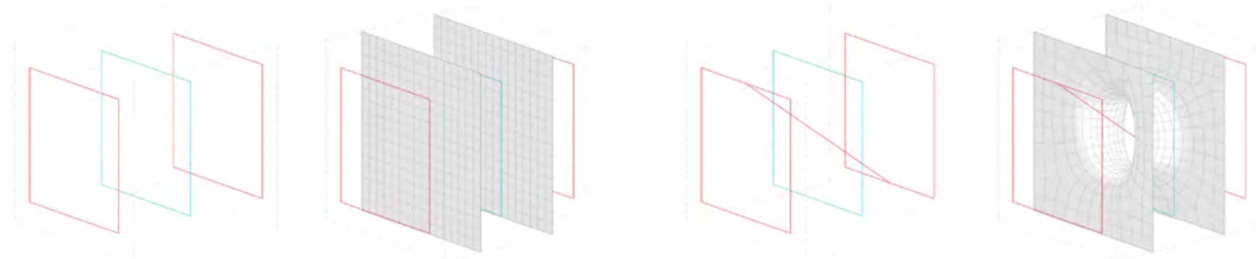
4 A minimal surface (left image) bisects the space into two separate yet interwoven volumes (Right image).

5 A deformation diagram presenting structural stability and stiffness is higher in areas closer to channels that create interconnected regions created in a minimal surface.



6

6 The perspective (middle) and front view (right) of the toolpath corresponding to the minimal surface (right) show that minimal surfaces (left image) do not require support structures.



7

7 Diagram showing MSSG method for generating Minimal Surface using two sets of curves in red and blue. Left two diagrams show MSSG generating a simple plane surface when inputs are two sets of parallel curves. The two diagrams on the right show the creation of a tube and interconnecting separate layers to create a connection between zones by just introducing a curve.

generate, alter, and manipulate minimal surfaces intuitively, enabling their geometric adaptation to functional and program requirements. A skeletal graph of a minimal surface can be viewed as a curve resulting from the shrinking of a minimal surface along the direction of its normal vectors while avoiding any pinching off that would change the topology of the surface (T. Hoffman n.d.). The MSSG algorithm takes two sets of curves, representing "skeletal graphs" of a minimal surface, as inputs and then generates a surface on which any point is equidistant from the closest curve in the two sets. A Marching Cube algorithm (Lorensen and Cline 1987) is employed to create triangle meshes by iterating, or "marching" over a uniform grid of cubes. Generating minimal surfaces through MSSG allows for intuitive interaction and a higher degree of control in the design process as the designer can easily manipulate sets of curves with a live update in the topology of the minimal surfaces rather than modifying mathematical expressions (Fig. 7).

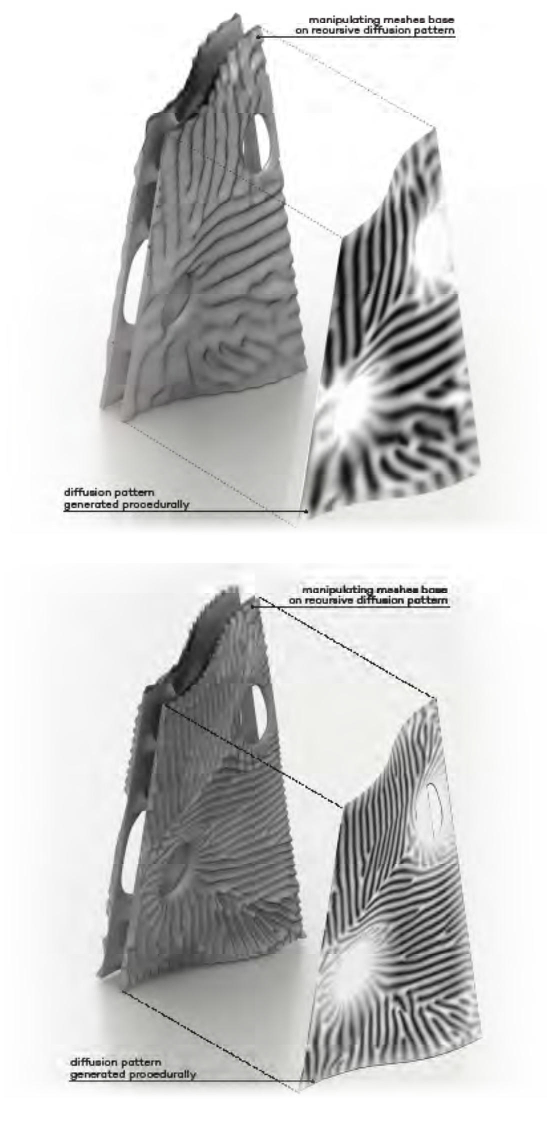
GEOMETRIC ADAPTATION TO FUNCTION AND TRANSLATION FROM ROUGH TO HIGH-RESOLUTION MESH

Once the desired topology with different regions and their inter-connecting channels are generated, it is input to an algorithm that regenerates the same topology from rough mesh faces with parametric variables, that allows adaptation of the topology to the functions and programs by enabling parametric changes in overall depth, spacing between different surfaces, dimensions of the interconnecting channel, and enabling an increase in the number of zones through offset surface (Fig. 8). Once the variables are fixed, the rough mesh is translated to high-resolution mesh using Catmull–Clark technique.

A RIB-STIFFENED SURFACE THROUGH REACTION-DIFFUSION ALGORITHM (RDA)

A rib-stiffened surface geometry can be generated to provide sufficient structural performance while minimizing material usage. Combining this surface with the multi-layered, interconnecting topology is geometrically challenging due to the continuously variable length of the individual layer paths, resulting in a variable number of ribs along the length of the layer. To solve this globally for the surface, a reaction-diffusion algorithm can be used (Fig. 9)). Reaction-diffusion (RD) models are often used to simulate chemical reactions or the diffusion of substances over a surface. By controlling the basic parameters of the equations, they can be tuned to generate a wide range of surface patterns. In this case, a vector field was used to weight the diffusion parameters and produce a branching pattern across the surface. By using a variation of the "heat method" (Crane et al. 2013), the vector field can be generated to follow the shortest path between mesh boundaries, designated as "cold and hot", resulting in radial ribs advancing from the openings to the edge of the components. However, while radial ribs were the optimal solution for stiffening the elements with respect to the element's topology, printing radial ribs is significantly more challenging than vertical ones. To ensure successful RPE of the ribs, parameters such as depth, width, and

8 Left is the resulting minimal surface with two topology regions and their interconnecting channels derived from the SGAMS algorithm. The middle a parametric adaptation of the topology to the functions and reconstruction of the minimal surface with rough mesh faces. Right is an increase in the mesh faces to increase surface resolution.



9 The up and down images show manipulation of mesh based on the generated recursive diffusion pattern. A more detailed diffusion pattern would require higher mesh resolution (down) in comparison to the less branched and detailed pattern (up)

overhang were refined and optimized based on feedback from physical prototyping.

CASE STUDY: MULTILAYER BUILDING ENVELOPE (MBE)

The proposed approach was further investigated by designing and constructing a lightweight building envelope prototype for the Plastic Architecture Exhibition at Cooper Union in New York. The prototype was made from two thermoplastic components with dimensions of 1,170 x 2,268 x 178 mm (height, width, depth), 3D printed using RPE, designed around the concept of a translucent multi-layer envelope consisting of separated volumes for natural ventilation and thermal insulation. The envelope system is composed of a) an exterior shell with undulated detailing of varied size, and b) multipleinterior air and liquid PCM layers for thermal insulation

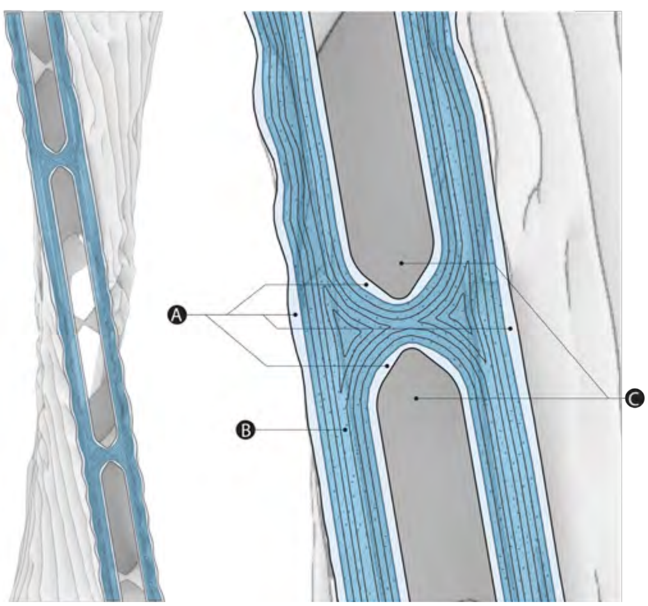
The outermost volume is designed to contain PCM that stores latent heat HVAC equipment run times. Interior volumes are designed to contain a vacuum, air, or aerogel for thermal insulation (Fig. 10). The air gap between the two main zones is an air-moisture barrier that removes water vapor by evaporation producing a breathable envelope system. Interconnecting channels between the two main zones create passages between their volumes, and the undulating geometry generated by a reaction-diffusion algorithm growing outwards from the channels to the edges provides structural stability.

RESULTS AND DISCUSSION

The resulting 1:1 scale prototype is made of two thermoplastic elements (2270 mm x 1170 mm x 200 mm; height x width x depth) 3D printed (Fig. 11). It showcases the advantages of FGF 3DP for construction scale components and functional integration in building envelopes. Each element entails a complex topology with multiple interior layers that separate volumes as well as connections that link related zones. Each panel weighs 44.5 KG and was 3D printed over the course of 44 hours (Table 1). To evaluate the impact of the mesh resolution on the production speed, one of the two elements entailed 10 times as many mesh faces.

Table 1: Geometric and production details of the low and high-resolution facade panels.

Dimensions of each panel	2270 by 1170 by 200 to 230 mm (height X width X depth) with 8 to 50 mm thickness for the outset layers
Material	thermoplastic PETG
Volume of material for one element	41.3 liters of polymer
Weight of one element	44.5 kilograms
Printing time of each element	44 hours
Number of mesh faces in the low-resolution panel	70,000 triangles
Number of mesh faces in the high-resolution panel	840,000 quads
Toolpath kilometer in low-resolution panel	10,323 meters
Toolpath kilometer in high-resolution panel	10,333 meters



10

10 Section through the MBE system shows the outermost volume is designed to contain PCM (A), inner volumes (B) designed to contain a vacuum, air, or aerogel and can increase the number of layers by 3DP increases, and the air gap between the two main zones is an air moisture barrier (c).

The design and development of a robust “raft” was necessary to ensure the stability of the prototype throughout the 3DP process. The six layers thick raft successfully secured the print to the heated bed throughout the printing time. The minimal surface geometry with its multiple interconnecting layers provided adequate stability throughout the 3DP process, eliminating the need for additional internal infill. The minimal surface’s double curvature effectively provided support for subsequent layers and eliminated the need for additional support. While minimal surfaces provide for supportless printing, successful 3d printing of overhanging geometries significantly relies on the layer thickness versus bead width of material extrusion.

The lead-in and lead-out design innovations allow excess extrusion material to collect within the printed geometry resulting in clean seams. Consequently, manual care during the fabrication process was no longer required.

CONCLUSION

This paper explores the fabrication of topologically complex geometries that have the potential to contribute to improved energy efficiency of buildings. It showcases that the Robotic Pellet Extrusion of thermoplastic is a viable method to produce such topologies and can profoundly change the way we conceptualize and design the envelope system by allowing for the integration of multiple functions in a singular component. 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 translated to other building envelope systems.

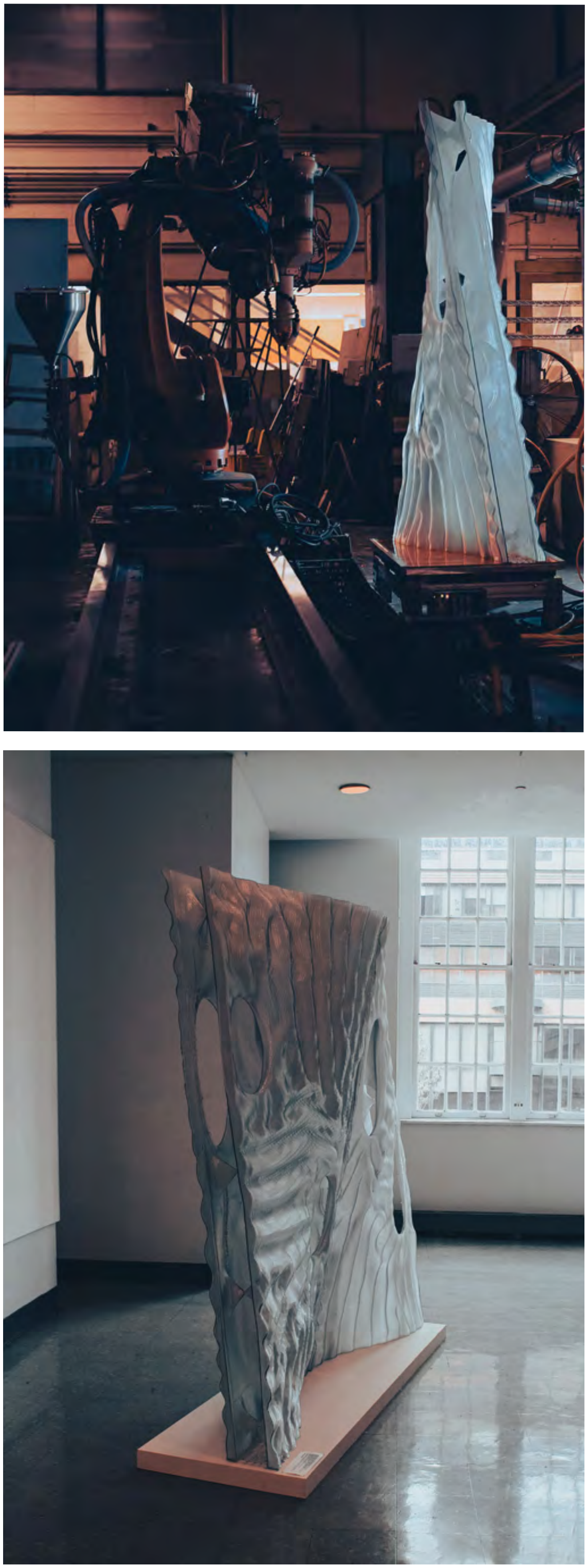
Future research will continue to advance research on functionally integrated sustainable building envelopes by a) developing the fabrication system to allow for the high-speed production of thinner plastic layers, b) performance testing for environmental factors like thermal resistance, natural ventilation, daylighting, and durability c) explorations of circular economic models using recyclable thermoplastic and bio-plastic building envelopes.

REFERENCES

Aghaei Meibodi, Mania, Bayramvand, Alireza, Mahnia, Mehrad, “Minimal Surfaces through Skeletal Graphs (MSSG)”, Collaboration between Digital Architecture Research Technologies (DART) at University of Michigan and Fabtory, Exhibition “On Air” curated by Kathy Velikov, 2022.

Aghaei Meibodi, Mania, Rena Giesecke, and Benjamin Dillenburger. "Digital metal: additive manufacturing for casting metal parts in architecture." In 1st International Conference on 3D Construction Printing (3DcP). 2018.

Aghaei Meibodi, Mania, Marirena Kladeftira, Thodoris Kyttas, and Benjamin Dillenburger. "Bespoke Cast Facade: Design and Additive Manufacturing for Aluminum Facade Elements." In ACADIA 19: Ubiquity and Autonomy. Proceedings of the 39th Annual Conference of the



11 The 1:1 scale prototype is made of two thermoplastic elements.

Association for Computer Aided Design in Architecture, pp. 100-109. Association for Computer Aided Design in Architecture (ACADIA), 2019.

Aghaei Meibodi, Mania, Pietro Odaglia, and Benjamin Dillenburger. "Min-Max: Reusable 3D printed formwork for thin-shell concrete structures-Reusable 3D printed formwork for thin-shell concrete structures." (2021).

Aghaei Meibodi, M., Craney, R., Mcgee, Wes. (2021). Robotic Pellet Extrusion 3D Printing and Integral Computational Design of Reinforced Thin Shell Formwork System for Sandwich Concrete Walls. (2021). ACADIA: proceeding.

Aghaei Meibodi, Mania, Andrei Jipa, Rena Giesecke, Demetris Shammas, Mathias Bernhard, Matthias Leschok, Konrad Graser, and Benjamin Dillenburger. "Smart Slab. Computational design and digital fabrication of a lightweight concrete slab." (2018).

Akilo, M. "Design and analysis of a composite panel with ultra-thin glass faces and a 3D-printed polymeric core." PhD diss., MSc thesis, University of Bologna, 2018.

Bedarf, Patrick, Dinorah Martinez Schulte, AyÃ Åženol, Etienne Jeoffroy, and Benjamin Dillenburger. "Robotic 3D Printing of Mineral Foam for a Lightweight Composite Facade Shading Panel." (2021).

Crane, Keenan, Clarisse Weischedel, and Max Wardetzky. "Geodesics in heat: A new approach to computing distance based on heat flow." ACM Transactions on Graphics (TOG) 32, no. 5 (2013): 1-11.

Cruz, Paulo JS, Bruno Figueiredo, João Carvalho, and Tatiana Campos. "Additive manufacturing of ceramic components for façade construction." Journal of Facade Design and Engineering 8, no. 1 (2020): 1-20.

Fang, Yuan, and Soolyeon Cho. "Design optimization of building geometry and fenestration for daylighting and energy performance." Solar Energy 191 (2019): 7-18.

Hemsath, Timothy L., and Kaveh Alagheband Bandhosseini. "Building design with energy performance as primary agent." Energy Procedia 78 (2015): 3049-3054.

Li, Danny HW, Liu Yang, and Joseph C. Lam. "Zero energy buildings and sustainable development implications–A review." Energy 54 (2013): 1-10.

Lekka Angelopoulou, Sofia , "studio RAP 3D prints ceramic tiles and red bricks for amsterdam boutique facade," designboom ,https://www.designboom.com/architecture/studio-rap-3d-print-ceramic-tiles-red-bricks-amsterdam-boutique-facade-01-28-2022/, January 28, 2022, February 06, 2022,

Liang, Ci-Jyun, Wes McGee, Carol C. Menassa, and Vineet R. Kamat.

"Real-time state synchronization between physical construction robots and process-level digital twins." Construction Robotics (2022): 1-17.

Lorensen, William E., and Harvey E. Cline. "Marching cubes: A high resolution 3D surface construction algorithm." ACM siggraph computer graphics 21, no. 4 (1987): 163-169.

McGee, Wes, Tsz Yan Ng, Kequan Yu, and Victor C. Li. "Extrusion nozzle shaping for improved 3DP of engineered cementitious composites (ECC/SHCC)." In RILEM International Conference on Concrete and Digital Fabrication, pp. 916-925. Springer, Cham, 2020.

Mungenast, M., O. Tessin, V. Blum, O. Khuraskina, L. Morroni, and T. Gutheil. "Fluid Morphology, 3D Printed Functional Integrated Buidling Envelope." Associate Professorship of Architectural Design and Building Envelope, TUM, support of Rodeca, Picco's 3D World, Delta Tower (2017).

McGee, W., K. Velikov, G. Thun, and D. Tish. "Infundibuliforms: kinetic systems, additive manufacturing for cable nets and tensile surface control." Fabricate: Rethinking Design and Construction (2017): 4-6.
McGee, Jonathan Wesley, and Asa Leland Peller. "Extrusion die and nozzle cooling system for large scale 3D additive manufacturing." U.S. Patent 10,807,292, issued October 20, 2020.

Peters, Brian. "Building bytes: 3D-printed bricks." (2013) , ACADIA 13: Adaptive Architecture, 433–434

Rael, Ronald, and Virginia San Fratello. "Clay bodies: crafting the future with 3D printing." Architectural Design 87, no. 6 (2017): 92-97.

Sarakinioti, Maria Valentini, Michela Turrin, M. Teeling, Paul de Ruiter, Mark van Erk, Martin Tenpierik, Thaleia Konstantinou et al. "Spong3d: 3D printed facade system enabling movable fluid heat storage." Spool 4, no. 2 (2017): 57-60.

Snooks, Roland & Harper, Laura. (2020). Printed Assemblages: A Co-Evolution of Composite Tectonics and Additive Manufacturing Techniques. ed. Burry, Jane, Jenny E. Sabin, Bob Sheil, and Marilena Skavara, eds. Fabricate 2020. UCL Press, 2020.

Torcellini, Paul, Shanti Pless, Michael Deru, and Drury Crawley. Zero energy buildings: a critical look at the definition. No. NREL/CP-550-39833. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2006.

Torcellini, Paul A., and Drury B. Crawley. "Understanding zero-energy buildings." ASHRAE journal 48, no. 9 (2006): 62-69.

Tenpierik, Martin, Michela Turrin, Yvonne Wattez, Tudor Cosmatu, and Stavroula Tsafou. "Double Face 2.0: A lightweight translucent adaptable Trombe wall." Spool. Journal of Architecture and the Built Environment 5, no. 2 (2018).

T. Hoffman, James. "Skeletal Graphs of Triply Periodic Surfaces" The Scientific Graphics Project, https://www.msri.org/publications/sgp/jim/geom/surface/global/skeletal/index.html , February 14, 2021

IMAGE CREDITS

Photographer: Christopher Voltl, copy right DART, University of Michigan.

Dr.Mania Aghaei Meibodi is Assistant professor of Architecture and Chair of Digital Architecture Research and Technologies (DART) Laboratory at Taubman College of Architecture and Urban Planning at the University of Michigan.

Wes McGee is an Associate Professor in Architecture and the Director of the Fabrication and Robotics Lab at Taubman College of Architecture and Urban Planning at the University of Michigan.

Alireza Bayramvand is a research assistant at the Digital Architecture Research and Technologies (DART) Laboratory at Taubman College of Architecture and Urban Planning, University of Michigan, with a specialty in computational design and robotic construction.