Vertical Wetland

Robotic Additive Manufacturing of Urban Vertical Green Systems for Biodiversity

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1 Photo of the construction scale prototype.

ABSTRACT

In the context of climate change, the urban ecological decline is exacerbated by the extensive use of impervious materials in urban structures, including the urban heat island effect, reduced water storage capacity in urban fabric, and biodiversity loss.

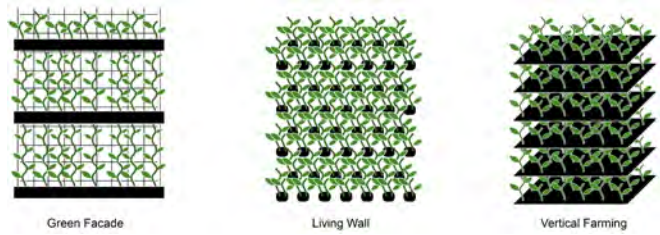
Urban Vertical Green (UVG) systems, represented by green facades, living walls, and vertical farming, offer solutions to mitigate these environmental degradations. This study investigates a method utilizing large-scale 3D printing to create a novel UVG system that supports multiple plant species through a hierarchical watering system. By adopting complex geometric designs with inner features, the proposed system can potentially provide diversified water and nutrient input to accommodate multiple plant species and facilitate biodiversity in urban settings.

The study involves designing, manufacturing, and testing a single construction-scale unit using robotic 3D printing with thermoplastic PETG. The successful prototype demonstrates the proposed system unit can be efficiently produced and easily maintained after installation. Therefore, the fundamental feasibility of the proposed UVG system is verified.

INTRODUCTION

Today, urban ecological decline has become a major issue in the urbanization process, with impervious materials such as glass, concrete, and asphalt being excessively used to create most of our urban structures. Impervious surfaces in urban environment intensify the Urban Heat Island (UHI) effect by producing and retaining redundant heat after being exposed to sunlight (Tsoka et al. 2020) and reduce the water storage capacity of urban structures through their low water permeability (Wang et al. 2021). Amplified by the UHI effect, urban temperature rise caused by global warming reduces urban comfort and damages air quality (Tsoka et al. 2020; Deilami, Kamruzzaman, and Liu 2018). With the shifted precipitation pattern as part of climate change, the huge amount of impervious surface also exposes cities to an increasing risk of pluvial flooding, damaging the economy and urban safety (Miller and Hutchins 2017, IPCC 2023). By introducing excessive impervious material and removing greenery, the current urbanizing method also causes fragmentation of natural landscapes, leading to the loss of urban biodiversity (Di Giulio, Holderegger, and Tobias 2009), jeopardizing critical ecosystem services, including air and water purification, pest control, and pollination, potentially impacting human health and altering local climates (Shochat et al. 2010). Replacing natural landscapes with non-green urban spaces also reduces carbon sinks and introduces new carbon sources, causing losses in carbon sequestration and contributing to global climate change through the greenhouse effect (Liu et al. 2021).

Adopting urban vertical green (UVG) systems is beneficial to alleviate landscape fragmentation and facilitate urban comfort through visual features, cooling effect, and noise reduction (Morakinyo et al. 2019; Oquendo-Di Cosola, Olivieri, and Ruiz-García 2022), especially in areas where traditional greeneries including gardens, parks, and nature reserves become scarce. These systems include green facades, living walls, and vertical farming (Figure 2). Common green facades often use climbing plants growing along building surfaces or designed frames, as shown by "Haus E" at Hunziker Square by Müller Sigrist Architects (2022). Despite their efficiency in providing greenery (Perini and Rosasco 2013), conventional green facades have limitations in facilitating biodiversity and achieving a high density of green coverage. Composed of supporting structures and small plant pots, living walls are well known for their high construction and maintenance costs (Perini and Rosasco 2013). This category can achieve higher biodiversity, as demonstrated by cases like the living wall at CaixaForum Madrid (2008) and the sustainable office building project "Eden" (2024) designed by Make Architects. As increasingly frequent extreme weather events threaten urban food security by disrupting agriculture and food supply chains (Jensen and Orfila 2021), urban vertical farming evolved as an efficient food production method. Industrialized vertical farms, represented by "The Plant Chicago Vertical Farm" project (2012), focus on maximizing spatial, energy, and water efficiency. The idea of stacking accessible plant-growing medium is also borrowed by architects, as shown by the office building of Vo Trong Nghia Architects (2023). Implementing this stacking greenery strategy into open urban spaces provides opportunities for food production and, simultaneously, helps mitigate the overarching urban ecological degradation closely related to climate change, including UHI and loss of biodiversity.



2 Different categories of Urban Vertical Green (UVG) systems.

STATE OF THE ART

Large-scale 3D printing enables material deposition only where it is needed, minimizing waste during manufacturing and allowing for considerable design flexibility and integration of various functions within a single printed object. Recent research has explored the use of 3D printing to incorporate vertical greenery into urban settings using various materials such as soil, clay, and plastic (University of Virginia 2022; Farinea et al. 2020; Pasquero and Poletto 2020; Zidek et al. 2022; BigRep 2019). Examples include:

- Living walls that sprout greenery, are created through robotic 3D printing using a mix of plant seeds with water and soil as feedstock (University of Virginia 2022).
- Smart and modular vertical gardens, 3D-printed with clay, are designed for cultivating aromatic and edible plants in dense urban settings, incorporating a bio-photovoltaic electricity generation system (Farinea et al. 2020).
- ecoLogicStudio's series of large-scale 3D-printed plastic living walls aimed at integrating living photosynthetic organisms like bacteria and microalgae into green facades or indoor installations. This is accomplished by injecting liquid or gel medium into the 3D-printed structures, enabling these organisms to produce oxygen and biomass (Pasquero and Poletto 2020).
- The large-scale robotic pellet extrusion of the Integrative Green Building Envelope (IGBE) project (Zidek et al. 2022) aimed to promote biodiversity through a multilayered

system featuring highly articulated, pot-like plant holders of various dimensions capable of accommodating roots of different sizes. By adopting organic form, multi-functional layers, and size-differentiated planters, the system demonstrated the potential of accommodating multiple species in an urban setting while improving building performance.
- BANYAN Eco Wall project (BigRep 2019), where the tunnels for water transportation were directly produced through the 3D printing of plastic, exploring geometry-based watering systems at a large scale.

Among large-scale robotic 3D printing, fused filament fabrication (FFF) with thermoplastic has specific advantages and is of interest to this research. The inherent lightweight and tenacity make printed thermoplastics —such as polylactic acid (PLA), polyethylene terephthalate glycol (PETG), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS)— ideal for composing skin structures for architecture. Plastic offers numerous benefits as a construction material: it is durable, lightweight, versatile, cost-effective, weather-resistant, low maintenance, and resistant to corrosion and chemicals. Moreover, it's easy to handle and shape through 3D printing methods and can be precisely deposited with minimal deformation. Large components printed with single thermoplastic material, such as rain screens or shading panels, have the capacity to achieve graded and complex forms and functionality (Taseva et al. 2020). If not coated with other materials, printed thermoplastic is potentially recyclable multiple times (Meibodi, Craney, and McGee 2021). As a type of thermoplastic, PETG, though a product of industrial processes of non-renewable resources, is potentially recyclable and already used in food packaging for their structural robustness, chemical stability, and water tightness, which makes them acceptable options for printed containers for water, soil, and plants (Zidek et al. 2022). While the weathering of additively manufactured PETG will accelerate when exposed to UV radiation (Romeijn et al. 2021), various research efforts are addressing these challenges. For instance, adding a UV absorber will slow down the weathering significantly (Zhang and Zhang 2015), but how it would affect recyclability is yet to be examined. While research on material performance for weatherability would be beneficial, 3D printing with thermoplastic for architecture has already garnered significant interest. Many architectural practices and research have explored large-scale 3D printing with thermoplastic to directly produce building facades, envelopes, canopies, and green facades (3F Studio 2019; Taseva et al. 2020; Zidek et al. 2022).

METHOD

Design Concept and Premises

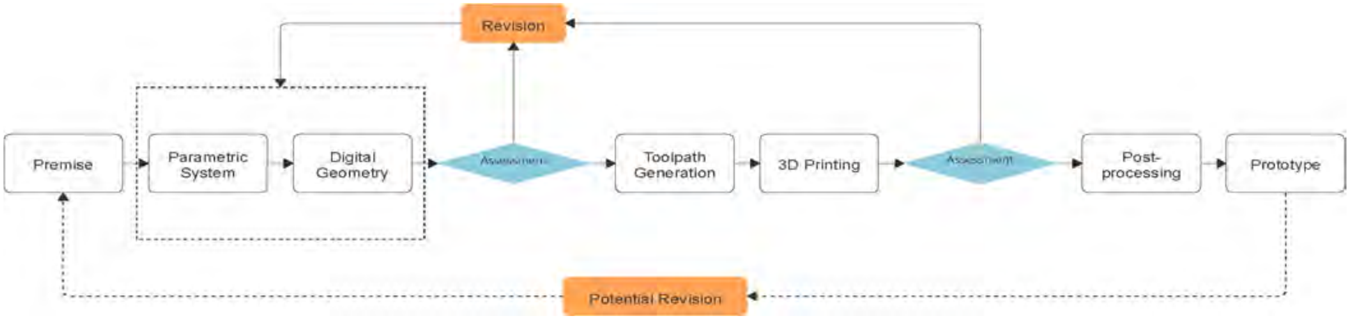
This research will focus on utilizing robotic 3D printing with thermoplastic to create a novel UVG system resembling a wetland, promoting biodiversity by integrating multiple plant species and implementing a customized multi-stream watering system tailored to each plant species' needs. Such a system will mitigate the UHI effect by supporting dense greenery. It will also function as a stormwater management system, fulfilling the requirements given by 2020's Stormwater Management Design Manual by the City of Detroit, which indicates that stormwater should be stored 48 hours before discharge to alleviate the risk of flooding and water pollution (PCSWMO Design Manual 2020). By maintaining large bodies of water, the system will facilitate thermal stability, biodiversity, and urban sustainability (Alikhani, Nummi, and Ojala 2021). Additionally, maintaining water in building envelopes improves building fire performance (Rathnayake, Lau, and Chow 2020), which can be crucial in UVG systems that produce biomass in hot and dry climates.

In Figure 3, we laid out a framework of possible beneficial interactions between a proposed UVG system and its surroundings, which, as a possible solution for urban environmental degradation at large, needs long-term experiments and multi-disciplinary research to validate. Within the scope of this paper, we aim to prove the feasibility of the proposed system by designing, fabricating, and testing a single-unit prototype. The anticipated results of this research include:

- A parametric algorithm to create the 3D geometry that fulfills the functional requirements of the proposed UVG system, including root-based plant growing, multi-stream watering, discrete storage of water, and multi-species support.
- A verified time-saving fabrication process for large-scale robotic pellet extrusion tailored to UVGs with complex geometries.
- A 1:1 scale physical prototype to validate the system's feasibility.
- Assessment of the prototype for future development by exposing it to natural environment.

Workflow

This research investigates integrating functions, including the storage and distribution of water and diversified support for various plant species, through geometric design. Further, it investigates the timesaving and material-efficient 3D printing of complex geometries on a large scale through printpath planning. The system is expected to be produced



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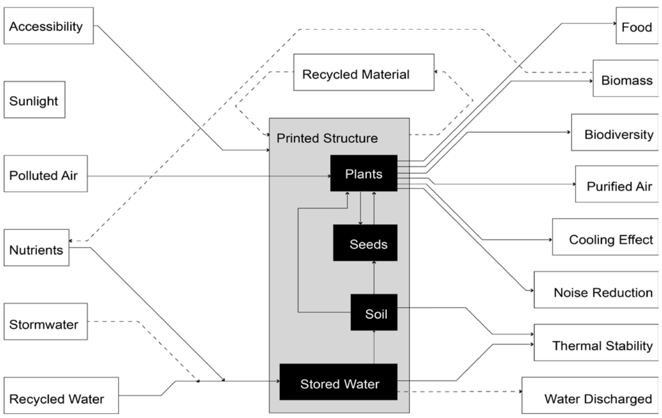

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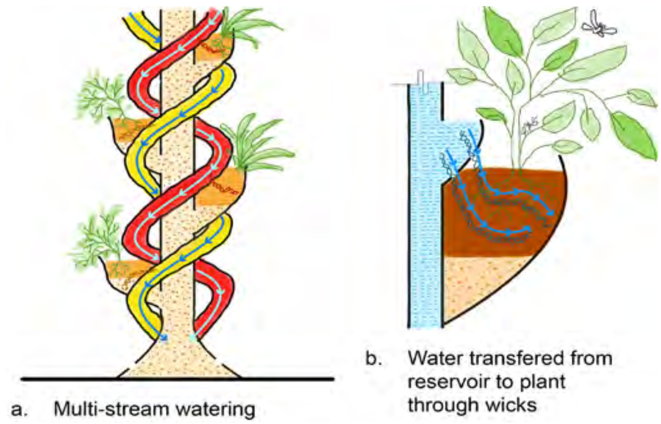

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3 Composition of proposed novel UVGs and beneficial interactions with urban environments.

4 Workflow & phases of research

5 Hierarchical water delivery approaches,

efficiently and maintained easily, as durability and stability can be potentially high. The design feedback loops contain phases that include computational modeling, fabrication, post-processing, and assessment of the final prototype (Figure 4). When assessing a design, major criteria included the printability of the geometry, surface quality and efficiency of the print, and physical model performance in achieving goals such as water-tightness, capacity to support living plants, and the design's potential to facilitate high biodiversity.

Irrigation System Strategy

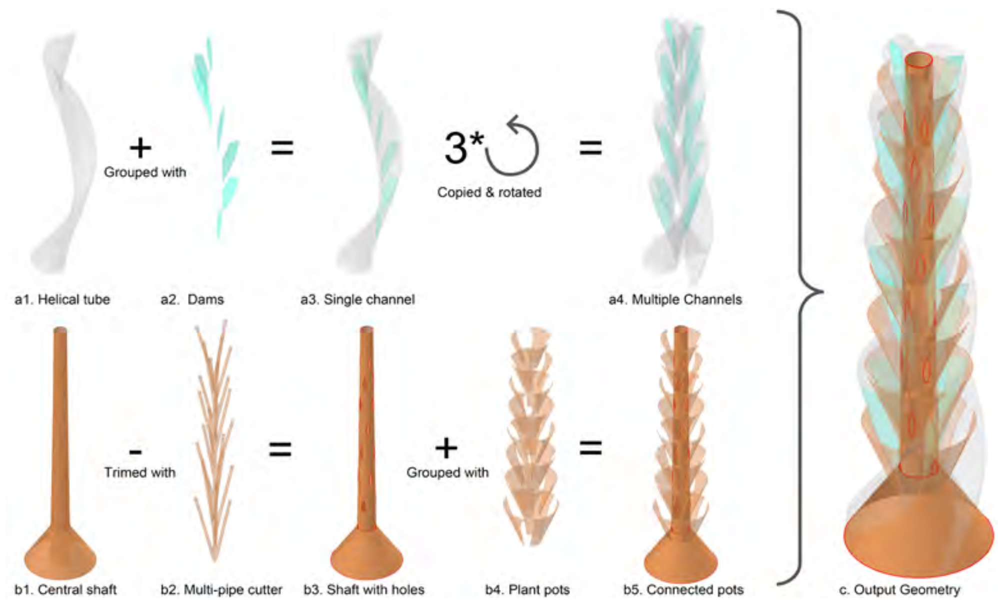
In order to simplify the watering process and support the diversified nutrient demands of various species, we developed a hierarchical irrigation system. This system divides several concentrated water inputs into discretely stored small water bodies feeding individual plants (Figure 5). The first step of this distribution is through multiple helical channels composed of a series of water-tight tubes and inner walls that function as dams for creating water reservoirs. Channels are separated from each other to allow differentiated nutrient input. The sequential filling of reservoirs is achieved through gravity-based overflowing. This feature also mitigates hydrostatic pressure within the overall system.

The reservoirs are separated from plant pots to avoid root rot —a condition caused by roots growing in persistently wet soil. A capillary wick-watering system was employed between pots and reservoirs to form the secondary water delivery infrastructure. The capillary wick-watering system (CWIS) is a sub-irrigation system that utilizes strip components, which allow capillary movement of water from localized water storages to plant-growing mediums (Roonjho, Kamal, and Roonjho 2022). This system ensures that each plant receives the precise amount of water needed to meet its evapotranspiration requirements over time, enhancing the efficiency of water and nutrient uptake by the roots.

System Design and Components

The system's geometry contains two types of spatial configurations, respectively designed to contain water and plant-growing mediums.

The first typeincorporates a series of plant pots of various sizes. While the upper halves of these planters are filled with soil, the bottom halves are connected to a shared central shaft, both occupied by perlite —a lightweight hydrophobic



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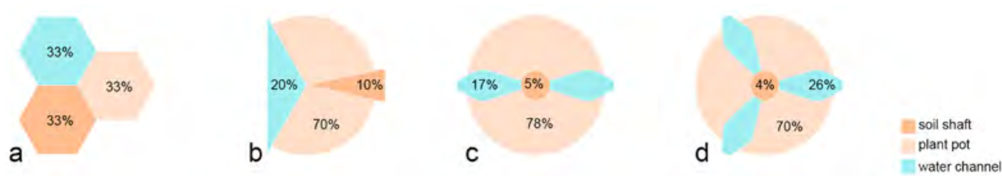

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6 Steps of generation using the developed parametric definition.

7 Estimated ratio between three designated functions in horizontal sections.

plant-growing medium. The central shaft with perlite allows the discharge of excess water that enters the plant pots, avoiding soaking the plants' roots. It also introduces air to the bottom of the pots. This approach, also known as air pruning, prevents overgrowth of the roots. The second type comprises three helical channels as the primary water distribution system that has been introduced in Section 3.3. Although the system contains two types of spatial configurations, combining them results in a series of interconnected surfaces that can be fabricated as a single continuous printed piece. Hence, a multi-functional and structurally reliable prototype can be produced through 3D printing.

Computational Modeling and Parametric Features

A series of algorithms were developed to construct the 3D digital model, which comprises four types of system components:

- Helical water channels for primary water delivery.
- Inner walls within water channels function as dams to create reservoirs.
- Fins between helical channels form plant pots.
- A central shaft with holes opened to all plant pots, later filled with plant-growing medium.

The components were then trimmed and unioned to create an interconnected final form with three helical channels, allowing for differentiated water and nutrient inputs to support multiple plant species. The channels were created first, followed by the formation of plant pots. Subsequently, dams within the channels and connecting holes between the pots and the central shaft were positioned according to the plant pot's locations. The central shaft has an enlarged base to collect overflowing water and to provide a structurally reliable bottom configuration to improve printing stability. The generation process is shown in Figure 6. The volume ratio between each component type was predefined approximately through horizontal section geometries, as shown in iterations in Figure 7. From Fig.7.a to Fig.7.d, more space has been reassigned from the central shaft and water channel(s) to plant pots, providing more root-growing space for plants. This adjustment connects more planting surface area to the exterior, allowing the plants to receive more sunlight and facilitating beneficial material exchange with the environment. After the section pattern (Figure 7.d) was selected, several parameters were made easily adjustable during the generation process in order to create design variations that suit diversified watering and plant-growing needs. Such parameters include:

- Lateral and vertical sizes of the entire unit.
- Numbers of channels and plant pots.
- Tilting angles for most surfaces (central base cone, helical channels, and fins to create plant pots) to avoid

unprintable overhangs. For helical channels, this is adjusted by changing the number of turns of the helix within the given height of the model.
- Locations and capacities of water reservoirs. Current locations of reservoirs are set horizontally aligned to the center of the plant pots and vertically 100 mm higher than the pots, allowing wicks to drain reservoirs empty with the help of gravity. The capacities of the reservoirs are defined by adjusting the trimming heights of the inner walls, as shown in Figure 8.

Toolpath Generation

This method utilizes an algorithm that generates one continuous toolpath for the entire 3D geometry (Gao and McGee 2024). This graph-based algorithm allows continuous printing path generation for given island-free 3D surface group, making it ideal for the generated 3D geometry for the prototype. Continuously printing the prototype is expected to improve the print's surface quality and water-tightness. It also reduces the machine time and energy needed to finish the print by eliminating stops/restarts of material extrusion and nozzle traverses, improving the efficiency of the printing process. This toolpath generation algorithm does not introduce doubled walls to create continuous paths, keeping the fabricated object closely matching the input geometry, thereby maintaining the lightweight feature and facilitating material efficiency.

After the union of geometry and exporting, the final generated 3D model for prototype construction has 24 functionally graded plant pots with variable sizes and changing water-to-soil (W-S) ratio from bottom to top (Figure 9). This variation is adopted to examine how the combination of differently sized plant pods and water reservoirs would affect the plant's survival and growth in the long term. The volumes of water reservoirs were controlled to be 1000 ± 150 ml, while the volumes of plant pots ranged from 1,342 ml to 4,122 ml. As a result, the prototype geometry possesses a changing W-S ratio ranging from 0.24 to 0.86, showcasing the system's potential for providing variant root growing space and water quantity. Using the toolpath generation algorithm, the geometry was sliced into one continuous printing toolpath with 0.8 mm layer height, which has been tested and proved to improve the water tightness of prints using the toolpath generation algorithm. The toolpath preparation processes are shown in Figure 10.

3D Printing with Robotic Pellet Extrusion System

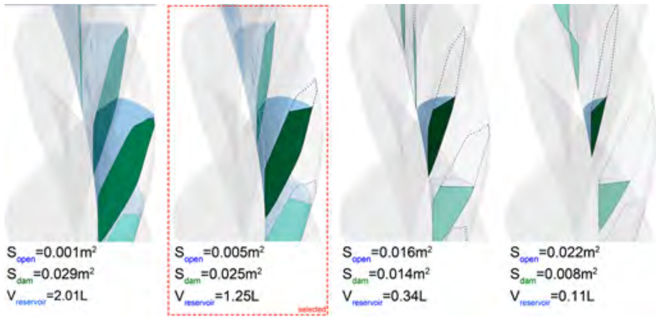
After generating a continuous printing path for the exported geometry, this path was translated into machine-readable code for execution on the RPE system. During the translation process, the path was segmented based on the RPE system's memory limits, with the programs running sequentially. Intervals between adjacent sections should ideally be kept under five minutes to ensure proper lamination. However, technical issues caused two intervals to extend beyond this, resulting in one delamination, which was later repaired with epoxy coating without compromising water tightness.

To ensure consistent surface smoothness and transparency, all PETG pellets were uniformly dried for the same duration and fed directly to the end-effector. A cooling fan was initially used but later removed during the printing process based on indoor ventilation and the temperature drop of the top layers. Previous tests informed the design to control overhangs effectively, preventing material sagging or delamination within sections. During early simulations, abrupt motions in a robotic arm joint near a singularity were identified. This issue was resolved by rotating the end-effector by five degrees along the z-axis. The printing process, including special moments and details, is shown in Figure 11.

Post-Processing

Upon completion of the print, a water-tightness test was conducted by pouring water into the helical channels from the top until the bottom reservoirs were completely filled. This test revealed a few small leakage points. To address this, an epoxy waterproof coating was applied to both the outer surface of the channels and the interior of the central tube. After coating, no visible leakage was observed. To integrate the wick-watering system, holes were drilled through the bottom of the water reservoirs using a soldering iron (Figure 12.a). Segments of woven nylon rope, 300 mm long, were manually inserted into the drilled holes (Figure 12.b), with half inside the reservoirs and half outside. Hot glue was later used to seal the gaps between the wicks and holes, ensuring water passage solely through the wicks. This setup was tested and confirmed to ensure the wick-watering system's functionality. Additional drainage holes were drilled at the bottom of the three helical channels to allow water overflow.

Perlite, soil, plants, and water were then introduced into the structure. Perlite was poured from the top of the central tube, filling 90% of its volume and the bottom third of the plant pods. Plants and soil were added simultaneously (Figure 12.c), with three varieties of Coleus used as placeholders for multiple species. These were placed in 8 pod-reservoir units with varying W-S ratios for long-term growth experiments. The watering process is completed by adding water to the top openings of the helical channels (Figure 12.d).



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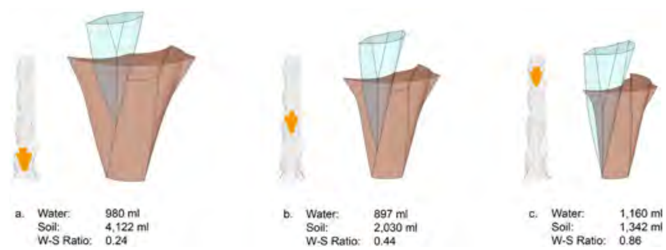

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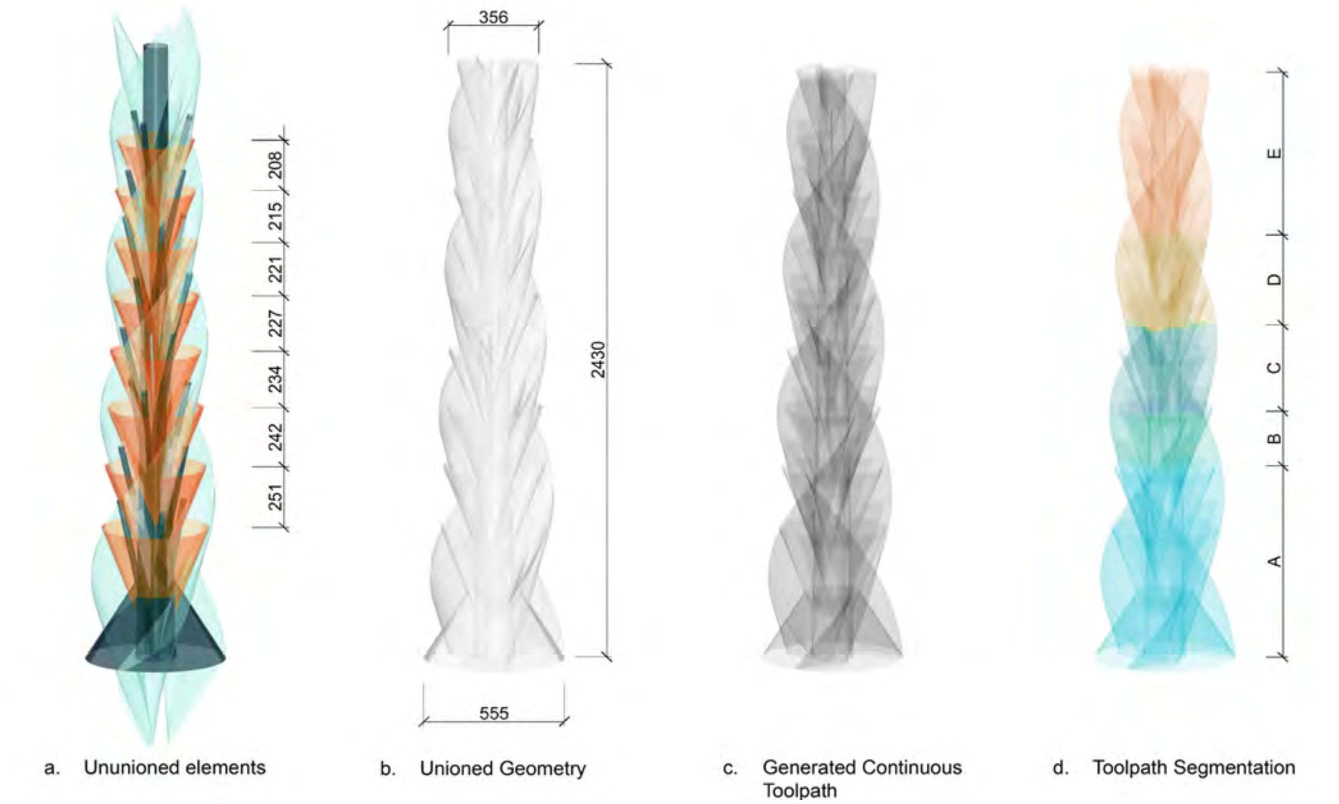

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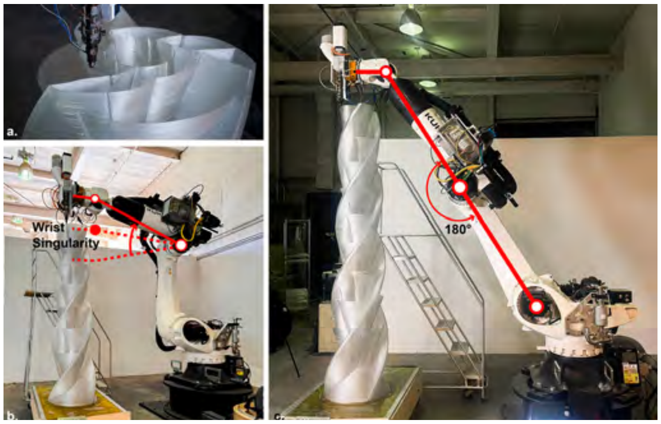
RESULTS AND DISCUSSION

The prototype with 3038 printed layers was produced in 59 hours, with printing speed set to 0.04 m/s. The whole print was divided into five continuously printed sections with no nozzle lifts or traverses within each section. Dimension right after printing was 555 * 555 * 2430 (mm). After putting in the plants, the lateral dimension extended by around 150 mm, making the final dimension of the prototype 850 * 850 * 2430 (mm). Figure 12.f shows the completed prototype as a construction scale test of the proposed system. Weighing only 28.1 kg, the empty printed structure provides 24 plant pods paired with 24 water reservoirs connected by three individual helical channels, showing a high material efficiency. The lightweight feature of this prototype also improves system feasibility by reserving the load capacity of any potential supporting structures for the plants, soil, and water it contains. After its completion, the prototype was placed outdoors during the spring season to test its ability to support plants' survival. The weekly maintenance of the system includes plant status checking, watering, and rotating the unit to ensure even exposure to sunlight for plants on all sides. One-month follow-up after prototype completion shows that the prototypes fulfilled the goals set for this study phase, proving that the proposed geometry-based wick watering system has the capacity to distribute, store, and slowly release the water to the soil that plants grow in, therefore, supporting the plants' survival in an outdoor environment (Figure 13).

Before and after the completion of the prototype, one key feature being examined is the water tightness through printing. We have proved that by reducing the printing layer height from 1mm to 0.8 mm, visible holes that cause leakage can be eliminated. While the essential goal is to achieve



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8 Changing the reservoir's capacity through dam adjustments.

9 Various water-soil ratios at different heights of the prototype.

10 Export and toolpath preparation (dimension unit: mm).

11 a. Printing detail; b. Wrist singularity passed; c. Reaching system limit and print finished.

12 Left: Post-processing and watering; e. Reservoirs filled with water; Right: Completed prototype accommodating three varieties of coleus.

13 Images showing a construction scale prototype. Left: After installation; Middle: One month after installation; Right: Four months after installation.

complete water tightness through printing with one single material, the current toolpath generation method and fabrication system create invisible holes at surface intersections in an unpredictable way. By filling the reservoirs with water and observing the water levels, these tiny defects that cause leakages can be observed. Before post-processing, one big outer leakage was observed from one of the 24 reservoirs. By observing the water levels dropping in an hour, it was clear that around half of the reservoirs were not completely watertight before being coated. Meanwhile, it is also important to notice that a third of these reservoirs were already watertight right after printing, representing a big leap from the results produced by early tests. It means by modifying the toolpath generation process or tunning printing parameters, complete water tightness should be achievable, therefore, eliminating the need for waterproof coating and facilitating the recyclability of the unit.

CONCLUSION

This study developed a novel, lightweight, integrative UVG system that supports diverse plant species by incorporating pots of varying sizes and multiple water streams. Using the RPE system, we successfully fabricated a construction-scale UVG with intricate geometries and internal features.

The prototype's performance in an outdoor environment demonstrated its functional capabilities, including soil retention, water distribution and storage, and plant support. The prototype was kept outdoors and exposed to sunlight in Michigan climate from April to August, with outdoor temperatures ranging from 26 to 93°F. No visible deformation or discoloration was observed on the printed PETG during and after the period (Figure 13). The successful implementation of these design goals indicates that UVG water distribution systems can be integrated through geometric designs, thereby reducing construction complexity and maintenance costs. The capillary effect in wick-watering proved to be an automatic and efficient method for irrigating UVG plants.

Furthermore, the tube-dam structure facilitates discrete fluid storage by using gravity to separate the continuously fed liquid into individual bodies, avoiding hydraulic pressure buildup. This 3D-printed geometric feature enhances the system's safety in storing large amounts of water and stabilizes the wick-watering process. While the prototype takes the form of a triple helix, it is expected that other configurations with similar spatial logic could be adopted in the future when the application scenario changes.

A possible extension of the study is to achieve complete water tightness only through 3D printing to eliminate the need for waterproof coatings, guaranteeing the recyclability of the unit. This is theoretically achievable through the refinement of the toolpath generation process and tweaking printing parameters. With the rudimentary feasibility of the system being proved, further study can explore the following aspects:

- An examination of how various plant species' demands on water and nutrients can be reflected in the design's parametric settings.
- Examining which plant species are most suitable to the system while providing ecological benefits to a designated urban environment.
- Explorations in automatizing or simplifying the process of the wick placement.
- The system's integration methods with urban environments
- Harvest and usage of produced biomass.

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