DIGITAL PLANTING

Fabrication of Integrated Concrete Green Wall via Additive Manufacturing

SIHAN WANG¹, CHI LIU², GUO LI ZHANG³, QI HUAN LUO⁴, WEISHUN XU⁵ and FELIX RASPALL⁶

¹Singapore University of Technology and Design
²sihan_wang@mymail.sutd.edu.sg
³kiki19970310@gmail.com ⁴qihuanluo@outlook.com ⁵xuweishun@zju.edu.cn
⁶Universidad Adolfo Ibáñez
⁷felix.raspall@uai.cl

Abstract. Green walls are becoming a symbol of modern architecture representing sustainability and aesthetics. However, the fabrication of wall components that can nurture the growth of plants and other living creatures requires components to locate soil and other substrates, a controlled rugosity for plants and moss to grip, and conduits to distribute water and nutrients. This is normally done by adding extra attachments to the façade. In this paper, we introduce a digital approach to design and produce architectural components that can integrate green wall’s functional requirements into the wall itself. Such components are fabricated via Additive Manufacturing (AM) extrusion with the assists of robotic arms.

Keywords. Green Wall; Additive Manufacturing; Robotic Fabrication; Clay Printing.

1. Introduction

Green wall is a general category in architecture that refers to varies types of vegetated wall components. Its history can be traced back to the Hanging Gardens of Babylon. Up to date, the green wall is divided into two types, the direct green façades, and the living walls. A direct green façade usually relies on the capability of climbing plants to attach themselves on the surface of vertical walls without support structures. On the contrary, living walls introduce frames as supports to hold soil and substrates for plants to grow upon(Manso & Castro-Gomes, 2015). Many examples could be found on Growing Green Guide. Our research focuses on the living wall system to sidestep the limitation of a direct green wall in which plants must have the self-clinging ability.

To facilitate the plants to grow, the living wall system always contains necessary elements such as supporting structure, growing media, irrigation, and
The efficiencies of installation, maintenance and replacement are also considered to improve the performance in all building phases (Manso & Castro-Gomes, 2015). However, such a green wall system has always been constructed as an attachment over the architectural envelope. To respond, we propose this green wall fabrication approach which integrates the functional elements that nurture the growth of plants into concrete walls.

2. Methodology

Our approach takes advantage of Clay Robotics (Wang et al., 2017), a digital fabrication method to produce clay moulds for concrete casting via AM extrusion. Such an AM process can not only fabricate the mould envelope but also realizes the interior growing media inside the envelope by spatially printing clay following a designated path. After the concrete casting and dehydration, the exterior clay envelope will be demoulded, recycled for reuse. In this scenario, the designed concrete component will allocate cavities for plants to root and grow, where clay may be left, serving as the substrate for plants, rather than removed.

2.1. EXPERIMENT SETUP

We utilized a KUKA KR 90 R3100 robot arm to control the motion of material deposition (Figure 1, left), with a bespoke end effector. Regarding the extruded clay which represents the outline of the wall and the geometries of cavities for plants to grow must have sufficient stiffness to maintain the shape when sustaining concrete casting, we considered two main factors of the clay extrusion mechanism: the necessary torque to extrude rather viscous material and the precise material deposition rate. In this scenario, we opted the ram pump mechanism to execute a constant clay extrusion (Figure 1, right). This extrusion system consisted of a NEMA 34 stepper motor, a 1: 40-reduction gearbox with cylinder, piston with frames.

Figure 1. Workcell Setup. Left: Diagram of Setup, (a) Personal computer, (b) Robotic arm controller, (c) Robotic arm as positioning apparatus, (d) Extrusion system & End effector, (e) Printed clay mould. Right: Assembly of Clay Pump.

The printing material remained the same from the authors’ previously research:
terracotta clay with 35-40% water ratio through extrusion. We first calibrated the clay AM system to match the extrusion velocity with the nozzle movement speed that facilitated a constant filament deposition. In the case of our pump, each round per minute (rpm) of the motor rotation could extrude 1/90 ml of clay. In this case, to match up a 15.6 mm/s nozzle movement speed, we set the rpm as 90 for 16 mm extrusion nozzle diameter.

2.2. GREEN WALL GEOMETRY

Our objective is to initiate a double-curved green wall prototype with the dimension of 1200*900 mm (length * height) and an average 130 mm thickness as shown in Figure 2. The green demonstrates the designated flat pattern of plants to grow and grey represents the double-curved concrete surface. Considering the fabrication efficiency and the possibility of success, we segmented the wall into 20 sections and printed each block respectively.

![Figure 2. The design of green wall prototype. From the left: The perspectives of front and back of the wall; the segmentation of wall on front view; the back view.](image)

2.3. PRINTING TOOL PATH DESIGN

The printing path of each block’s mould envelop was given by the contour lines. As for the internal cavity printing, we considered three key factors: 1. The continuity of cavities that enables sufficient room for plants to root in and eases irrigation and drainage, 2. The controllability of the positions on the surface where plants grow and 3. Adequate space among cavities which implements a successful concrete casting.

To respond, we applied the spatial printing strategy that vertically layered zigzag lines as interior printing path with the same height and number as envelop printing layers. Every two adjacent layers of zigzags interlaced to accomplish the continuities of the extruded clay through the intersections between layers. This also introduced a coherent mould space for concrete casting (Figure 3a).

As for the positioning of plants, we applied two scenarios on the relations of zigzag paths and envelop paths. When the zigzag path came across the envelope, the interior clay would expose on a concrete surface at the intersections (Scenario I). Such exposures implemented the planting of vegetations. On the contrary, the detachment of zigzag to envelop resulted in a solid concrete surface (Scenario II, Figure 3b).

In relation to the ease of concrete casting, the minimal length of the shorter
diagonal of each quadrangular interspace should no less than 22 mm (Figure 3c). Due to the two scenarios whether interior zigzags intersect with envelope, each segment on zigzag lines underwent cantilever and span. According to (Im, AlOthman, & Del Castillo, 2018), longer span of clay printing would cause a larger deflection. In this situation, we restricted the largest span and cantilever distance as 50 mm.

Figure 3. Printing Path Design. (a) The layout of zigzag printing path within a block boundary. (b) The plan view of a single layer: A in black is the printing path that followed by the nozzle centroid, B in khaki represents the width of clay filament, C in gray stands for concrete. (c) The span and cantilever in clay printing due to Scenario 1 and 2, respectively.

To realize the plant’s pattern of the whole green wall, we first divided the projection of the wall into two 30 * 90 grids with 40 mm * 10 mm cells on both front and back sides. Such cell size would restrict the maximum span distance under 50 mm. The nodes of two grids functioned as the control points of zigzag lines. Each node on the grid represented a checkpoint to identify whether it is Scenario I (Plants) or Scenario II (Concrete). For example, the checkpoints fell in the range of designated plants area (green color in Figure 4) belonged to Scenario I that plants should grow, vice versa. In this scenario, combined with the outlines of each block, we could generate the printing path for 20 segments.

Figure 4. (a) Checkpoints on the front of wall: green points represent Scenario I and red points stand for Scenario II. (b) & (c) The rendered distributions of cavities from top & perspective views.

2.4. FABRICATION

During the printing process, one limitation was revealed that the 50mm span distance resulted in a huge downward deformation, even fracture. In this scenario, we applied a middle point acceleration which was to increase the nozzle movement
speed to double when the nozzle met the middle point of a span while maintaining the extrusion speed. In this case, all of the moulds for 20 blocks were successfully printed with continues interior lattice distribution.

Figure 5. Fabrication Procedures. (a) Printed clay mould. (b) Sandbox reinforce the concrete casting. (3) Demoulded concrete block.

In regard to the concrete casting, we proceeded the casting within 6 hours after the clay mould been printed. The intention was to cast concrete into humid clay mould to avoid the potential surface crack and structural fracture due to dried clay mould absorbing water from concrete (Wang et al., 2019). Firstly, we built sandbox support for wet clay mould to sustain the concrete pressure (Figure 5b). Subsequently, we cast concrete with the paste of fine aggregates, cement, water and plasticizer (3:2:1:0.005). After 24 hours of dehydration, we peeled off and recycled the clay envelope for succeeding the vegetation planting (Figure 5c).

3. Result

Figure 6. 20 segments of the green wall.

The twenty finished concrete blocks were successfully cast and demoulded as presented in Figure 6. We chose mosses, pileas, and ferns as vegetations for our
green wall system. The planting was carefully executed that we wet the clay in the cavities and gently inserted the roots of plants in. Finally, we layered the vegetative blocks as the layout shown in the cover photo (Figure 7).

4. Conclusion and Further Development

This paper proposed a digital fabrication approach that integrates green wall’s functional requirements such as growing media for plants, irrigation, and drainage into the concrete components without the necessity of extra attachments as support structures. It takes advantage of AM which enables the design freedom of building envelopes from a vast geometrical variety and also facilitates the precise vegetative pattern. Furthermore, during the fabrication process, almost all the clay as mould envelopes can be recycled for subsequent prints, that contributes to environmental sustainability. However, it has to be pointed out that the upscaling that fabricating the façade in a monolithic piece other than segmented is still a challenge.

In a material context, we propose to further develop the mould material (clay paste) and the casting material (concrete) respectively. For clay, researches will follow two aspects that to increase its mechanical performance as a mould material and to hybrid necessary nutrition to facilitate plants’ growth. For concrete, we will improve the mixture on its fluidity which enables ease of casting to small spaces while maintaining the structural strength.

Moreover, different types of printing paths for interior cavities can be investigated. Although zigzag-strategy offers a valid solution, the size and dimension of each cavity are unified, meaning the amount of earth in each cavity
is nearly equal. This might not be suitable for the varieties of plants since some might require larger room to root in. Additionally, an optimization to enhance the drainage along cavities has also been concerned.

Finally, concerning the challenge of transplanting the whole plants, we propose to investigate an automatically seeding approach that either seeding after demoulding or mix a certain amount of seeds into clay mixture.

References