Integrating The Bio-digital Aesthetic Value and Architecture Potential of RLP-Concrete 3D Printing Technology

Chenshu Li¹, Xiaoyan Zhou¹ and Xiangyu Liu*¹

¹ Bartlett School of Architecture, University College London, London, WC1H 0QB
*Corresponding author’s e-mail: chenshu.li.18@alumni.ucl.ac.uk

Abstract. Rapid liquid printing (RLP) is a new research direction for 3D printing technology holding great promise for the field of architecture. It boasts an environmentally friendly, personalised free form mode of printing which is able to produce complex structures with ease. This paper explores recent research into the use of rapid printing technology in architecture and the bio-aesthetic value of its own properties. We have experimentally investigated the materials and techniques required for rapid liquid printing on concrete, with complicating issues pertinent to the printing system identified. A suitable digital design language was investigated following completion of the research. The combination of rapid liquid printing technology and concrete breaks away from the single research direction of 3D printing technology and moves the academic literature towards focusing on biomaterials in ecological architecture fields. Finally, we explore design systems for spaces dominated by collaboration between non-human bodies. The simulation and feedback of specific environments and the cooperation of 3D printing technology create a new and extended space of possibility between nature and architecture.

1. Introduction:

3D printing has been utilised across a wide range of fields, often to perform specific tasks or fulfil particular needs. 3D printing is new to the construct industry (as a whole), it is being more frequently used in specific processes within the construction industry. The materials used for printing are primarily metals, polymers, ceramics, composites and so-called smart materials.[1] However, 3D printing technology is still immature in its control of accuracy. For example, Layer-by-layer printing style, the most common printing technology today, is inevitable in terms of voids and errors between the layers.[2][3] Until recently, prohibitively challenging to apply 3D printing in a cost-effective manner to mass production processes. Still in its infancy compared to its application in other industries (such as medical and health, automobile manufactory) [1], 3D printing technology is predominantly used to produce models during the design process or for the printing of a few complex constructions. [3]

Concrete is the most widely used construction material. Currently, concrete printing techniques are contingent upon the relatively time-consuming layered approach. The level of detail in the print is related to the resolution and the thickness of the layers, with highly accurate prints taking a longer time to complete. Especially for free form structures, increasing the print thickness or reducing the number of layers to gain speed can result in a compromised final form and even print failure. [4] A notable example is “XtreeE”, a global company that prints concrete, layer by layer, and in so doing it thus able to achieve a distinct, organic form.

For the moment, the application of 3D printing technology in the bio-architecture field is still limited to the study of biomaterials. Research Cluster 7 in the Bartlett School of Architecture has been exploring new bio-design workflows and digital fabrication methods. Bio-architecture includes both direct
biological inspirations, drawing upon biological materials and functions, as well as the extraction and translation of natural principles.[5] In such an exploration, the relationships between modern 3D printing technology, bio-architecture and the eco-environment are further elucidated.

The first section of this paper offers an overview of the current status of 3D printing technology in the field of bio-architecture. It also briefly describes the contemporary development of concrete printing, and some of the latest results. The development of Rapid Liquid Printing (RLP), which has already shown great potential, is explained in more detail in the second section, where experiments on printed materials are also discussed, including the proportioning of gels as suspension systems and concrete as extrusion materials. Following a series of model results, a new digital design language for growth properties is devised.

2. Materials and Methods:

2.1. Rapid Liquid Printing Technology
Massachusetts Institute of Technology’s (MIT) self-assembly lab introduced the technology for Rapid Liquid Printing in 2017, successfully printing a series of silicone products, achieving both two-dimensional and spatial forms. This printing technique is fast, prints varying sizes and can be used for small and large shaped objects. At the same time, thanks to its unique liquid deposition system, many high-quality liquid materials for printing, significantly expanding the range and by extension, the potential.[6] The MIT report claims to have tried a range of materials such as plaster, concrete, urethane expanding foam, epoxy, UV curable resin, marine sealants, casting alloys, silicones, and metal-filled epoxy. [6] However, neither the report nor their website details any actual models or specific information on the application of concrete materials.

2.2. Supporting Gel
Unlike layer-by-layer 3D printing, RLP technology requires a gel as a support body for the print. In the past, 3D printed support structures tended to be printed from the same material. Some of the more unusual forms of printing also applied other materials as supports, such as sands. RLP however utilizes gels, which have a combination of solid and liquid properties. The appropriate gel has the right viscosity to perfectly support the extruded material before it has been solidified and shaped. Second, the same gel can be reused and recycled as a printing medium. This feature means that the waste materials that often accumulates during the general printing process can be solved. Third, the gel's viscosity and suspension can solve the problem of multi-directional support, an issue which has been difficult to overcome using existing 3D printing technologies. Materials that are self-supporting in traditional 3D printing processes need to support their weight and the stresses brought on by other printed structures under relative gravity loads. Fourth, the gel form can be quickly recovered after being shaped by the nozzle, allowing the print path to be repeatedly overlap or cross itself.

Due to copyright restrictions, we cannot ascertain the exact formulation of the gels used by MIT, so the gels in this present paper have been derived on the balance of probabilities. Several requirements need to be met to achieve a gel that is equivalent to the experimental state of the MIT lab:

1. The gel's consistency needs to be regulated, as different print materials will require different ratios of gel consistency. It is also necessary that the gel corresponds to the right density to ensure that the print material is consistent and uniformly extruded.
2. The gel must not be turbid and needs to have high visibility. A gel with high visibility ensures that the Designer can monitor the printing process. In this way, the Operator can identify problems during the printing process and adjustments can be made at any time. Visibility also ensures that the curing of the printed material can be observed.
3. The gel's stability needs to be ensured because the printing material needs to have sufficient curing time and/or may require specific curing methods (e.g., the UV resin needs to be exposed to UV light).
According to the MIT report, the main component of their gel is Carbomer 940. Since the gel needs to be stable during printing, some additives are necessarily added. The gel's viscosity and shear stress are determined by the pH value of the subsequent Carbomer and water mixture. In order to determine the exact ratio, a series of experiments were carried out. Different ratios result in different viscosities and visibility of the mixture. The viscosity is indicated in the MIT report and the pH value of the gel is between 6.0 and 9.0. In our experiments, we observe that the lower the pH value, the worse the visibility (figure 1). The gel's lower viscosity will not support the print material and will result in its collapse or deformation. The gel's high viscosity will prevent the printing fluid in the gel or even the printing material from being extruded continuously (figure 2). As different materials have different weights, densities and fluidity, the gel needs to be adjusted for each material.

2.3. Extrusion Material
The choice of printing material also needs to meet the following requisites:
1. The material itself has the potential to flow continuously.
2. The material can cure quickly. Fast curing ensures that the flow of the gel does not interfere with the path of the material during the printing process.
3. The material must be sufficiently stiff after curing. This prevents the material from being damaged by loss of support during removal of the gel after curing.
The choice of extrusion material was originally inherited from the previous year's research at RC7. Last year, a group in the studio had successfully printed arch-shaped structures via a continuous process using UV resin (figure 3). The structures were printed as normal and not successfully printed continuously in liquid. UV resin has also been initially selected in this present research, as it boasts the advantage of good flow and fast curing. No matter whether it is a 2D line or grid, or a 3D cube or spiral, UV resin exhibits high degrees of perfection in the printed result (figure 4). However, the disadvantages are obvious: UV resin is not environmentally friendly and remains expensive. In the field of architecture, UV resin is not a good choice of building material because of its low flexibility and brittleness after curing.\[7\] This material has only a small potential for decorative use.

Concrete flows well when mixed with water and is what 3D printing in construction has been pushing for. However, the mixing ratio of concrete and water can also affect the printing result. Accordingly, we conducted tests regarding the ratio of concrete to water. What becomes clear when considering concrete as a printing material is that concrete has a certain initial setting time. The time at which concrete loses its plasticity but does not have mechanical strength is called the initial setting time. Concrete is perfectly suitable for printing prior to the initial setting time, but no further movement or vibration is allowed once the initial setting state has commenced. Further, too high a proportion of water in the mixture can result in a weak concrete joint that is susceptible to breaking or failure to connect. If the concrete mixture is too dense, the concrete will not extrude evenly during the printing process. Following the relevant water and concrete proportioning experiments, the final ratio was summarized as cement 90ml: sand 100g: water 100g: SBR Bond 15ml: Accelerate 0.8ml: Mortar plasticizer 0.5ml.

2.4. Exploration of Different Printing Tools and Structures
The printing steps of our experiment closely mirrored those reported by the MIT lab: (1) the designer uses 3D software to model and determine the print path; (2) the extent of the print is thus determined, with reference to the size of the tank that holds the gel; (3) the amount of concrete and gel is calculated for proportioning; (4) the robotic arm controls the print path. To print the designed model, a clear and observable path direction is required. The designed lines are translated into several serial-numbered points in the grasshopper. The nozzle of the extrusion system determines its movement direction by the tangential direction of each point.

First, small pilot experiments were undertaken, including some simple circular spiral print paths, followed by tests where different paths crossed or overlapped. Due to the free-form nature of the spiral shape, it is difficult to print directly without adding additional structures in a normal 3D print design. Our experiments required only a few seconds for the shape to be observed (figure 5). The tests on the intersection and overlap of the print paths reveal that the concrete can be joined together before the initial setting time, as long as we can complete the print paths before the concrete's initial setting time. After setting, it can be seen that the two print paths are solidly joined and do not require a second assembly after curing. This means that RLP technology has the potential to print many complex printing paths.
3. Result & discussion:

3.1. Distinctive Spatial Form and Stylistic Potential

These initial tests were then followed by larger model tests. An automatic extrusion device system was designed in order to control the flow rate of the concrete mixture through the print. During the liquid printing process, both the speed at which the material is extruded in the gel and the speed of the robotic arm's print path are simultaneously reflected in the final printed model form (figure 6, 7). The model printed would become thicker or thinner when, for instance, the arm is printing at a constant speed, but the extrusion mixture is simultaneously too fast or too slow. Printing can achieve different thickness by fixing the extrusion mixture's speed and adjusting the robot arm's speed.

This type of printing not only allows free shape spatial forms to be created via the print path, but it also controls the volume variation of the printed object by controlling the movement speed of the robotic arm and the outflow rate of the extruded material.

Figure 6. Concrete printing tests progress with robot arm, London, Liga print group

Figure 7. Robotic setting, London, Liga print group

3.2. Study of Liquid Printed Model Removal and Assembly Methods

A further challenge is to extract the printed model out from the gel following the curing process. Unlike silicone and UV resins, concrete is a great deal larger and heavier. Attempts to remove the model result in multiple stresses placed on the model: the weight of the model, the tension of the structure and the adhesion of the gel all factor in the outcome. The use of conventional hooks or other pulling methods may cause the model to break due to the brittleness of the concrete during the setting phase. To mitigate this, it is necessary design appropriate methods of taking it out prior to printing.

A sandwich sheet was thus designed in the tank that holds the gel. (figure 8) The gel does not pass through the interplay until it is printed. This layer can withstand the tension of the gel to give the concrete a stable initial setting environment. Once the model has set, the gel automatically flows away from the surrounding area upon removal of the sheet. The steel frame, which is already in place before printing commences, can then move the entire model without damaging it. The gaps between the frame and the tank prevent the tank wall from sticking to the frame during the printing process. This method not only protects the model, but also provides a flexible way of assembly. Placing the steel frame close to the...
print path and a flat plate will appear at the intersection of the model and the steel frame (figure 9). The size and shape of this flat plate can be designed according to specific needs. Models printed in this way can thus be modular, facilitating very complex assemblies. Each printed part can be a unique shape as long as the model is designed with a reasonable number of connections (figure 10).

Figure 8. The diagram of sandwich sheet, London, Liga print group

Figure 9. Printing assembly model, London, Liga print group

Figure 10. How to form a connection flat, London, Liga print group

3.3. The Potential of RLP Technology for Ecological Aesthetics

Contemporary methods of increasing greenery in urban city environments are primarily focused on applying green roofs and facades. However, these methods have minimal impact on how we design buildings and often do not link to the interior space. In most cases, the design of ‘nature’ in buildings is currently limited to potted plants and indoor green wall systems. These systems are expensive, require filtration systems and have low microbial diversity. Our printing results indicate that the voids and the thickness of the printed concrete columns can be controlled (figure 11). It is possible to print density control in conjunction with a diverse range of plant growth environments. The sunlight and growing space required for the growth of different plants are different. Although existing green wall systems can also be made to allow plants to grow on vertical walls, they are generally designed to be more homogeneous for the sake of construction efficiency. RLP technology customises the spatial form required to grow different plants fully controlled from the design stage to the construction stage.
The free print path characteristics in terms of density and path morphology are very similar to the root growth or vine growth in a natural forest. The space created by such a linear growth path has the advantage of digitally controlled accuracy and avoids the problems of homogenisation and elitism of parametric design. In this way, the path to freedom is the human-controlled utility space move towards the disorder from nature. The layer-by-layer printing technology has always been limited to the stacking of paths in two dimensions and cannot be created freely in three dimensions. RLP technology, however, makes it possible to print in three dimensions using gel as the medium. This technology's linear print language helps designers find a balance between the aesthetics of disorderly natural wildness and the control of practicality necessary for human space. It is thus feasible to argue that RLP technology has the potential to be in dialogue with nature through its printing properties.

3.4. Research on Corresponding Design Languages
Based on the analysis and findings derived from the aforementioned experiments, a new design language has been devised for this purpose. The uniqueness of liquid 3D printing is primarily reflected in the perfect fit to the linear printing language. It is possible to control the spatial orientation of the print target with great precision and achieve volumetric changes in single lines, which are incidentally more difficult to achieve with other printing methods. A pixel matrix was utilised as the foundation for a linear language direction to implement the computational design.

Digital simulations of the model results were conducted. This design language was developed based on the principle of the shortest path. The print area of the design model is first determined and transformed into a volume space, the point matrix being evenly scattered within the space (figure 12). To select the starting point and control the direction of line growth, a daylight analysis algorithm was designed. This algorithm selects meaningful point locations for each piece based on the daylight exposure and the requirements of exposure. In so doing, the algorithm is actually controlling the print results to intelligently match the amount of light required by the different plants. Not only can the shape of the space be designed during this step, but the integration of the design of the space with nature has also already commenced, marking a shift in the design process. RLP technology has the potential to be in dialogue with nature through its printing properties.

The lines that are grown continue to be further optimised by the algorithm of daylight exposure. The result is reflected in the variation in the thickness of the printed concrete. Where sufficient light is needed, the printing speed can be increased. This reduces the diameter of the printed model, providing more void space, and conversely, the model becomes thicker (figure 13). Whereas previously, the designer could only control this variation by adjusting the number of layers printed, Rapid Liquid Printing can quickly achieve this change in thickness in just one pass. Based on this growth algorithm, we have designed a number of habitable walls suitable for an array of different conditions, which can be adapted to different plant growth contexts and usher a more conducive spatial basis for urban greening. It is possible to say that the RLP technology is in dialogue with nature through its printing properties (figure 14).
4. Conclusion
The main contribution of this paper is its exploration of a new design approach for environmentally driven spatial configurations by combining rapid printing technology and concrete. Having considered the materials available, emerging technologies in the trend of non-human architecture are considered, specifically Rapid Liquid Printing. This new printing technology breaks away from the limitations of layer-by-layer printing modes, enabling freely variable shapes to be printed within a short time. A corresponding automated design system is proposed. This system is able to respond to specific environments to produce a variety of densities, privacy, microbiological environments and spaces.

Nonetheless, this system is, for the time being, subject to the limitations of our experiments. Theoretically, this technology is not necessarily required to necessitate an assembly method. However, this paper is not intended to propose an excellent, industry-ready printing technology; rather, it seeks to explore the potential of the latest technologies within the design contexts of ecological architecture and bio-aesthetics.
Acknowledgments
This work was undertaken at Bartlett/UCL and on the BPro course. We would like to thank the Bartlett/UCL, providing our tests place and instruments. We are deeply grateful of Bpro RC7 improved this topic. High tribute shall be paid to our tutors, Beckett Richard and Barry Wark, for guiding us in the completion of this project. We are also deeply indebted to all the other tutors and teachers in Translation Studies for their direct and indirect help to me.

References
[1] Shahrubudin, N., T. C. Lee, and R. Ramlan. (2019) An Overview on 3D Printing Technology: Technological, Materials, and Applications. Procedia Manufacturing., 35: 1286–96.
[2] Luo W., Xinchen M., and Jian Y. (2020) Application and Research on Building 3D Printing. Journal of Critical Reviews., 7 (12): 564–78.
[3] Martelli, Nicolas, Carole S., Hélène V. D. B., Judith P., Patrice P., Isabelle B., and Salma E. B. (2016) Advantages and Disadvantages of 3-Dimensional Printing in Surgery: A Systematic Review. Surgery., 159 (6): 1485–1500.
[4] Ortega, Guillermo S., Javier A. M., Nils O.E. O., and José A. T. R. (2020) The Application of 3D-Printing Techniques in the Manufacturing of Cement-Based Construction Products and Experiences Based on the Assessment of Such Products. Buildings., 10 (9).
[5] Riply, R.L., Bhushan,B. (2016) Bioarchitecture: bioinspired art and architecture—a perspective. Royal Society., 374 (2073): 1471-2962.
[6] Hajash, Kathleen, Bjorn S., Christophe G., Jared L., and Skylar T. (2017) Large-Scale Rapid Liquid Printing. 3D Printing and Additive Manufacturing 4 (3): 123–31.
[7] Vipin S., and Madhu B. (2004) Overview on basic chemistry of UV- curing technology. Pigment and Resin Technology, 33(5):272-279.