Robotic Additive Manufacturing of Glass Structures

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This paper proposes a glass 3D printing system that can be used at room temperature. The system employs high-frequency electromagnetic induction heaters and stone-ground carbon tubes to heat glass raw materials. In this study, a digital control system was fully utilised to control the extrusion of borosilicate glass materials. Through a calculated design and communication between a six-axis robot arm and an external computer, the robot's printing path and speed and the feeding state of the glass printing machine can be automatically controlled for different geometric shapes and velocities. This study examines digital manufacturing processes and material properties to investigate the novel glass printing of textures and free-form surface modelling.

Keywords: *Glass, Induction Heating, Rapid Prototype, 3D Printing, Robotic Fabrication*

INTRODUCTION

This research explores the concept of fused deposition modelling (FDM) by utilising the fluidity of molten glass and integrating a six-axis industrial robotic arm and a digital control system to propose a novel method for 3D printing of glass under ambient temperature. A graphite tube heated by high-frequency induction heating is used to replace the traditional glass heating method. In this way, the temperature can be instantly controlled and the heating section can be controlled within a specific temperature range.

In traditional glass manufacturing, in order to produce shaped glass, floating molten glass is poured into custom moulds for cooling and forming. This is a very stable glass manufacturing method that has been fully applied to the mass production of industrial and consumer products. However, such a method must rely on customized moulds to produce unique glass shapes; if a design aims to produce a large sculpture by assembling various different glass objects, many customized moulds must be built. As a design-to-fabrication process, this method is neither efficient nor economical. Therefore, the field of contemporary design, art, and engineering began to explore different methods of forming 3D glass objects, such as glass 3D printing.

Among existing innovative glass fabrication methods, this research was inspired by Glass 3D Printing 2 (G3DP 2) (Klein et al. 2015) proposed by MIT Media Lab in 2015. Their paper demonstrates a customized robotic glass printing technology and then explores initial design applications based on it. The high melting point of glass has always been a huge challenge in the glass processing industry. In the G3DP 2 project, raw glass is placed in a traditional glass heating kiln for melting, and the gravity acting on the molten glass is utilised as the driving force for glass extrusion. Segmented heating and temperature control in the extruder is used to control the flow rate of melting glass. In this example of glass 3D printing, printing glass shapes could not be continued after the feeding was suspended because of the limitations of the glass heating and feeding systems.

The present research proposes a novel glass heating and melting mechanism using high-frequency induction heating and attempts to add the feeding and withdrawing systems of traditional 3D printers to the process of glass 3D printing. The printing status can be controlled more effectively through the integration of the feeding method of wire-shaped raw materials, the printing path programming, and the digital control system. This study takes full advantage of the viscosity of borosilicate glass material and the integration of the digital control system to control the robotic arm and external devices (a computer and a glass heating and feeding system), so that the design of glass objects can be further explored.

The contributions of this paper are

1. Demonstrating the potential of glass 3D printing in architectural design applications in a dry assembly method with full play to the value of modelling design and additive manufacturing;
2. Utilising the setting of the digital control and the printing path, showing the possibility of a novel glass printing texture and object opening;
3. Presenting a free-form glass surface assembled by various printed glass units and a glass column with weaving patterns.

BACKGROUND

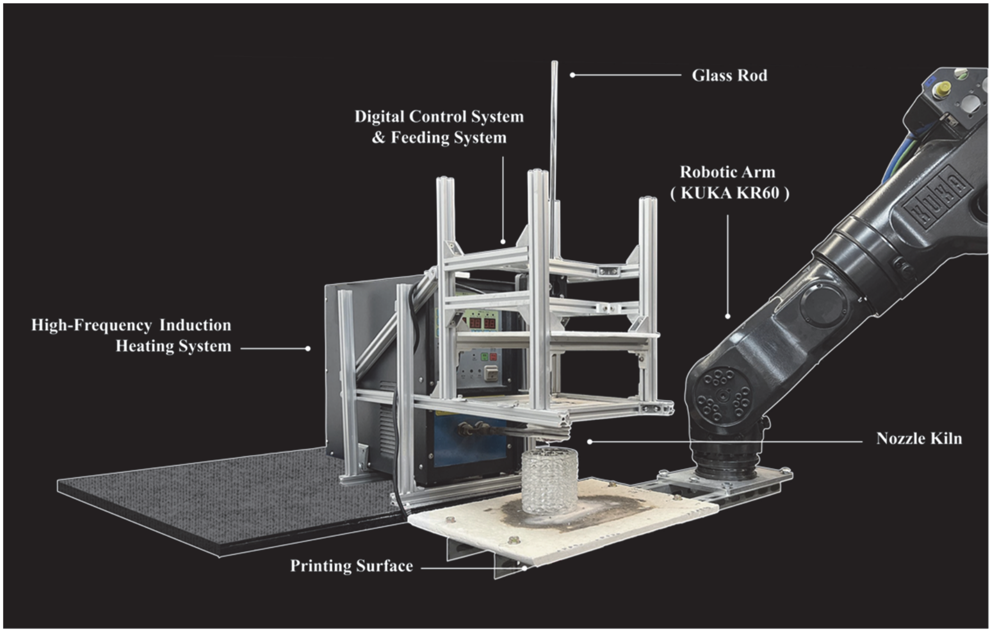
The light transmittance and high temperature resistance of glass often play a key role in the facade decoration and functional performance of architecture. However, with trends in digital architecture and the advancement of technology, the demand for free-form shapes is increasing. In recent years, designers and engineers have also begun to explore a digital workflow to produce free-form glass efficiently and precisely. It appears that building a large sculpture assembled from different glass units is a good solution. In the case of Re3 Glass (Oikonomopoulou et al. 2018) (Figure 1.1), a unique interlocking glass brick developed by the TU Delft Glass & Transparency Group was used to construct the Crystal Houses facade in Amsterdam. This example demonstrates the high compressive strength of glass and the elimination of the need for additional support structures. In the case of PlyGlass (Parreño 2015) (Figure 1.2), compared with traditional methods such as glassblowing or casting glass, the techniques of lamination and making different shapes of flat glass (cut by machine) can be applied to assemble a free-form installation on a large scale.

FDM additive manufacturing is another possibility for making glass. Similar to traditional plastic 3D printers, a glass 3D printer that can be applied to the manufacturing of delicate objects was proposed by Micron3DP (Micron3DP 2017) (Figure 1.3). Owing to the machine design, the size and fineness of the finished product are more suitable for use in commodities and components.

MIT Media Lab proposed G3DP 2 (Figure 1.4) in 2015, which improved the finished product scale of glass 3D printing and the possibility of its application in architecture. Due to the difficult processing conditions, glass will only fully transform into a molten state at 1200°C. MIT's approach is to pre-melt the glass raw material in a traditional glass heating kiln to the molten state and then pour the molten glass into a customized 3D printer for secondary heating and extruding. Gravity acting on the molten glass was employed as the source of printing power

Figure 1
Related works mentioned above. (1) Re3 Glass (2) PlyGlass (3) Micron3DP (4) G3DP2 (5) Transient Materialization - Robotic Metal Curving

Figure 2
Glass 3D Printing System



to control the extrusion flow rate of the molten glass to carry out glass 3D printing.

The present research proposes a novel glass heating and material feeding system to reduce the need for manual intervention. In the research "Transient Materialization – Robotic Metal Curving" (Lu et al.2020) (Figure 1.5), high-frequency induction heating is applied. This method can quickly and precisely heat and melt a metal rod in a specific temperature range to complete the bending of the metal rod. Inspired by this study and G3DP 2, this research applies high-frequency induction heating technology to the heating system of the glass rod material and uses a programmable extruder and robot to explore a new glass 3D printing system. A programmable digital signal and robot control system realises not only continuous discharge but also a stop-and-extrude method in the glass 3D printing process. On the basis of this technology, more changes and explorations can be made in the process of material research and modelling.

SYSTEM INTRODUCTION

There are three parts to the whole system (Figure 2): (1) a heating system, (2) a power feeding system, and (3) a real-time robot control system. Heating via electromagnetic induction is integrated into a ceramic nozzle through a feeding principle similar to a traditional FDM 3D printer: a glass rod is heated to a workable molten state and then printed on a platform on the end flange of a robotic arm with six degrees of freedom. Through the real-time control system, the printing parameters can be adjusted according to the need for different openings or textures of the glass object.

Materials Research

Two kinds of glass raw materials—soda lime glass and borosilicate glass—were used in the testing of glass raw materials.

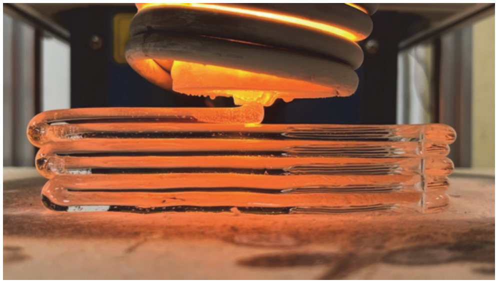


Figure 3
Operation of the heating system

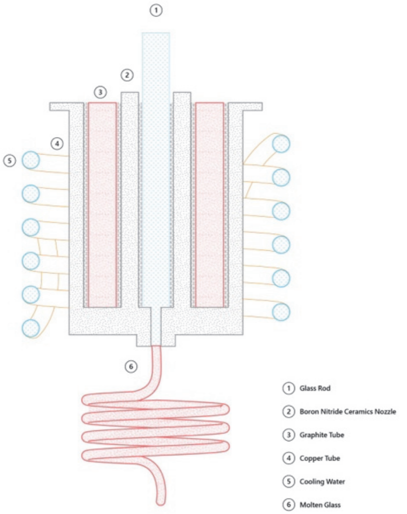


Figure 4
Section of the boron nitride ceramic nozzle

Although the sodium calcium glass was found to have a lower melting temperature, after repeated tests, the quality of the sodium calcium glass printed and the state of cooling and solidification were not ideal. If the glass came into direct contact with the cold air after flowing from the heating head, it was easy to produce cracked lines and blistering, which will eventually lead to cracking and breaking of the glass work. However, borosilicate glass was relatively stable during the entire printing and extrusion process, and it was relatively stable and easy to control from the molten state (the softening point of borosilicate glass is 821°C) to the process of cooling and condensation. It not only maintained a clear and transparent high light transmittance after printing and extrusion, but it also did not have a crack path that expanded and contracted when heated. The printed product also had quite a high mechanical hardness. Thus, in the end, this study adopted a borosilicate glass rod with a diameter of 7 mm and a length of 120 cm as the raw material for glass printing.

Heating System

The high melting point has always been a major challenge in glass processing. In traditional glass processes of the past, a large glass furnace was used to heat and melt the glass raw material, and the heat was provided by oil, gas and electricity. Once in a molten state, the glass went to the next shaping workflow. In the manufacturing of some glass handicrafts, direct fire is used to heat and melt the parts that must be softened to bond or shape multi-section glass rods. The heating method in this experiment was electromagnetic induction with a high-frequency metal heater and graphite carbon tubes (Figure 3). The employment of high-frequency metal heating coils for heating is not only safer, but the heating range is also more uniform and easier to control.

A boron nitride ceramic nozzle was specially designed for this experiment for heating, softening and melting the glass raw material to a molten state (Figure 4)**.** The nozzle is divided into two parts. The innermost part is the heating chamber, which is responsible for holding the glass. A graphite carbon tube (a graphite circular tube with a diameter of 35.15 mm and a thickness of 7.53 mm), which was used as an induction raw material for electromagnetic induction, was placed in the middle chamber. The end of the nozzle was a circular hole with a diameter of 5 mm. The glass raw material rod was remixed from the solid glass in the heating chamber, and after heating and softening, it was remixed in a molten state. Through the power extruder at the back, the extrusion line diameter of the glass strip was reshaped to about 8 mm~13 mm (the size of the line diameter will vary with the printing parameters and the size of the nozzle) to carry out the glass printing job.

High-frequency induction heating systems are widely employed in metal heat treatment, welding and thermoforming in traditional industries. Induction heating adopts the method of electromagnetic induction to generate electric current inside the heated material, and then it induces the molecules inside the material to collide violently with each other to generate high temperatures to achieve the heating effect. The high-frequency induction heating method enables heating up to the corresponding processing temperature in a very short time, performing local surface hardening and melting for specific parts, thus making it safer and more stable in processing and manufacturing. The heated object also does not need to be in contact with the heat source, and such heating characteristics are widely used in some situations where contamination is a concern. However, because glass cannot conduct electromagnetic induction with metal coils, annular graphite carbon tubes were adopted in this experiment as the reaction material for electromagnetic induction. Such heating logic is also widely employed in wafer processing in the semiconductor industry. This graphite carbon tube is consumable, and it will gradually decrease with the heating time; therefore, it must be replaced regularly to prevent affecting the heating effect.

Robotic Printing System

The feeding method of this system is different from that of traditional glass processing. This method melts glass through extruding glass rods into the boron nitride ceramic nozzle. Therefore, the supply of glass raw materials can be continuously extruded, and the printed objects will not be limited by the capacity of the heating kiln.

Robotic Arm Printing Platform

In this experiment, to produce various 3D-printed glass objects, a hot bed was installed on a six-axis robotic arm (KUKA KR60). Through computing the robot's pose and the planning of the printing path, various geometric shapes can be created. The relatively stable material properties of borosilicate glass determine that the acceptance of temperature difference is also relatively large. When printing 3D glass with this method, it is only necessary to maintain room temperature for printing, and after completion, the object is placed in an annealing furnace for annealing and cooling. In the future, if the temperature control and environmental conditions of the processing environment can be strengthened, it will be possible to print large glass objects without being limited by the dimensions of the printer table.

The temperature of the glass when it flows out of the ceramic nozzle is usually around 1,200 degrees; therefore, the printing platform is made of a high-density ceramic fibre board with a low heat ratio and high temperature resistance. Its low heat conduction rate can prevent high-temperature melting glass due to violent temperature changes and crimping or cracking.

Heating Power

This method employs a high-frequency induction heater with a power of 77,000 W to heat the glass raw material in the heating chamber, and then the molten glass is extruded by the power of the extruder to perform the printing operation. The size of the heating power affects the forming effect and transparency of the glass extrudate. The softening temperature of borosilicate glass is 821°C. However, to perform glass 3D printing, it is necessary to further heat the glass raw material to 1,200°C for thorough dissolution and then reshape the extrude (Figure 5).

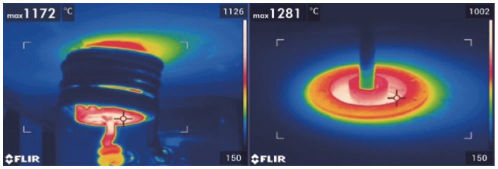


Figure 5
Infrared thermal image of the operating nozzle kiln

Feeding System with Digital Control

In this case, the state of the outflow of glass is mainly controlled by the speed and direction of the extruder motor, which can be achieved in real-time mode. Through the digital control system (Figure 6), the programming of the digital output signal can be added to the printing path in advance; the command can also be manually issued to the extrusion system through the digital signal controller.

Print Parameters

In this stage of the experiment, the glass raw material was melted and extruded by a high-frequency induction heating machine to melt and extrude the glass rod. Suitable parameters for this method were found by adjusting variables such as temperature, printing geometry, layer height and printing speed.

Thickness and Layer Height of the Printing Material

The size of the glass filament extruded by this method will be affected by the distance between the ceramic heating nozzle and the printing platform, extrusion rate, heating temperature, etc. (Figure 7) Taking a nozzle diameter of 5 mm as an example, in the case of a layer height of 4 mm, glass filaments with an extruding thickness of 9.5 mm can be printed. Such a size is best controlled and considers structural strength when performing single-layer or multi-layer printing. The fusion state between layers is relatively firm. During the process, the glass will cause distance errors in the Z direction due to thermal expansion, contraction and heat accumulation. To solve this problem, a lift of 0.5 mm in the Z direction will be made every time two layers of printing are completed to solve the error between the printing path and the actual situation.

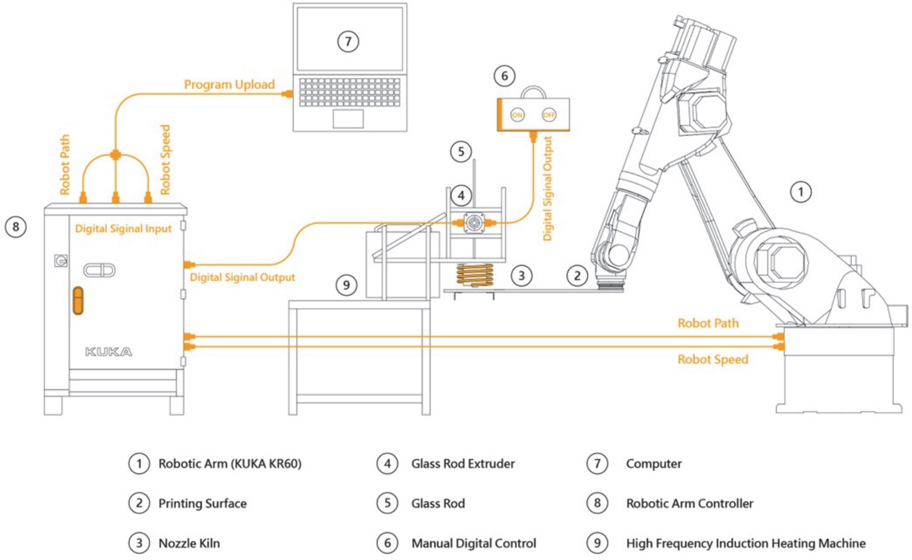


Figure 6
The digital control system

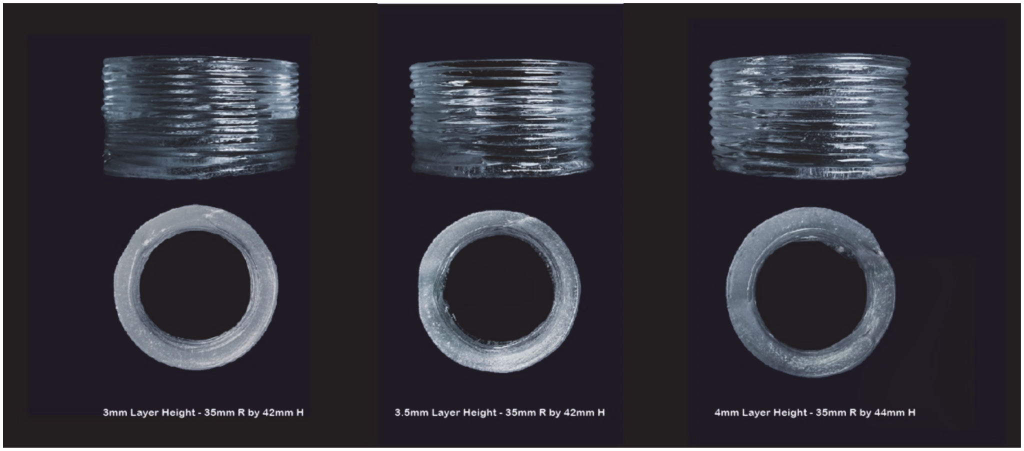


Figure 7
Results of different printing parameters

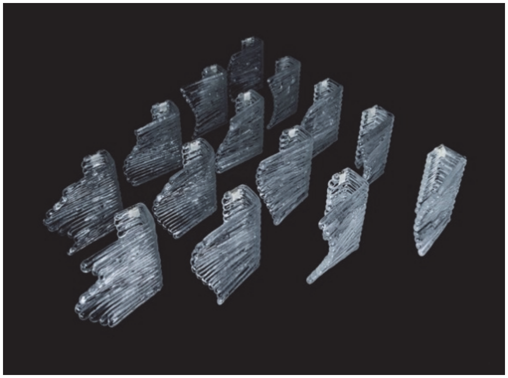


Figure 8
Fourteen units of the free-form glass curtain

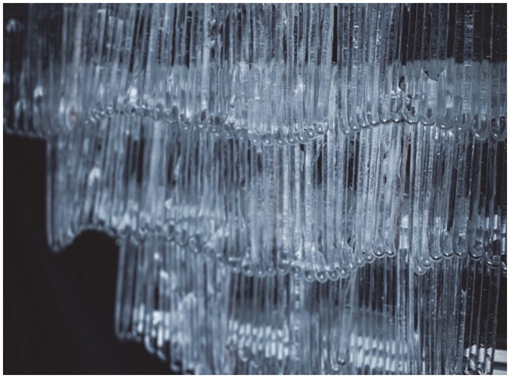


Figure 9
Detail of the assembled curtain

EXPERIMENT DESIGN

Free-form Glass

During installation, free-form glass is normally fixed with a dry clasp or screw lock. In this experiment, 14 different types of curved glass units were generated (Figure 8). Each unit was 90 mm wide, 60 mm deep, and 120 mm high, showing the possibility of applying this design process to architectural design using a dry prefabricated frame assembly method (Figure 9).

Glass units with different curvatures (Figure 10) were used to test the glass 3D printing of overhangs. Due to the high viscosity of glass and the rapid cooling and forming time, curved shapes or other complex shapes can be printed without support materials. The back of the glass-making unit was designed in the shape of a hook that matched the design of the frame system to assemble the glass curtain (Figure 11).

Parametric Column with Weaving Pattern

The controlled feeding system enables the ability to control the state of glass extrusion. By controlling the amount of glass extrusion, a weave-like texture can be created (Figure 12). In this experiment, the

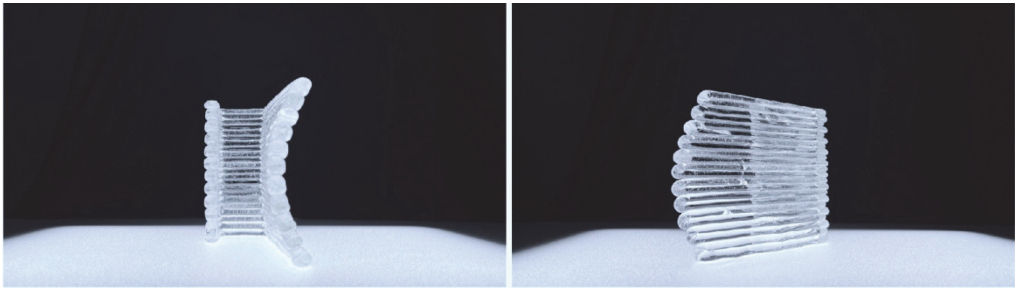


Figure 10
Closeup of single unit

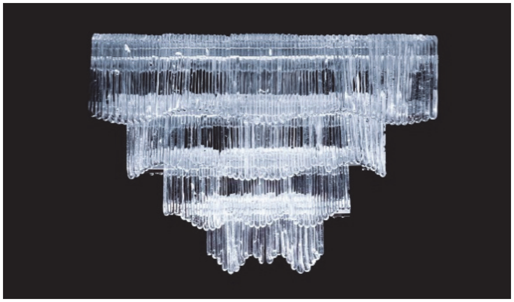


Figure 11
Free-form glass curtain

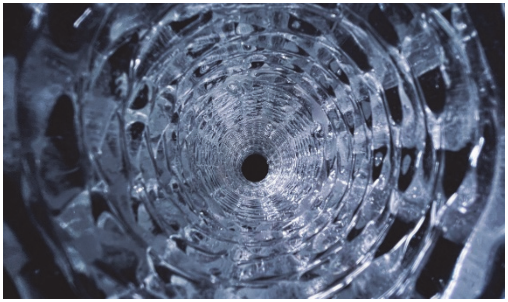


Figure 12
Weave-like texture of printed glass

same geometrically shaped glass column (about 10 cm in diameter) was printed with three different states of digital control to explore the special effects and possibilities of glass modelling and textures (Figure 13). Such a real-time control system can not only make the printed shape escape the limit of being made in one continuous line, but also enable creating new possibilities for 3D objects in terms of their functions. Additional print units add more splicing possibilities.

CONCLUSION

This paper adopted a new glass heating device and digital control system combined with a six-axis robotic arm and a computational design to propose a novel glass 3D printing method that can be performed at room temperature. After a series of experimental studies, this paper carried out and verified the applicability of this glass fabrication method. This novel glass printing technology is suitable for furniture, such as those that use curved glass ramps, or art installations. Two examples, a curved glass surface and a glass cylinder, were demonstrated in this paper.

Figure 13
Pattern control with different digital information

A curved glass surface was divided into small glass units, which were assembled through dry fabrication. This more economical method of glass splicing reduces the difficulty of manufacturing large sections of curved glass. In the future, it could be applied to manufacturing architectural decorations, glass bricks, and the glass of building facades. Furthermore, a glass cylinder was adopted to demonstrate the digital control effect on the extrusion state. Compared to previous glass 3D printing technology, this study proposed a novel glass heating system using a high-frequency electromagnetic induction heater to melt the glass raw material and a digital control system for feed extrusion in a programmed print path. With this process of glass 3D printing, the extruded glass can be paused to achieve the desired geometries and can continue to be fed until it reaches the target position, creating a variety of unique weaving textures.

Future research will optimize the temperature control of the heating system to enhance the transparency of the glass. During the printing process, the problem of warping occasionally occurs due to the temperature difference between each layer. Therefore, more accurate environmental parameters will be targeted, and the heat bed platform will be strengthened. Furthermore, in order to mount all printing mechanisms on the six-axis robotic arm, the size of the high-frequency electromagnetic induction heater will be reduced. Consequently, single and large-scale glass products can be manufactured.

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