Abstract. This research is to develop a robotic glass crafting dip-forming process by dip forming. Instead of employing molds, we utilize repetitive dip coating and gravity to shape the glass. In addition, its morphogenesis process is similar to the certain growth mechanisms in nature, such as geotropism and branching. During the forming process, melted glass is accumulated layer by layer gradually until the target geometry is completed. The process takes advantage of the precision of the industrial robotic arm and the viscosity property of the material. This process requires the custom-made tool to operate in high temperature and controlling the timing of heating and annealing to eliminate Z artifacts caused by layered deposition, achieving the crystal-clear effect of the glass craft without the post cure process after printing. In addition, the robotic arm provides a higher degree of freedom for forming. This research demonstrates glassworks in the organic form including variations in thickness and branching to test the proposed method.

Keywords. Robotic arm; glass craft; Digital Fabrication; additive manufacturing; dipping forming.

1. Introduction

Glass craft is commonly seen deployed in numerous daily life and in numerous industries, fascinating people by its appearance and unique properties. The form of glass can be varied by employing industrial process. The architecture, South Australian Health and Medical Research Institute, demonstrates that contemporary architects master using glass to create unique dia-grid façade system by a parametric design tool and analysis software, accommodate the best solar orientation and daylight need (Burger 2014). It manifests that architects have interests and ability in manipulating glass in design. However, the majority of usage of glass in architecture are window glass and glass panels on the curtain wall. This paper explores the possibility of using other forms of glass in architecture. For example, appropriate light can reinvigorate space; if the form of glass can be controlled to scatter light precisely and appropriately, it will meet needs in
architectural or interior design. Additionally, a fully functional glass extrusion printer has been developed, enabling the FDM printer to print optically transparent glassworks (Oxman et al. 2015). From then on, the designer could utilize the sophisticated glass 3D printing as a means of dealing with the complex form of glasswork. It demonstrated that highly customized glasswork by using FDM machinery is possible. In this research, we attempt to challenge the possibility of forming the multidirectional glasswork. To do so, it is necessary to review and redesign the conventional approaches and redesign the glass dip-forming process.

On the one hand, there are several kinds of the industrial process for this long-lasting material, such as glass molding, glass blowing. These customized fascinating forms can be produced by customized mold (Koh 2014). However, certain forms might be restricted by the draft angle of molds. For instance, in the majority of the time, the process of making the complex organic forms, animal shape with curved limbs, and the branch shape rely on the handmade process. On the other hand, the handmade process provides varying and unique glassworks easily; however, the reproducibility is difficult to be controlled by hand. Even with the identical forming process, the shape of every glass object is unique because it is affected by various forces in microscale during the process – which is vastly different from those products made by ordinary molding processes. On top of that, the high-temperature environment is detrimental to glassworkers. Subsequently, it also restricts the result of glass craft.

For dealing with these mentioned problems, this research explores the glass dip forming process in which makes the good use of the precision and the degree of freedom of industrial robotic arm, exploring the new method manipulating the robotic arm to achieve varying and organic form with high reproducibility. Moreover, the control interface and mechanism would be as simple as possible.

The procedure of this forming process involves manipulating robotic arm and gripping a rod to be dipped into the molten glass repeatedly (Figure 1), then shaping the form by controlling the directions of the rod and let the gravity pulls the flow; furthermore, the depth and the timing of the dipping is carefully controlled. In order to smooth out seams and strengthen the structure, two strategies were implemented in the procedure, such as preheating the part that new material will be added and annealing through keeping the part of the glass that is just dipped closed to the high-temperature area near furnace for a while.

Figure 1. Robotic glass crafting by dip forming.
2. Preliminary Test

In order to develop the robotic glass dip-forming system, reducing the complexity and energy consumption, the forming process that we choose is repeatedly dipping and the material is low-temperature lead-free glass that can be melted at 450 degrees Celsius. There was a research paper discussing the properties of this kind of glass and their feasibility to metal bonding (Chen and Chou 2007). We can use this characteristic to accumulate glass on a metal rod as a base. The approach can be addressed as an additive process. It is similar to the dip coating technique that designates the deposition of liquid (Puetz and Aegerter 2004) and the shape of the glass is altered by changing its direction and using the gravity to control the flow of the semi-molten glass. There are various factors that might influence the result of the glasswork. Therefore, before starting prototyping this robotic arm based forming process, we did pretest to confirm the feasibility of the dipping process. In the pretest, the glass was accumulated by the manual dipping process and the appearance can be as clear as crystal (Figure 2) and the process enables the glasswork to be curved and long. During the pretest, we found that the proper temperature for dipping should be 800 degrees Celsius although the melting point is at 450 degrees Celsius. Additionally, it is possible to anneal the glass appropriately by keeping it at the position with 100 millimetres distance above the 800 degrees Celsius liquid surface of the glass base on the pretest.

![Figure 2. The preliminary test by hand.](image)

2.1. SYSTEM DEVELOPMENT

2.1.1. Apparatus Design

The composition of this fabrication process includes one 6-axis industrial robotic arm and a mini electric furnace; consequently, it is implemented compactly in a small laboratory room rather than the traditional glass craft factory with a huge machinery room. Because glass is extremely sensitive to temperature, it is crucial to manipulate the cooling and annealing process in order not to shatter the glass by cooling down suddenly in room temperature. Utilizing the robotic arm enabling us to deal with the difficulty of glass forming such as extreme temperature and repetitive precision. The control code for the industrial robot is generated by KUKA PRC in Grasshopper. The tool which mounted on the robotic arm is made up of metallic springs, rods, and holder part by micro spot welding (Figure 3). As a result, these weld points on the tool are heat-resistant. It keeps the distance between flange and holder to avoid robotic arm be heated. In addition, the springs
on tools can absorb the external force that might break glass works during forming. Each glasswork will be accumulated on the metallic rod gripped by the holder. After forming, the glasswork can be taken out from holder easily like taking out the pencil from pencil compass.

2.1.2. The Interface

The Interface of controlling the process is developed in grasshopper (Figure 4). It basically contains three main parts. First part is to process the geometry by inputting polyline. The second part is to define the spacing of each dipping step. The final part manages the performance of each iteration, including the input for setting position of a furnace. Those components of KUKA|prc are employed in the final part.

Figure 3. The tool on robotic arm.

Figure 4. The program in Grasshopper.
2.1.3. Forming Process

The procedure of this forming process involves manipulating robotic arm and gripping a rod to be dipped into the molten glass repeatedly, then shaping the form by controlling the directions of the rod and let the gravity pulls the flow (Figure 5).

Furthermore, the depth and the timing of the dipping is carefully controlled. In order to smooth out seams and strengthen the structure, two strategies were implemented in the procedure, such as preheating the part that new material will be added and annealing through keeping the part of the glass that is just dipped closed to the high-temperature area near furnace for a while (Figure 6).

2.2. LINEAR FORMING

The linear forming process can form a straight line or curved curve, varying the width by manipulating the spacing of each dipping. The result can be seamless or segmented (Figure 7).
The result can be varied by various compositions of dipping spacings. In addition, duplicated dipping position widen the forms’ radiuses, in contrast, and long-distance spacings thin the form. Gripping nibs to be dipped can produce various forms of glass pen bodies (Figure 8).

2.3. BRANCH FORMING

The branch forming process is sophisticated. When designing the path planning process, it is crucial to regard various factors, such as interference between the robotic arm, the glasswork, the furnace in each movement, acceleration of every movement, the directions of each branch, and timing of cooling and annealing. Each factor will affect the outcome of the glassworks tremendously. The setting of the timing for cooling and annualization is closely related to the material properties based on the experiments.

In order to enable the branching to be possible, we utilize several means to deal with the branch forming process. First of all, the dipping positions are sorted according to the distances from the original point (The red point underneath the branch); subsequently, the dipping steps are operated in that order (Figure 9).
Besides, the direction when dipping on the liquid surface of the melted glass is based on the direction that starts from the origin point for the sake of avoiding collision between glass and furnace. For instance, when two branches are closed and have different length, the longer branch will collide when dipping the shorter one. After each dipping, the glass on the rod will be raised and turned to the actual direction of the designed branch to face the ground, letting gravity to modify the direction. As a result, this approach lets branches grow synchronously, avoiding any interference caused by inconsistent growing that might break the glass. Second, the nodes of forks will be modified to average the angles between each branch (Figure 10) in order to deal with the problem that branching might fail when the angle is too small, sticking branches to be one knob.

![Figure 10. The Original Fork vs. The Modified Fork.](image)

Furthermore, averaging these angles of forks will enhance the structure of the form. The simulations of original and modified forks manifest different outcomes when bearing the same force (Figure 11). Modifying the fork will reduce the stress concentration.

![Figure 11. The structural performance of branch.](image)

The Algorithm of modifying forks for averaging the angles, it draws sphere centered at the node of the fork, finding the intersection points between the sphere and branches. Then it averages these points to get the new node (Figure 12).
This process can be repeated by a couple of iterations to modify the forks and the angle between branches will be evener and evener (Figure 13).

In this glass dip-forming system, the designer just needs to draw a tree in grasshopper and then it will generate control code for the robotic arm to form the glasswork. The result will be branching glassworks with crystal clear and organic appearance (Figure 14).
3. Contribution and Future works

The technique can be employed in making the hanging screen, the façade, and the chandelier, enabling the control of the form of glasswork precisely; furthermore, it can be utilized to control the direction of light by the refraction caused by the form. Besides, a research paper, The Magic Lens: Refractive Steganography, demonstrates a technique that can automatically generate the lenses, reconstructing the random image background to several images from different directions (Papas et al. 2012). The technique might be used to collage the view on the facade in architecture. The glass dip-forming process in this research can be also utilized to collage the vision of Surrounding. Consequently, the next work is to develop an algorithm to analyze and control the result of light easily. Additionally, the designer can use the tool with the psychology of colour and environment to manipulate natural light, designing the architecture.
4. Vision

In addition to the application in architecture, the dip-forming process has other potential applications. For instance, it can dip different materials to form a structure as a synthetic material. The formation of accumulation can be varied to achieve particular structural performance. Furthermore, it could even be utilized as a new method of 3D printing living structures. To date, it is still difficult to print organs because the cells often move and collapse on the printed structure printed by FDM approach. In this dip-forming process, cells can be fixed in the balance between viscosity and gravity. It can also dip the prefabricated structure and accumulate cells on it to accelerate the process, manipulating the direction of gravity to modify the form. Hence, the dip-forming process provides the not only relatively convenient but also more favourable approach for Interdisciplinary applications.

References

Burger, S.h.a.n.e.: 2014, South Australian Health and Medical Research Institute (Sahmri), ACADIA 14: Design Agency [Projects of the 34th Annual Conference of the Association for Computer Aided Design in Architecture.


