Spatial Glass Bonds

Computation and fabrication system of complex glass structure

Yu-Ting Sheng[1], Shih-Yuan Wang[2], Mofei Li[3], Yu-Hung Chiu[4], Yi-Heng Lu[5], Chun-Man Tu[6], Yi-Chu Shih[7]
[1,3,4,7]School of Architecture, Feng Chia University
[2,5,6]Graduate Institute of Architecture, National Chiao Tung University
[1]ytsheng@fcu.edu.tw [2,5,6]{yuan|luyiheng|chunman}@arch.nctu.edu.tw
[3,4,7]{mofeilee27|viencent60210|jasmin.syc}@gmail.com

This paper introduces an adaptive robotic spatial aggregation system for the development of an intricate self-supporting glass structure. Rather than using discrete and standardized building elements in the design and fabrication process, this research focuses on utilizing a non-arbitrary shape as an aggregated material for autonomous robotic assembly. More specifically, this paper presents an adaptive robotic fabrication pipeline that measures the size of hollow glass balls (inaccurate materials) as fabrication units to aggregate the entire glass structure. Ultraviolet (UV) curing adhesive is used as the bond between each glass element. Thus, through the live robotic programming as well as various combinations of spherical glass objects and UV curing adhesives/devices, the entire glass structure is self-supported. The project is aimed not only at the development of algorithms and a robotic fabrication system, but also the exploration of the aesthetics of glass materials. In other words, this project investigates a flexible and adaptable framework in response to live sensor data for the design and fabrication of nonstandard spatial structures aggregated out of discrete spherical glass elements, and it further explores glass material aesthetic and perception of architecture.

Keywords: *Robotic Fabrication, Computational Design, Digital Craft*

INTRODUCTION

Architecture manufacturing is a highly non-standardized process. Architects usually need to overcome the limitations of artificial or natural materials with non-standardized sizes. In such cases, controlling robotic arms with offline programming is not an efficient way to complete a task for the unpredictable construction environment. As a consequence, this research aims to develop an adaptive and flexible robot control system using a combination of sensors for design and fabrication, which would enable the robot to interact with external elements. That is, through this system, the robot would be able to sense and respond to the surrounding objects and environment and adapt its motion when facing complex tasks. This research design aims to develop a complex and self-supporting glass structure in order to bring a new spatial experience to audiences. The choice of glass structure aggregation was inspired by the idea of chemical bonds (the bonds between atoms and by the joining of two or more atoms that enable the formation of chemical compounds), and therefore, spherical glass objects were used as fabrication units to aggregate the entire glass structure. In addition, regarding the fabrication process, an ultraviolet (UV) curing adhesive was used as the bond between the hollow spherical glass elements. Due to their ambiguous dimensions, this project develops an adaptive fabrication workflow utilizing a six-axis industrial robotic arm to position and orient the spherical glasses in space and join them with the UV curing adhesive. Furthermore, the measuring sensors used for calibrating dimension of spherical glasses. Regarding the computation phase, this research design develops two algorithms, one for the generation of flowing spherical glasses along a surface from given geometries and the other for evaluation of a robotic path that enables the robot to perform stacking tasks autonomously based on the network of spherical glasses and their actual dimensions as measured by the sensors. This paper first describes the existing works that inspired this research. Second, it explains the materials, experiment, and computational fabrication system. Third, it describes the current test results. The following are the contributions of this paper: 1) the development of an adaptive design and fabrication workflow for spherical glass with a non-standardized diameter, 2) the investigation of a UV curing adhesive as a structural glue to join the spherical glasses into three-dimensional (3D) structures without external reference or a support system, 3) the demonstration of novel spatial structures aggregated out of discrete elements (spherical glasses) and the exploration of glass material aesthetics, and 4) a summary of current progress for further development.

CONTEXT AND PREVIOUS EXPERIMENT

Several robotic aggregation projects have been developed within the past few years that utilized the capacity of industrial robotic arms (repetition and precision) in combination with various industrial standard building materials, such as brick, metal, and wood, for the exploration of architectural form. However, a number of other projects have leveraged robotic sensing by working with organic raw materials or irregular materials. For example, a Fiber Composite Compression Shell with Pneumatic Formwork by Ehsan et al. in 2015 and Autonomous Robotic Stone Stacking by Fadri et al. in 2017 both aimed to propose an adaptive and nonstandard robotic fabrication workflow for workpieces with unknown dimensions. A fiber composite compression shell was used to develop a live robotic fabrication system, and pressure feedback information from integrated sensors was used to maintain criteria for fiber extrusion on unpredictable pneumatic formwork. In another example, robotic stone stacking was used to develop an autonomous robotic system that constructs a balancing vertical tower out of stones with an unknown geometry.The projects described above developed a design and fabrication workflow for objects with uncertain geometry for autonomous robotic assembly or an adaptable taping task through the integration of computational tools and sensors. Therefore, inspired by these projects, this paper develops an adaptive robotic spatial aggregation system for the construction of an intricate glass structure by utilizing hollow glass balls with deviations in their diameters as a fabrication unit. In other words, instead of relying on explicit information about the workpiece (spherical glasses), this project presents a real-time material measurement method and computational analysis for the sake of the robot's adaptive trajectory planning. Additionally, it aims to demonstrate and examine this system by fabricating a glass structure as a case study.

Figure 1
Robotic fabrication system.

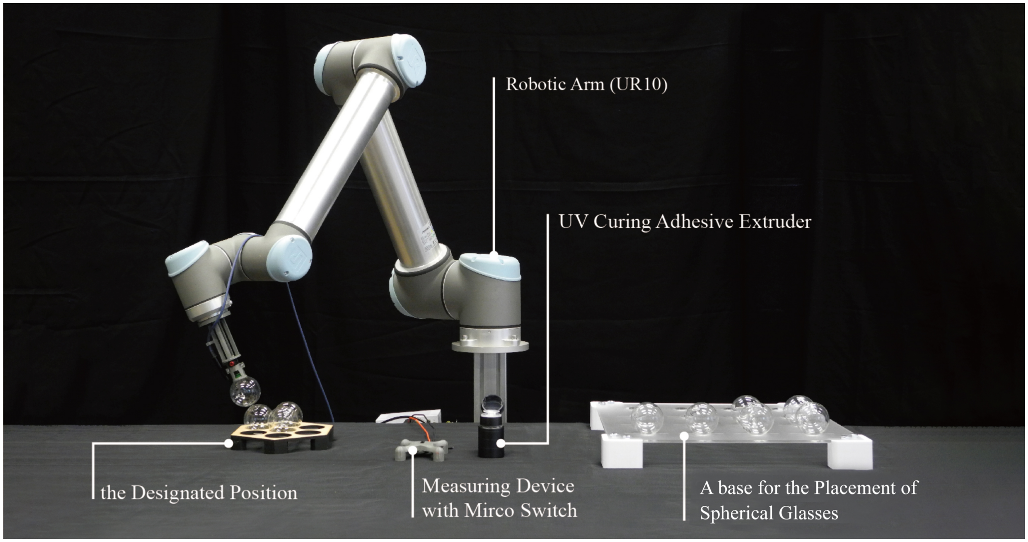
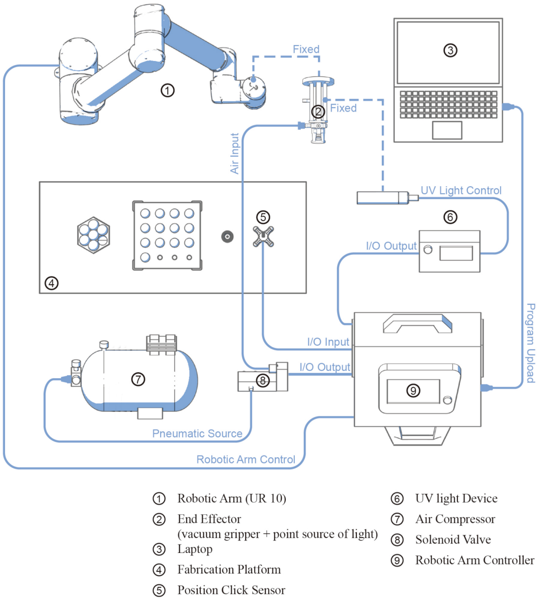


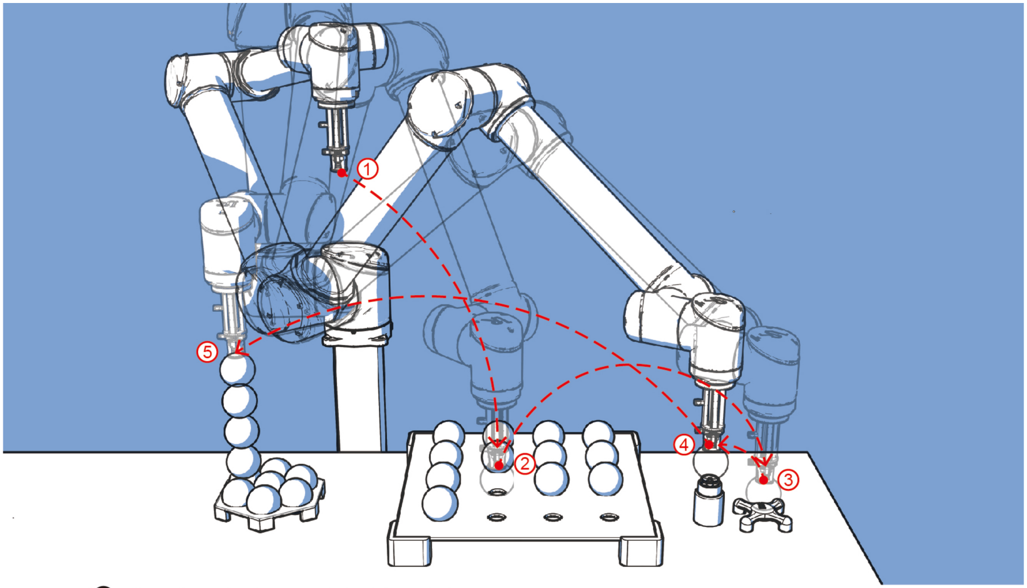
Figure 2
Related devices in the system.



ROBOTIC FABRICATION SYSTEM

The system consists of a collaborative robot (Universal Robot UR10, 100-cm reach and 10-kg payload) and a fabrication platform. The robot was equipped with a vacuum gripper and a UV curing device as an end effector. The fabrication platform was comprised of three parts: a base for the placement of spherical glasses, a measuring sensor, and a UV-cured adhesive extruder (Figures 1 and 2).In the process of fabrication, the collaborative robot was programmed via TACO (Frank, Wang, and Sheng) based on a Rhino and Grasshopper platform that is used to grip, move, and accurately place each spherical glass object. After the placement of each object, the UV curing device on the end effector was activated to cure the adhesive that binds the glasses together. The base for placing spherical glasses was made of acrylic with laser-cut circular holes (about 1/3 of the diameter of the spherical glass objects) arranged in a matrix, which the spherical glass objects were placed on. A micro switch was the primary part of the measuring device, which was attached to a 3D printed base fixed onto the fabrication platform for measuring the actual diameter of each spherical glass object (to the nearest mm). The UV curing adhesive extruder allowed the robot to attach the adhesive to each glass object at a designated place when the device was touched and pressed, and it included a push pump, a bowl-like structure placed at the discharge end of the pump to prevent spillage, and a black light-shielding container to contain the UV curing adhesive.

Through this fabrication system, the process of



① Start from the home point of the robot.

② Pick a spherical glass object from the matrix board.

③ Calibrate the deviation of spherical glass objects via touching the position click sensor.

④ Apply UV curing adhesive on the surface of spherical glass object.

⑤ Grip the spherical glas object in place and cure the UV adhesive for approximately 20 seconds.

Figure 3
Fabrication steps of the system.

generating the complex glass structure can be described in seven steps (Figure 3):

- The diameter of the first spherical glass was manually measured, and all glass objects were placed in the matrix on the placement platform.
- The robot was adjusted to be perpendicular to the fabrication platform and to move to the top of the first spherical glass object in the matrix. Meanwhile, the vacuum gripper controlled by solenoid valves was activated and gripped the glass object.
- The vacuum gripper remained active, holding the spherical glass object on the top of the measuring device and gradually approaching it until its micro switch was touched. Meanwhile, a digital signal was sent from the switch, and the robot paused as soon as it received the signal. The computer retrieved the position of the robot (TCP) and assumed that the distance between the current TCP and the switch were the same as the actual diameter of the spherical glass manually measured in the first step. Thus, this current TCP and the dimensions of the spherical glasses were used as a reference to calculate the deviation of the other spherical glasses.
- After the previous calibration step, the computer automatically adjusted the 3D model based on the value of deviation, and it recalculated the position where the glass object would be placed as well as the trajectory of the robot.
- According to the recalculated path, the robotic arm (holding a spherical glass) moved to the top of the UV curing adhesive extruder and then pressed the bowl-like structure downward until the UV adhesive attached to the surface of the glass object.
- After adding the adhesive to the surface of the spherical glass, the robot placed the glass in the position specified by the algorithm. After positioning, the curing device on the end effector was turned on after reacting to a digital signal, illuminating the UV curing adhesive for approximately 20 seconds to bind the glasses. Finally, the process was repeated from the second step until task completion.

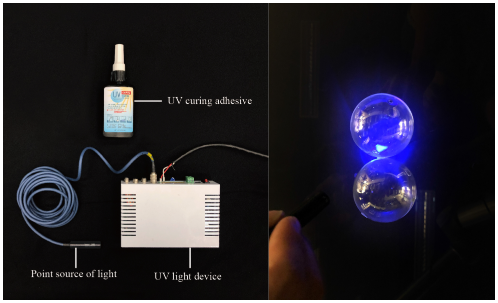


Figure 4
(A) Point source of light and UV light device. (B) Adhesive curing by UV light.

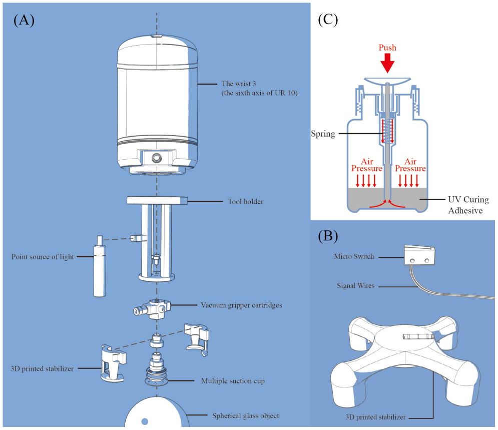


Figure 5
(A) End effector with vacuum gripper and 3D printed stabilizer. (B) Micro switch and a 3D printed base. (C) Plastic pump dispenser bottles.

MATERIAL STUDY

In this experiment, we emphasized the investigation of the material behavior of the UV curing adhesive, examining how it reacted with the hollow spherical glasses under a point source of light via a UV light device. The setup for this material experiment consisted of two components (Figure 4). 1) The UV glue used in this project was KIKAITO-TS01-A (applicable materials: glass, plastic, metal, and fiber; curing time: 10-20 seconds) with high bonding strength and excellent optical clarity. 2) The UV light device used to cure the adhesive in this project was ARK AWILL, which can be triggered by DC 24V via the robot's I/O. After several tests with the material and device, we found the proper curing time to be approximately 20 seconds.

VACUUM GRIPPER, MEASURING DEVICE AND UV CURING ADHESIVE EXTRUDER

In order to avoid deviation during the robotic aggregation (fabrication) process, the vacuum gripper installed on the end of robot needed to meet the following criteria. 1) An elastic suction cup was needed to grip and place each hollow glass with slightly different diameters. 2) The direction and distance of the vacuum cup needed to be restricted to stabilize the position of the spherical glasses while they were being gripped by the robot. The first criteria was met by using a rubber suction cup, and the second one was achieved by using a custom 3D printed stabilizer equipped around the suction cup (Figure 5a) to ensure that the suction cup could be stretched only slightly and in one direction.The measuring device shown in Figure 5b consisted of a micro switch with a 3D printed base located in the fabrication platform. This device mainly utilized a micro switch as a touch sensor to calibrate the diameter of each spherical glass. The UV curing adhesive extruder consisted of a plastic one touch pump dispenser bottle. The UV adhesive would rise to the surface instantly with one touch of the dispenser (Figure 5c).

DESIGN EXPERIMENT

In this paper, we designed a tower-like structure for the fabrication to validate the feasibility, accuracy, and limitations of the system. This design research used the spherical glass objects to highlight two important features. 1) Each spherical glass was not identical. They were around 60 mm in diameter with a deviation of ± 0.5 mm (Figure 6). 2) Because the material was transparent, it was difficult to accurately locate and obtain their actual size using vision recognition.

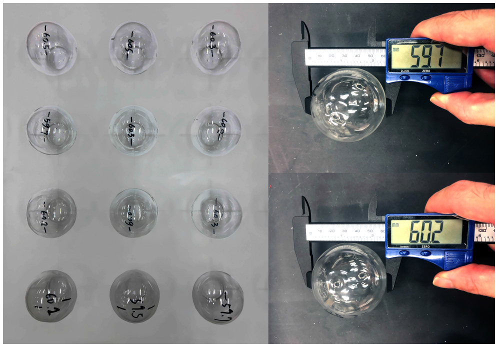


Figure 6
Hollow glass balls with deviations in their diameters.

Figure 7
Twisting tower constructed by aggregated spherical glasses.

During the design experiment process, each glass object followed two primary rules. 1) Based on the designed shape, the robot sequentially arranged each spherical glass for the assembly task. 2) Based on the stability of the structure, each object had at least one connection to the other, and none of them intersected with each other.

In this project, we designed a twisting tower constructed by aggregated spherical glasses (Figure 7). The following steps are the rules of creating it. 1) An ellipse was selected as a primitive geometry and then copied, rotated, and deformed along the axis to create a 3D twisting tower based on a Rhino and Grasshopper parametric modelling platform. 2) This twisting tower was then sliced into layers (the spacing of each layer was around 60 mm), and each layer was comprised of 11 spherical glasses arranged in specific places according to the desired pattern of the tower.

Regarding the stability of the twisting tower structure and the deviation of the spherical glasses, we developed algorithms (Figure 8) to ensure each spherical glass had at least one connection to another, and we also relocated the position of each spherical glass informed by the measuring sensor. For example, one of the spherical glass objects above the first layer is t1, the actual radius measured by the measuring sensor is r1, and Ga is the index of the layer where it belongs. The lower layer is G(a - 1), the upper layer is G(a + 1), and so on.

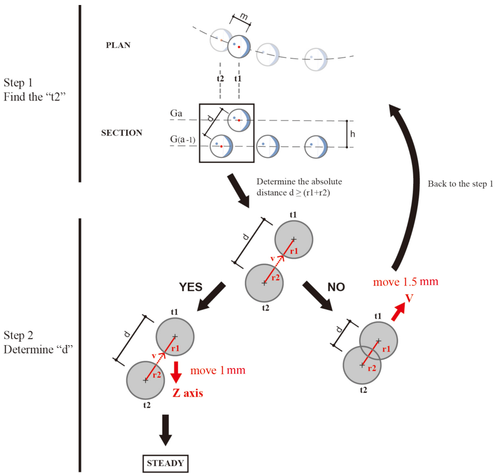


Figure 8
The logic of the algorithm.

Step 1. Find t2, the glass object which has the smallest distance from t1 in G(a - 1). The radius of it is r2, the vertical distance from t1 is h, and v is a vector from t1 to t2.Step 2. Determine whether the absolute distance (defined as d) between the centers of t1 and t2 is greater than r1 + r2. If Yes, t1 should gradually (1 mm at a time) be moved vertically downwards until $\hbar = \sqrt{[(r1 + r2)2 - m2]}$. If No, this means that r1 and r2 will intersect. Thus, t1 will be placed 1.5 mm from t2 in the direction of v. After that, the process returns back to Step 1. and recalculates t1 new position, This self-correction process is executed until each spherical glass object meets the conditions $d \geq r1 + r2$ and $h = \sqrt{[(r1 + r2)2 - m2]}$, which means it has reached a steady state.

CONCLUSION AND FURTHER STEP

Based on a series of experiments, this research project introduces a computational fabrication workflow for the development of the initial phase of a glass structure on a 1:1 scale assembled using hollow spherical glasses with ambiguous dimensions. The workflow mainly consisted of a continuous loop of object measurement, correction of the robotic path, and the UV adhesive curing process. The paper presents a pipeline that is suited for stacking spherical glasses and a robot target planning algorithm to generate a complex glass aggregate structure. Furthermore, this research is also aimed at the exploration of material aesthetics, include the material and immaterial effects of glass, such as how light, shadow, transparency, and reflection affect the perception of architecture. For the next step, the project aims at building larger and more complex stable geometries (such as arches, walls, etc.) through an intricate network of each spherical glass.

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