AUTOMATIC BRICK MASONRY SYSTEM AND ITS APPLICATION IN ON-SITE CONSTRUCTION

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Abstract. Although research on robotic brickwork assembly systems has long focused on the automatic assembly of bricks, most studies are conducted in the laboratory with refined environmental and material conditions. This paper presents the development and application of a novel robotic masonry system that directly confronts the challenges and constraints of on-site construction in a generic site in rural China, including low-quality bricks, thick mortar connection, and critical temperatures. The construction process includes site surveys, foundation construction, wall masonry, landscape construction, and ground paving. During the process, the robot’s arms are used for making formworks for the foundation and creating a pipeline for brick masonry, including printing mortar and brick tiling. A novel duel function end effector is developed to include the accurate printing of thick mortar, and the design is developed in consideration of the site condition and construction process.

Keywords. Robotic Construction; Brickwork assembly; Digital Design.

1. Introduction

Manufacturing industries have already been celebrating the progressing level of automation for decades, and the automobile industry is a prime example of such a trend, as the entire process from the production of single parts to the final assembly is often fully automated (Balaguer and Abderrahim 2008). However, architecture, especially on-site construction, is dragging behind. The building industry holds unique characteristics that make it difficult to apply an automated process compared to the other industries. In contrast to automobile manufacturing, where an established system automatically manufactures a standard piece repetitively, each construction site or project is drastically different and thus requires a great deal of customization for each project. Additionally, the different building standards, technical skills of workers, site conditions, and strict time and budget plans are making robotic automation fall behind in the construction industry, as there is no established or pre-existing reference that addresses a similar set of challenges. Currently, most fabrication still occurs in a controlled laboratory.
environment or an experimental project for exhibition or for the public that allocates abundant resources. In this paper, I present our latest research project—a brick labyrinth garden with robotic automated assembly—that brought lab research to a typical site in rural China. We also developed a workflow that adapts the technology to the design workflow in practice and a system to confront the raw challenges of construction practice in reality.

![Figure 1. Brick Labyrinth, Zhangjiako China, 2018.](image)

2. Background

As a self-contained subdomain of construction (Bonwetsch 2015), the process of brickwork assembly holds many positive features that are especially suitable for robotic automatic assembly. For example, the brick, as a basic component, is widely accessible around the world. The size and weight of a brick make it suitable for manipulation by robotic arms but labor intensive for workers. The assembly process of bricks is largely repetitive and thus easy to program into robots. Additionally, as a component-based assembly, architects with parametric tools can quickly iterate a range of dynamic forms. Owing to these positive features of brickwork, many pioneer researchers have established workflows and experimental projects with on-site robotic automation.

Utilizing robot automation for brick construction can be dated back to the late 1980s (Anliker 1988). Since then, decades of research have been conducted on the construction of straight walls, with a focus on unit labor and productivity in construction (Jesus and Utsav 2011). With the progress in digital design and parametric form generation in architecture, discussion on the robotic assembly process of brickwork has shifted to its potential as an accurate digital fabrication method and its adaptivity for complex nonstandard brickworks. The Gramazio
Kohler research group is the leading research team on this topic. Ever since 2008, their research lab has carried out numerous studies on the assembly system of nonstandard brickwork (Gifthaler et al. 2016), which has a great influence on the set up of our system. However, as technologically advanced as their robotic system is, because it was developed in an ideal laboratory environment in Switzerland, there are several issues restricting its direct application in an underdeveloped rural site in China. New solutions are developed to address these challenges.

3. Practical challenges

There are three key local challenges that need to be addressed when developing a new automatic assembly system for the committed project in rural China.

3.1. SELECTION OF BRICKS

In the work of the Gramazio Kohler research group, high standard facing bricks were selected as the construction material. Each brick was very consistent in size and quality. However, in the rural village site in China, there was only one brick factory in the region and it could only manufacture a low-quality, nonfacing brick. Nonfacing bricks cause many problems, not only because of their appearance but also because of their inconsistent size and uneven, nonflat surface quality that is porous and full of bumps. Such issues have a direct impact on the selection of mortars and the end effector of robotic arms. An end effector that uses vacuum suction to pick up the brick on the top was developed to accommodate the uneven and inconsistently sized bricks at different angles. However, it needed to be readjusted with a filtering plate to prevent the intense dusts from the low-quality brick from blocking the suction system.

3.2. SELECTION OF JOINT MORTARS

In the earlier references, thin mortar was used in most projects because the application of a normal mortar system is a complicated process that includes
placing surplus mortars and scraping out the overflows. Thus, using a thick, adhesive-based mortar instead of a typical cement-based mortar would largely reduce the time and effort required in this workflow. However, in practice, there is another key function of the thick mortar system. That is, the thick mortar system levels the uneven surface of the bricks. This is not a problem the lab experiments because high quality bricks were used. However, with the low-quality brick we were using, a thick mortar system became problematic, as the deviation in the bricks quickly accumulated as the layers increased, and very soon, the top surface of the wall became so uneven that new bricks would not level and would slip down frequently. Thus, we had to return to the typical thick layer solution and develop a system to include accurate in-place robotic printing or mortars combined with advance sensory perception. Owning to budget constraints, we used modified off-shelf mortar for the brick construction.

3.3. CONSTRUCTION ENVIRONMENT

One more challenge that greatly influenced the design and setup of the system was the construction environment. The construction site was located in a rural village near the 2022 Winter Olympics site, where the temperature easily drops below 0 degrees in winter and varies greatly on a day-to-day basis with strong wind. The onsite construction lasted from October 2017 to April 2018. Because the construction was constantly halted due to the extreme weather, an effective system was developed to facilitate the positioning and orientation of the robotic arms on site. Additionally, further material and structure study was conducted on the mortar printing system because the mixture has different material performance and may even damage the mechanical system in critical temperatures.

3.4. A COMPREHENSIVE PROJECT

As this project was an on-site construction of a real project, which differs from a research project where the goal is only to construct a wall, there were many more aspects to consider—for example, how to case the foundation to support not only the wall but also the robotic arm. Additionally, the placement of the robotic arm during construction was carefully studied because it could not be placed on the area that was designed to be plantation and could thus not cast a concrete foundation. What was the construction sequence so that the robotic arm would not be “trapped in” and build a wall around itself? What was the limitation on the vertical cantilever and curvature of the wall that the structure allowed based on the properties of the customized mortar? As the foundation casting, paving, and landscaping were constructed by local low-skilled workers, thus making human error inevitable, how were we to coordinate between the accurate robotic automation and the inaccurate handiwork of local workers and where were we to insert tolerance? The design and construction sequence progressed together, and the final outcome was an interplay of design intention, site restriction and the pragmatic requirements of the robotic automated construction process.
4. Technical Solution and Adjustments

To accommodate the challenges, we made technical developments in two main aspects:

4.1. DUAL-FUNCTION END EFFECTOR

To achieve accurate placement of the thick cement-based mortar, the end versatile effector was redesigned to integrate bricklaying with 3D mortar printing in one, thus achieving a pipeline for brick construction including uninterrupted brick placing and mortar printing. The automatic masonry system changed the typical clamps used for picking up bricks in robotic brick assembly to a vacuum, which could tolerate the slight variation in the sizes of the low-quality, nonfacing bricks and could lay bricks in variegated walls without collision. Meanwhile, with the same effector, the mortar could be printed in a more accurate manner to avoid excessive superflux that would require scrapping off later.

A vacuum lifter was used instead of the typical clamps for grabbing the bricks. As the touching region of the vacuum lifter was smaller than the surfaces of the brick, it required no buffer space around the brick, which clamps typically need, thus allowing the bricks to be laid in variegated walls with different tiling methods without collision. The filter was also added to the vacuum lifter to filter the dust from the low-quality bricks.

Additionally, to accommodate the large deviations between each piece, a distance sensor was added to scan the top layer of the piled bricks to calibrate the print path of the following layer. Thus, before printing the mortar of each layer, the extruder moved along the expected path on the top and measured the distance along the top. The measurements were accumulated and evened out for the most appropriate height of the mortar printer.

4.2. INTEGRATED SYSTEM DESIGN

To coordinate such a complicated mechanical system and plan for its use in the construction process, there are three systems in the integrated system that run parallel and are controlled by a central controller; which coordinates the inputs from the control and sensor, processes commands and sends out signals to the three mechanical systems. The first system controls the robotic arm, and the control of the movement comes from the motion planning in Grasshopper based on the geometry of the wall. The second signal controls the mortar-printing system, which includes the control of the external mortar pump that pumps the mixture and the motor head that starts and stops the printing. The last system is the brick-lifting system, which mainly consists of an air pump, an air tube and a brick lifter. The brick-lifting head is controlled by the air pump receiving an on/off signal from the central control.
Figure 3. End-effector Design.

Figure 4. System Design and Workflow.
5. The Process

The following presents the comprehensive workflow from design to construction. This provides a reference that is adaptable for a broad variety of real projects that utilize robotics in construction.

5.1. SITE CONDITION

The garden is located in Wujiazhuang Village (Dingfangshui, Xiahuayuan, Zhangjiako), a village featuring brick buildings specially designed for the 2022 Winter Olympics. The village owns the only brick factory in the neighboring area, so red bricks have been used widely in the renovations as construction materials and decoration in recent years, making the village famous in Zhangjiakou. The garden is located in a triangle site near the entrance of the village. After its completion, the garden became a place for villagers to gather and relax.

5.2. CONCEPT OF DESIGN

The base of the garden is a circle with a diameter of 13 m with irregular carved areas. Three winding brick walls laying on the circle form continuous drapes in the plan and adopt a curved form in the vertical direction as well. With more changes in the bricks’ position and angles, these walls form a labyrinth both visually and spatially. Bamboo and grass are planted in the outer area of the curved walls, while the inner space is designed for the villagers’ activities, which presents the relationship of Chinese Yin and Yang in relative complexity.

5.3. FORMAL GENERATION

The design of the garden is based on digital generation technology. First, a curved shape was generated in Rhinoceros. The shape, is like a flowing ribbon, and the shape of the surface was optimized to ensure that it met the basic requirements of circulation flow, human scale, and the construction sequence plan of the robots. The base curve was then introduced into Grasshopper to arrange the bricks. We extracted curves in a series of profile heights of the surface as the reference lines for each row of bricks and then divided the lines to arrange the bricks and ensure a staggered position in adjacent rows. Finally, we used additional reference lines to generate changes in the bricks’ positions perpendicular to the surface, making gradient patterns on the curved surface.

5.4. ROBOTIC PATH PLANNING

After the digital model of the brick walls was generated, the design team designed the robotic arm’s path of movement in combination with the construction method and used KUKA|PRC to export it as program codes recognizable to the robotic arm. The process included picking up bricks by vacuum lifters, releasing bricks in designated positions, flipping the tool to print the mortar and printing the mortar according to the designed path. The codes also integrated commands for external devices such as air pumps that were issued by the robotic arms’ IO module and passed the obstacle avoidance test in simulation. After simulation in the program, the PRC exported the program for the robotic arm execution so that we could
achieve accurate conversion from the digital model to the actual building. To meet the schedule of the project, multiple robots participated in the construction to meet the deadline. The paths and locations of the robots were meticulously planned and synchronized to avoid collisions and interference with the working path.

Figure 5. Project Plan.

Figure 6. Lab Testing of the Planned Path and the Automatic Brick Assembly System.

5.5. SIMULATION

There were two robotic arms working together in the construction process: the KUKA KR210 with an arm length of 2.7 m and the KUKA KR120 with an arm length of 3.9 m. The positions for construction and their procedures were designed to maximize the efficiency of this automatic system and avoid any collisions between the robots and the walls or between the robots themselves. The two
robotic arms were moved 7 times to complete the entire process, and each course was simulated in the PRC program. The result of such simulations also gave feedback on the initial form-finding process to increase construction efficiency.

5.6. DESTRUCTION TEST
In the experimental phase, a brick wall damage test was also carried out to test whether it reached the standard of the design and construction specifications of the brick walls. We used different types of mortar according to the environment temperature to satisfy the demands of both winter and summer construction and so that the fluidity and early strength time of the mortars could met the requirements of 3D printing. The mortar used no.425 cement, while the water-cement ratio was approximately 0.7 and the mortar strength was up to 45 MPa. After the maintenance period, sandbags were used to destroy two experimental walls, and their strength was up to China’s specified standards.

5.7. CONSTRUCTION
The construction process includes measuring, foundation construction, wall masonry, landscape construction, and ground paving. After we used the total station to measure the site, we used the robotic arm to cut 30 cm-thick foam blocks to make molds for the outer curved green area and poured reinforced concrete inside the forms to make a slab for brick walls and activity areas. The masonry process with the smart construction system required at least two workers. One of them operated the system, and the other moved mortar and bricks. A forklift was used to move the robotic arm to the designated positions. To ensure construction precision, robotic arm positioning calibration was conducted after each movement. After the completion of the walls, we removed the surrounding foam and refilled the soil; we plan to plant grass and bamboo in the future. Concurrently, inside the wall, hollow bricks were used to pave the garden.

![Figure 7. Construction Site.](image-url)
6. Conclusion

Onsite construction poses a different set of challenges for robotic automation. Instead of the development and optimization of a system to solve universal problems, developing a system for onsite construction for real projects requires the system to be able to accommodate local challenges and constraints. In this paper, we present a set of challenges that are very specific to rural China and the method developed to address such issues. However, even though the technical solutions are specific to this project, the overall project workflow and framework are applicable to many other projects that utilize robotic automation for on-site architecture construction.

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