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From Concept to Construction

A Transferable Design and Robotic Fabrication Method for a Building-Scale Vault

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1

1 The full-scale glass *LightVault* displayed at the "Anatomy of Structure: The Future of Art & Architecture" exhibition at Ambika P3 gallery in London, UK

ABSTRACT

The *LightVault* project demonstrates a novel robotic construction method for masonry vaults, developed in a joint effort between Princeton University and the global architecture and engineering firm Skidmore, Owings & Merrill (SOM). Using two cooperating robotic arms, a full-scale vault (plan: 3.6 x 6.5m, height: 2.2m) made up of 338 glass bricks was built live at the "Anatomy of Structure: The Future of Art + Architecture" exhibition. A major component of the project was developing a fabrication method that could be easily adapted to different robotic setups since the research and prototyping, and final exhibition occurred at locations on different continents. This called for approaches that balanced the generic and the specific, allowing for quick and flexible construction staging and execution despite the variability associated with building in a new setup (i.e., varying robots, material, and scale).

The paper is structured as follows. First, we introduce the notion of transferability in robotic construction and then elaborate on this concept through the four major challenges in the LightVault project development: 1) prototype scalability, 2) end-effector design, 3) path planning and sequencing, and 4) fabrication tolerances. To develop and test solutions for these challenges, we iterated through several prototypes at multiple scales, with different materials for the standardized bricks, and at three distinct locations: Embodied Computation Lab, Princeton, US; Global Robots Ltd., Bedford, UK; and Ambika P3 gallery, London, UK. While this paper is specifically tailored to the construction of masonry structures, our long-term goal is to enable more robotic fabrication projects that consider the topic of transferability as a means to develop more robust and broadly applicable techniques.

INTRODUCTION

The last ten years have seen significant growth in the use of industrial robots (IFR, 2018). In the architecture and construction fields specifically, robotics is most commonly applied to the prefabrication of building elements. However, the disadvantage is that prefabrication cannot occur for structural and material expressions that can only be assembled in-situ (e.g., masonry vaults (Davis et al., 2012), cast-in-place concrete structures (Echenagucia et al., 2018; Veenendaal & Block, 2014), and sequentially designed structures (Bruun et al., 2020; Parascho et al., 2017)). We believe that more emphasis on developing generalized and transferable on-site methods is necessary to achieve the goal of widening the applicability of robotic fabrication in the construction industry.

On-site robotic technology was first introduced to the construction industry with a patent for an automated bricklaying robot in the early 20th century (Thomson, 1904) and a working prototype of such a machine in the 1960s (British Pathé, 1967). However, the building sector has generally benefited much less from robotic technology than other fields like the automotive (Bock, 2015). Some reasons for this latency in adoption are as follows:

- Technical Challenges: further advancements are necessary in areas such as sensing, path planning, spatial navigation, and communication to ensure a smooth workflow on-site (Petersen et al., 2019)
- Managerial Considerations: efficient and robust robot-human coordination is required to form a safe building environment while maintaining an economic distribution of tasks and decision-making structure between human and robot teams (Cao et al., 1997; Fong et al.,2003; Kangari, 1985; Yokota et al., 1994)
- Design Philosophy: robotic fabrication processes are often designed for niche applications, so it can be challenging to adapt techniques for broader applications.

This paper addresses the last point by starting a conversation on how a robotic fabrication process can be designed from the outset to consider broader applicability over specificity. The concept of transferability for a robotic fabrication process is a measure of how readily it can be adapted to alternative sites and setups with little adjustments. In general, a transferability-oriented design paradigm is desirable to facilitate the broader adoption of new methods in the construction industry as design possibilities are calibrated to the process rather than a specific setup or site. This emphasis on generality will help bring robotic arms from a prefabrication factory environment to construction sites and enable more freedom in architectural articulations.

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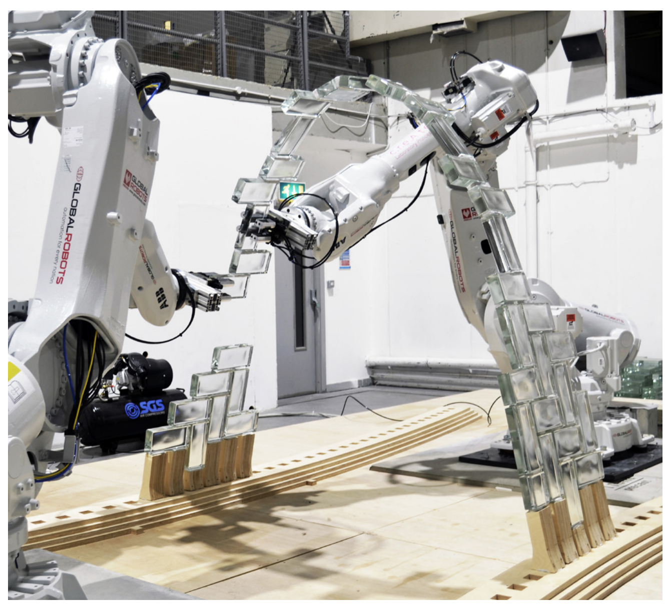

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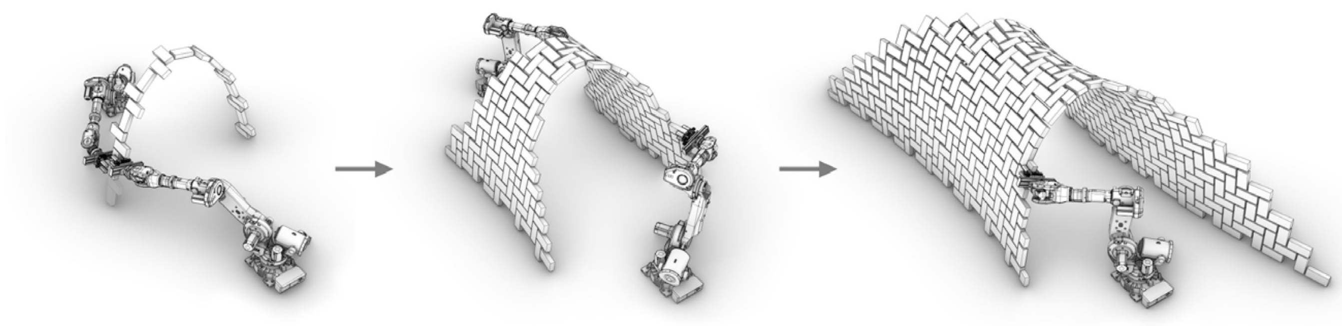
2 Robotic arm placing new brick onto the vault's side extension

3 Middle arch construction



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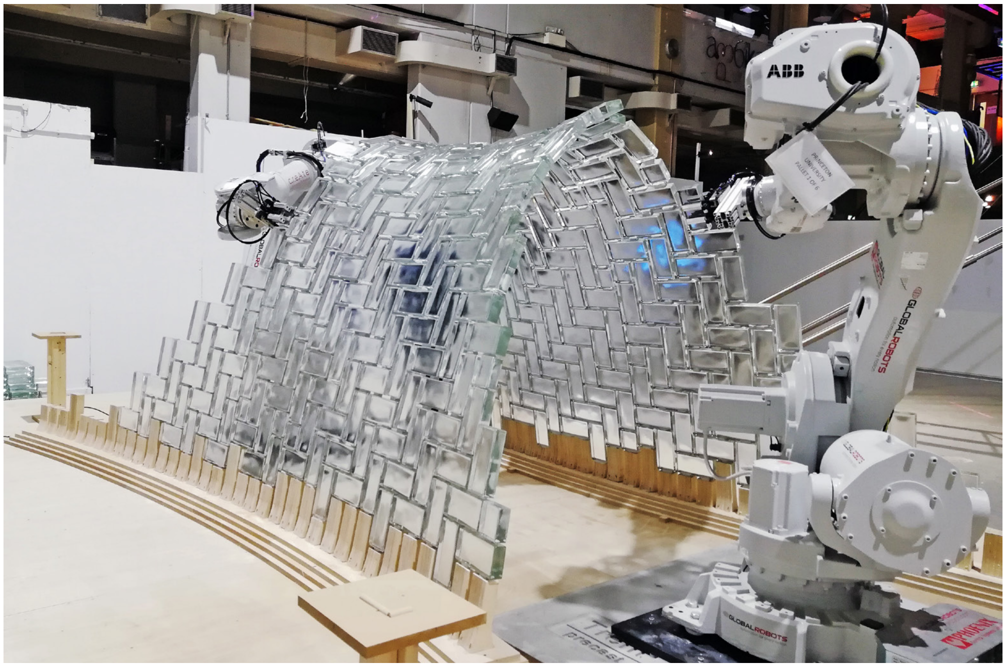
The proposed method is discussed in the context of *LightVault* (fig. 1) – a building-scale robotic vault where industrial robotic arms alternate between placing bricks and supporting the structure to eliminate the need for form- or falsework (Parascho et al., 2021). This structure was developed with the specific intention of being built robotically with different construction setups because the nature of the project was such that the development lab, testing site, and exhibition space were all in different locations and partially unknown at the onset of the project. We identified the four following considerations as essential to developing a fabrication method that would achieve this goal: 1) prototype scalability, 2) end-effector design, 3) path planning and sequencing, and 4) fabrication tolerances. The following sections present a general discussion of transferability in the context of these features with specific examples of their implementation in the *LightVault* project. Based on this specific project experience, the scope of the proposed methods is constrained to large-scale robotic assembly processes for vaulted structures.

BACKGROUND

Robotic construction of masonry structures was first performed at the architectural scale in the Gantenbein Winery project, where robots were used to construct the undulating brick walls of the structure (Bonwetsch et al., 2006; Bonwetsch & Kohler, 2007). The *LightVault* project builds on this methodology by using standardized construction units, but breaks from the layered vertical construction approach to build a spanning masonry structure out of glass bricks.

Discrete element assembly projects that feature three-dimensional geometric complexity often achieve it through a high level of customization on the local scale (i.e., customization of individual building units is used to achieve complexity globally). For example, in the field of glass construction, Gustave Falconnier patented an interlocking construction system using blown-glass bricks that could be used as building blocks (Falconnier, 1886). Other examples of customization on the local scale are seen in spanning masonry structures such as the Armadillo Vault (Block et al., 2018; Rippmann et al., 2016), or in drone-assisted construction of structures (Goessens et al.,2018) as a way to ensure interlocking behavior between units.

Over the past decades, advancements in robotic technology and architectural expression have constantly influenced each other. While novel robotic tools have stimulated new masonry expressions (Bonwetsch et al., 2006; Dörfler et al., 2016) and functional performances (Abdelmohsen et al., 2019) in architecture, masonry construction in return also informed the development of corresponding robotic fabrication processes and machinery (Piškorec et al., 2018). The introduction of integrative design methodologies suggested the co-development of the design formulation, material experimentation, and robotic fabrication strategy to accelerate the iterative progression between tool and design (Parascho et al., 2015). However, tools and techniques developed in such a manner may face difficulties due to over-specialization when applied in contexts outside their original intent. Therefore, a balance between generality and integration is desired in developing a transferable robotic fabrication method.



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4 Concept diagram showing the distinct construction phases: middle arch (a), strengthened middle spine (b), and full vault (c)

5 Perspective view of final glass *LightVault*

METHODS AND RESULTS

The following chapter will discuss four considerations that are essential in developing a highly transferrable fabrication method. A general discussion of transferability in the context of these features is followed by specific examples of their implementation when developing the *LightVault* project.

Prototype Scalability

Developing new construction methods using robots requires the design team to explore the full range of limitations and abilities of a selected robotic setup for a particular site condition. During the development stages of a robotic fabrication project, it is necessary to verify and solve technical challenges before attempting large-scale construction. As such, it is advisable to aim for a scalable design that does not compromise the overall intent – it allows for both a robust prototyping strategy and final adjustment on site. In *LightVault*, the structure itself was materially efficient since the shell was form-found to exhibit membrane behavior once fully constructed. The membrane stresses from self-weight in the final state were far below the glass bricks' strength; thus, it was the stability during construction that governed the design. This meant that explorations of stability as a function of sequencing, tessellation, and connection methods could be performed at the smaller scale and then applied to large-scale prototypes.

The development of the *LightVault* project began with three small prototypes built with two UR-5 robots; these prototypes were used to develop the construction sequence logic (i.e., brick tessellation and placement order) and the overall feasible shape based on the robot's position and overlapping reach volume. The next set of prototypes, constructed using two ABB-4600 robots, assessed the overall structural performance at the intended building scale. Figure 4 shows schematically how the final vault was planned around a phased construction approach – alternating segments of the vault were built while maintaining both global and local stability at each phase without the need for temporary scaffolding (for further information on developing a scaffold-free cooperative assembly sequence see Parascho et al., 2020). The project was then rebuilt with a new setup using two ABB-6640 robots at the final exhibit location. A test construction was first performed at Global Robots Ltd., Bedford, UK, where the grippers and pneumatic systems assembled and tested within ten days. The final *LightVault* structure was then assembled live at the "Anatomy of Structure: The Future of Art + Architecture" exhibition in London, UK. Unfortunately, the construction of this final vault was cut short due to the COVID-19 pandemic.

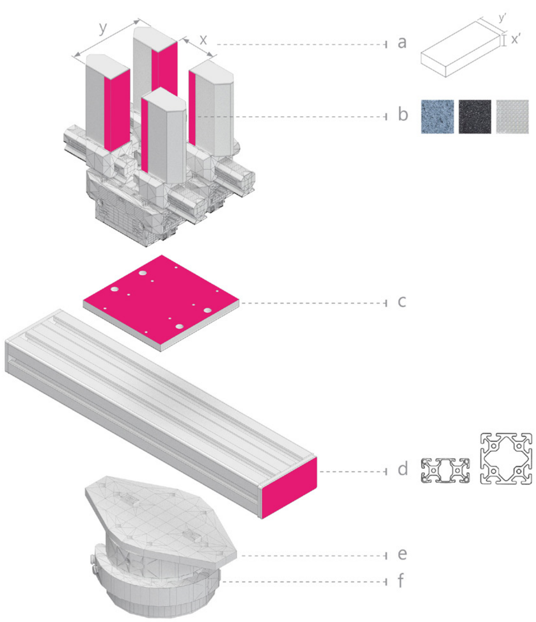
In building the *LightVault* at Ambika P3 gallery in London, we encountered few space and access limitations for on-site masonry construction. Whilst the floor construction was solid reinforced concrete, the gallery operators stipulated that there should be no structural anchoring to the floor, which meant we had to design the robot bases and the arch floor framing with this in mind. The need to prevent movement of the robot bases was of crucial importance. Each robot was bolted down to a relatively heavy (1.8t) reinforced concrete base that was strategically arranged to align flush with the arch plinth. The base design was optimized to resist over-turning, with appropriate factors of safety against the worst-case loading scenarios throughout all building stages. Using conventional timber sections and plywood flooring, we created a raised platform to ensure that the floor was leveled and that the robot arms with attached grippers could reach all areas of the proposed arch geometry. All power cables and air lines were concealed below the floor frame, eliminating potential trip hazards for the operators and ensuring a clean and clutter-free site. Each of these components was developed to be simple to piece together and dismantle, and with sufficient tolerance for a fast in-field and on-the-fly setup.

End-Effector Design

In contrast to a custom-built robot, a robotic arm is a generic tool whose application is mainly defined by the attached end-effector. As such, the end-effector design is crucial in determining what types of material manipulations are possible, which in turn shapes and defines the construction procedure. While more complex material processing such as welding and 3D printing might suggest bespoke end-effectors, over-customization should be avoided as it can result in low overall transferability of the project. Designing an adjustable end-effector that is independent of the robotic system and can accommodate different materials and dimensions has proven advantageous for applications in different environments.

The grippers designed for *LightVault* consisted of a combination of standard products (fig. 6 a, d, f.) and customized interfaces (fig. 6 b, c, e.). Standardized SCHUNK PGN, fingers, and optional quick changers simplified the overall process of assembling new grippers at different sites. Their design also made them transferable across projects as they were easily adjustable for use with construction units of different dimensions and materials. Specifically for *LightVault*, the grippers were designed based on the following fabrication-related requirements:

- The finger spacing (fig. 6 x) shall be constrained by the precision tolerance and gripping power associated with the proposed fabrication method – too narrow a gap between finger spacing and brick thickness (fig. 6 x and x') can cause collisions, while too wide a distance can result in insufficient gripping power.
- The fingers (fig. 8 a-c) shall be longer than the half brick width (fig. 8 b-m) plus tolerance gap (fig. 8 a-b) to



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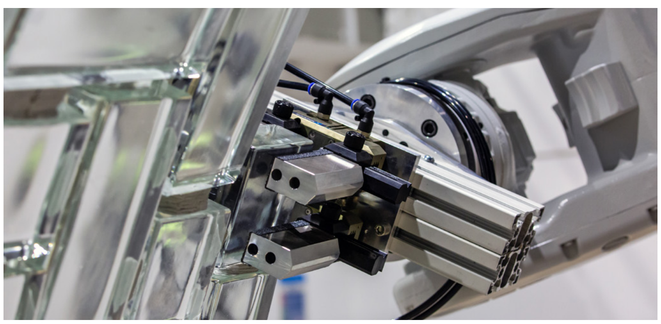

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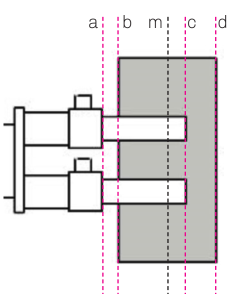

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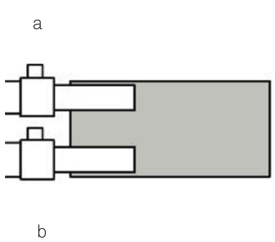

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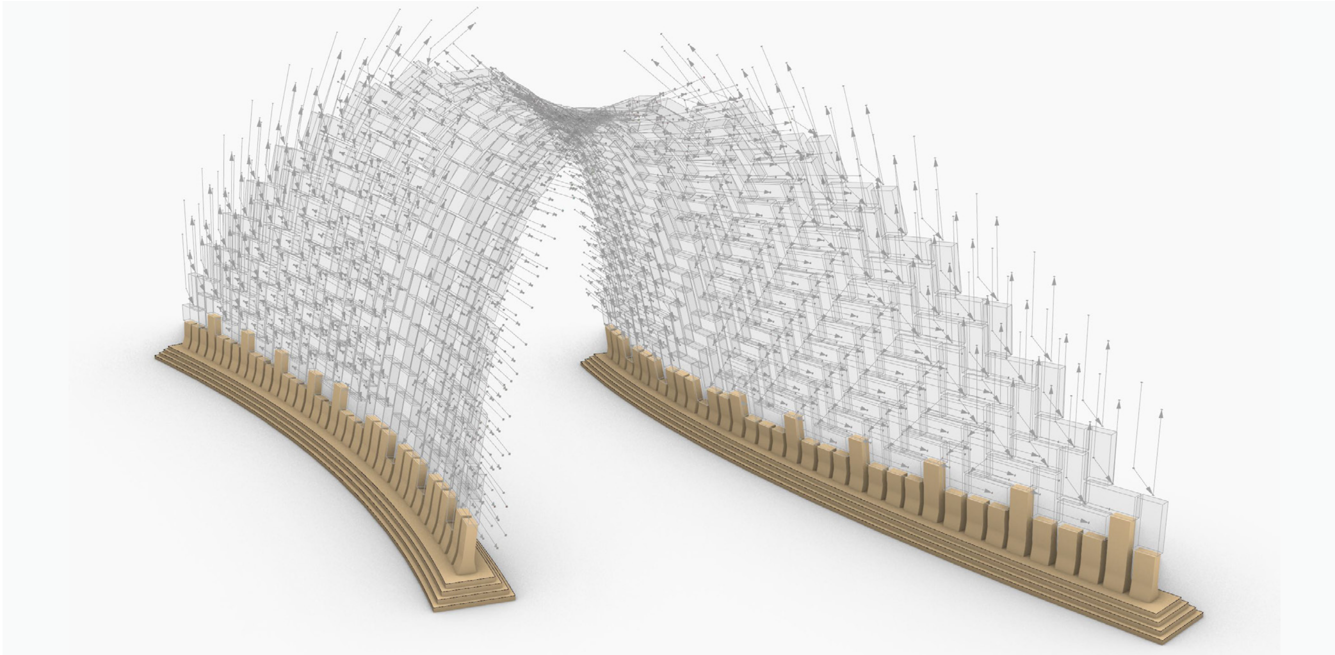
6 Exploded axonometric projection of customized gripper showing: adjustable fingers (a), replaceable finger surface (b), customized plate between finger and extrusion material (c), optional aluminum extrusion to extend reach (d), and quick changer and corresponding plates (e & f)

7 End-Effector detail

8 End-Effector dimensional constraints: finger base (a), brick's inner edge (b), brick's middle line (m), finger tip (c), and brick's outer edge (d)

9 End-Effector with asymmetric pneumatic component distribution: the side with pneumatic extrusions (a) and the unobstructed side (b)



10 Parametric path planning for brick placement

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prevent eccentric loads caused by off-centered gripping. However, long fingers that exceed the brick's outer edge (fig. 8 d) should be avoided due to collision risk between the finger tips (fig. 8 c) and existing vault structure.

- The distance between the two pairs of fingers (fig. 6 y) shall be as wide as possible for stable gripping without exceeding the brick's width (fig. 6 y', fig. 8 b-d) to allow the brick to be picked up in different orientations.
- The pneumatic components shall be oriented in such a way that one side of the gripper is left unobstructed (fig. 9 b), which is necessary to avoid collisions in precise placement operations.
- An extension element (e.g., an aluminum profile, fig. 6 d) can be used to prevent collisions in cases where the industrial robot's wrist joint is at high risk of hitting neighboring bricks during construction. However, too long of an extension is not advisable as it results in higher chances of collision during movements and more considerable instability caused by robotic arm deformation.
- The gripper finger surface (fig. 6 b) shall be selected based on the type of brick material used for desired performance (e.g., sandpaper with timber blocks or rubber-based tape with glass bricks).

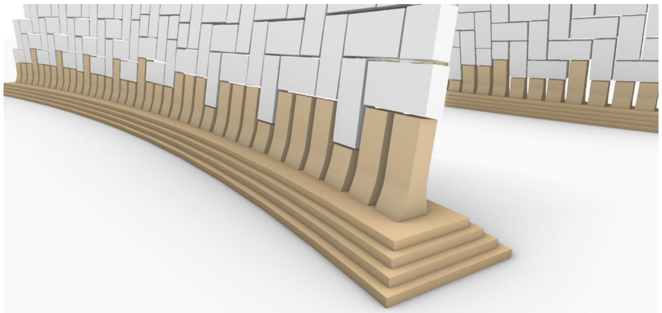
The design of the proposed end-effector is flexible due to its modularized components. We were thus able to use the same end-effector for wooden, concrete, and glass (both textured and glossy) bricks with minimal adjustment.

Path Planning and Sequencing

Defining the assembly and path planning process parametrically, rather than prescriptively, improves the adaptability of the robotic construction process for complex geometries. But for a construction method to be transferable and robust, it should also take into account that robots are well-suited for a process with repetitive tasks. Therefore, the ideal approach is one that calculates movements parametrically where needed (e.g., for intricate 3D geometric areas) and relies on predefined repetitive movements otherwise.

In *LightVault*, the bricks were added to the vault following an overall diagonal stepping sequence, which was established to maintain global structural stability (Parascho et al., 2021; Parascho et al., 2020). Since the general construction sequence was based on growing the vault outwards from the central arch, this allowed for more space to maneuver the robots around the structure without collision. Only when approaching the structure for the final brick placement was it necessary to generate a precise movement path parametrically. This process involved assessing the nearest neighbors for a new brick being placed into the structure and then calculating either a diagonal or orthogonal insertion vector to best avoid collisions with the existing structure.

In contrast to the parametric paths determined for the insertion movements, the pickup location and associated motions were discretely categorized based on the brick type (half and full bricks) and gripping orientation (from the



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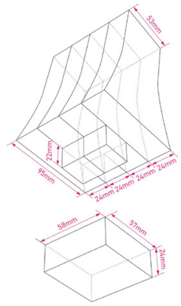

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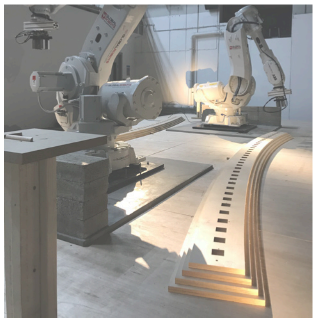

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11 Base shoes

12 Axonometric drawing of one base shoe element showing tenon and oversized mortise connection detail

13 Base platform setup

14 Slip test with 35kg weight at Global Robots Ltd., Bedford, UK

15 Middle arch pre-final test at Global Robots Ltd., Bedford, UK

shorter or longer edge of brick). The robot went through a fixed transition pose before moving on to the parametric insertion path steps. Making such repetitive movement explicit from a path-planning perspective greatly simplified the computational component of the project. It also gave the user more control over the robot configurations, which helped mitigate the risk of unexpected collision and robotic singularity errors.

In summary, this hybrid path planning approach allocates computational efforts in areas where it's most needed (i.e., around final brick placements) and uses predefined discrete paths in less critical zones (i.e., around pick up station and areas away from the structure). This hybrid approach was computationally efficient and highly predictable from the perspective of human operators, which is particularly important when developing methods that will be transferred to different robots with different kinematic behavior.

Fabrication Tolerances

Differences between the simulated and physical setups are inevitable in any robotic fabrication project. While certain systematic errors can be corrected when working with a constant setup, this is not always possible when a project is applied to a new setup. Therefore, including a certain level of fabrication tolerance as a design feature is a robust way to improve a project's transferability.

To construct *LightVault*, we developed an adaptive mechanism for both the brick-to-brick connections and the vault foundation base. We used a flexible epoxy putty and acrylic shims to account for the different gap sizes and connection angles between the bricks. The epoxy putty was manually mixed and placed by a human, and acrylic shims were additionally used in larger gaps to shorten epoxy curing time and lower material cost. In the final placement step, the robot would move the brick into the correct location, compressing the malleable epoxy layer into the best fitting position, forming a solid connection between bricks.

While the epoxy-shim connection absorbed local-scale imprecision, a series of uniquely designed base shoes offered global-scale tolerance for the entire vault (fig. 11). These base shoes connected the bottom row of glass bricks with the ground. The tenon and oversized mortise connection (fig. 12) allowed the base shoes to slide freely in all directions before being anchored with screws into the floor stacks (fig. 13). The base shoes were prefabricated from high-quality birch plywood with CNC routers.

We performed a few tests before initiating the final construction to assess whether the robotic tolerances were small enough to be absorbed by our construction method (i.e., offsets less than 5mm). Gripping strength, brick slipping behavior, robotic deformation must be checked when a new setup or building unit is adopted. The key parameters for the *LightVault* were: (1) evaluating the load capacity of the robots and grippers, (2) guaranteeing deformations in the setup were minimized and did not lead to collapse during construction.

16 *LightVault* constructed live during “Anatomy of Structure: The Future of Art + Architecture” exhibition at Ambika P3 gallery in London, UK 16

With respect to the load that the robot would support, the critical stage was reached in the second-to-last step before completing the middle arch (fig. 16). At this point, one robot was required to support a load of 32kg, corresponding to 30% of the partial arch’s weight, while the other robot picks up and inserts the last brick to complete the arch.

Several tests were carried out in advance to assess the gripper's ability to hold the required peak load without slip. We conducted these slip tests by hanging a weight on a glass brick that was being held by one robot, as shown in Figure 14. We identified the air pressure under which the grippers operate to be a significant factor: a minimum air pressure of 7 bar was needed to withstand the required load with no slippage. Therefore, speed of construction, air-tight connections with no leaks, and air compressor restart/recharge pressure became essential aspects in the construction sequence planning.

With respect to deflections in the setup, the base structure stiffness and deformability of the robot arms were of paramount importance for global stability during the temporary construction stages of the central arch. As a robot releases a brick, there was an instantaneous shift of load from one gripper to another as a new equilibrium configuration was reached. During this dynamic load shift, a deformable base or excessive deformations of robot arms under sustained load may cause vibration, which could compromise the structural stability.

CONCLUSION

This paper provides a basic framework for developing robotic fabrication projects which are to be executed at different construction sites and using varying setups. The *LightVault* is an example of such a project, with construction occurring in various locations: several small and large-scale prototypes in Princeton, followed by a test fabrication at the robot factory in Bedford, and the final vault built at a live exhibit in London. This project aims to start a discussion on how to make on-site robotic fabrication more accessible to the construction industry. By invoking a transferability-focused design philosophy and without reverting to using custom, expensive, and time-consuming robotic manipulators, a robotic fabrication project can be explicitly designed to be adaptable to different setups. In developing the *LightVault* project, we found the following to be important considerations: scalable prototypes, end-effector design, path planning and sequencing, and robotic fabrication tolerances.

Future research will aim to expand the design space of cooperative robotic processes and generally increase the accessibility of robotics in construction. For example, mobile robots could be coupled with stationary industrial robotic arms to expand the application range of cooperative processes to larger fabrication spaces and more complex geometries (i.e., more intricate construction sequences would be possible with an additional robotic agent). To improve the transferability of robotic processes, we aim to address the main challenges that we encountered, namely unpredictable inaccuracies and difficulties in path-planning with a new setup through feedback systems (e.g., force or visual). This information, coupled with results from a structural analysis framework, could be used as the basis for dynamic adjustments to the design and fabrication process to guarantee stability and buildability during construction.

Another approach is to address the used robots themselves by developing new industrial machines based on modularity and standardized components with the potential to customize. Providing easier access to more adjustable machines, rather than more specific ones, could strongly impact the future scale at which robots are employed in architecture and construction. Even though designing and constructing custom robots is an active research field, striving for generality through modular, but still ensuring availability through standardized systems, would simultaneously provide more freedom of construction and easy implementation and operation.

Similar to hardware requirements, we believe that finding the balance between customization and general validity is key for all software components of a fabrication process. Thus, developing new overall design, structural analysis, end-effector design, and robotic control tools that provide a base of knowledge but allow for quick adaptability is crucial for the successful transferability of robotic fabrication methods. As we experienced firsthand through the COVID-19 shutdown, being able to quickly react to unexpected changes even during the construction process is not only helpful, but a necessity to ensure that fabrication processes are successfully advanced.

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IMAGE CREDITS

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