Augmented Bricklayer: an augmented human-robot collaboration method for the robotic assembly of masonry structures

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Abstract. The *Augmented Bricklayer* research project proposes a new augmented human-robot collaboration method for the robotic assembly of masonry structures. It aims to resolve the conventional limitations of the robotic bricklaying process by incorporating object recognition and Augmented Reality (AR) technologies. Towards this aim, we present a human-robot collaboration method consisting of two phases: a) the object recognition phase, in which bricks are recognized by a point cloud scanning sensor and analyzed by our calibration system as a feeding object for the robotic gripper to pick; b) the augmented human-robot collaboration phase, in which the masonry adhesive is being applied manually assisted by AR holographic guidance and gets assembled by an AR-assisted robotic operation method. The validation of our method is achieved with the robotic assembly of two real-scale building elements, a masonry column and a wall. Our findings highlight a more flexible, efficient, and convenient AR-assisted human-robot collaboration bricklaying method capable of dealing with complex on-site construction requirements.

Keywords: Mixed Realities (Augmented Reality), Object Recognition, Human-robot Collaboration, Robotic Assembly, Masonry Structures

1 Introduction

Recent approaches to digital fabrication, combing methods of computer-aid design (CAD) and robotic fabrication, have shown great potential for integrating architecture design and engineering practices to establish a highly effective interplay between digital design and conventional construction process (Dörfler et al., 2016). Additionally, CAD computational tools such as *Grasshoppe*r expand access and exploration of nonlinear parametric design solutions for architects, which means the complex design-oriented shapes require the assistance of industrial robotic fabrication methods to achieve precise construction (Adam et al., 2019). Over the past decade, many digital fabrication applications have proved that the architectural industry stands to benefit tremendously from increased digitization and automation (Carra et al., 2018).

Bricks are standardized, prefabricated building components, which have been used in architecture since the ancient times of building construction history. Over time, the evolution of their design and construction methods never ceased to stimulate architects to explore their aesthetic potential (Kahn and Twombly, 2003). Brick masonry structures are ideal candidates for automated assembly, as they remain a complex and dexterous construction craft, traditionally performed by trade specialists. Bricklaying is fundamentally a repetitive process and is therefore well suited for robotic fabrication, which could increase its efficiency and assure complex traditional or novel brick constructions in a moment of scarce skilled labour (Oliveira and Sousa, 2016). Moreover, CAD computational design tools can support architects in the tectonic exploration of parametric and nonlinear brick structures. These CAD-designed parametric brick structures surely need the precise and efficient help of the automated bricklaying process.

Robotic automation displays advanced potential, but its application in real construction projects is still limited (Dawod and Hanna, 2019). The robotic automated bricklaying process currently lacks practical and flexible on-site construction solutions, regarding brick feeding systems, and spatial operation freedom, or includes messy usage of automatic mortar adhesive application on-site (Mitterberger et al., 2020). Mitterberger et al. proposed the AR guidance for manual bricklaying, but the AR-assisted manual bricklaying system lacks the accuracy of robotic operations. Additionally, there is a shortage of end-to-end solutions between architects and automated construction methods. The data is not shared in real-time, which means architects and engineers cannot operate or deal with each other's errors during the automation process because of different knowledge backgrounds.

The upper-named limitations may be eliminated by applying object recognition and AR technologies and setting up a human-robot collaborative bricklaying process. As Papazov et al. (2012) presented, using point cloud data generated by computer vision cameras provides robots with the ability to reference objects. Moreover, human builders are more flexible than programmed robots in dealing with on-site uncertainties, while robots are more efficient than human builders by keeping their accumulative error at an acceptable level (Sun et al., 2018). Digital fabrication tools can never fully replace the role of humans in construction processes, which means human-robot collaboration can flexibly solve unanticipated difficulties that cannot be solved by pure automation (Yoshida et al., 2015). Additionally, AR technology provides non-professionals with the possibility of visual programming robots with its object-attached holograms and convenient interactive input functions, which could bridge the gap between humans and robots (Song et al., 2021).

This paper proposes an augmented human-robot collaboration method by combining the above unique characteristics and functions of object recognition and AR to discover how these technologies are changing and evolving the current shortcomings of the automated bricklaying process in architectural construction.

2 Research Methodology

The *Augmented Bricklayer* research project proposes an augmented human-robot collaboration method for the robotic assembly of parametric masonry structures. The method consists of two phases: a) the object recognition phase and b) the augmented human-robot collaboration phase (Fig. 1). To validate this method, we conduct an assembly experiment, which includes the object recognition and augmented human-robot collaboration for assembling an architectural scale masonry column and a wall, to evaluate our proposed method as well as evaluate the advantages and disadvantages of each phase. The prototype structures were assembled with the Class B red engineering bricks (215*103*65mm with 2.33kg each), which are suitable for sensors to recognize, and able to be picked and placed by the robotic gripper. Considering the laboratory environment, we adopt the hybrid polymer adhesive as the brick mortar, which is fast curing with high strength and easy to apply with a standard mastic sealant gun.

The software includes *Rhinoceros/Grasshopper*, the *Xbox Kinect* sensor toolkit *Tarsier* and the AR toolkit *Fologram* plugin for object recognition and calibration, as well as the *Robots* and *Fologram* plugin for the augmented human-robot collaboration. We use *Tarsier* to connect and get the point cloud data, RGB and depth data from *Kinect* sensor in *Grasshopper* for further analysis by our calibration system; *Fologram* to scan *ArUco* Marker (AM) for alignments and provide AR holographic guidance for manual fabrication and identify interactions for operating robots in the human-robot collaboration process; and *Robots* to develop and operate the robotic trajectory and gripper commands.

The hardware includes a *Kinect* sensor for point cloud scanning, a head-mounted device (HMD) – *Microsoft HoloLens 1* for augmented human-robot collaboration, and a *Universal Robots 10*e robotic arm with *Robotiq 2F-140* grippers for the robotic equipment. We fix the Kinect sensor to the top of the gripper by designing and 3D printing the connecting joint structures. Additionally, we use a laptop for back-end program running and debugging. All the devices are connected to a wireless WIFI router (data transfer rate - 50MBps) in the same IP address network environment for transforming the data from different stages, and live streaming commends on software and plugins to visualize and output response ports.

Our original contribution is to integrate and combine the different functions from various plugin applications into one augmented human-robot collaboration workflow for the robotic assembly of masonry structures.

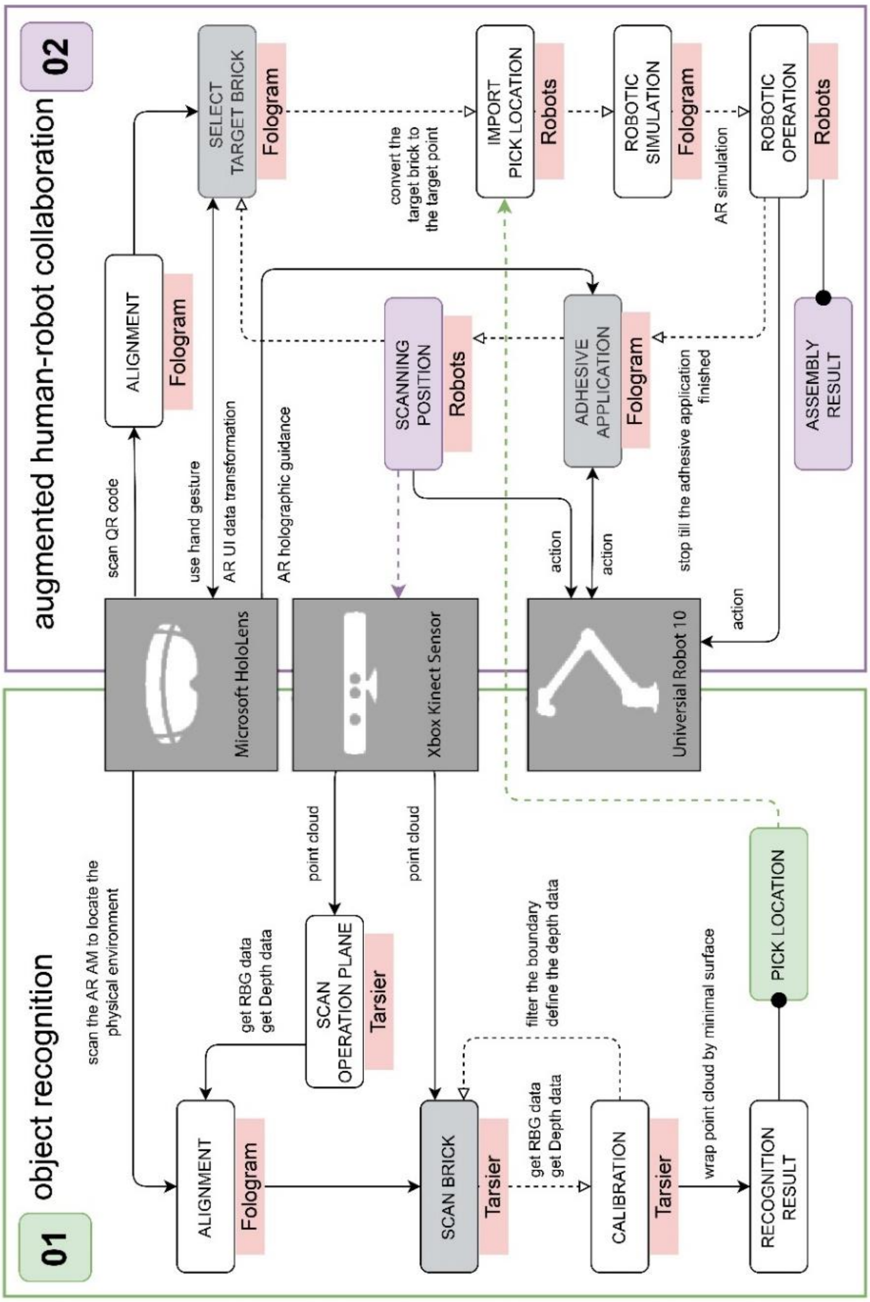

Figure 1. The *Augmented Bricklayer* project flowchart. The framework is divided into two phases: a) a robotic object recognition phase and b) the AR-assisted human-robot collaboration phase. (The connected device is coloured in grey, and the related software in each step is coloured in red above). Source: Yang Song, 2022.

3 The *Augmented Bricklayer* Experiment and Findings

3.1 Phase A: the Object Recognition

Object recognition is the first phase of the *Augmented Bricklayer* experiment, which contains the point cloud scanning method and analysis calibration system. The idea of proposing the object recognition method is to evolve the conventional fixed brick feeding installations by translating the point cloud data from RGB-D sensors to the robotic operation plugin for the robot to recognize, analyze, locate, pick and place the bricks flexibly.

At the recognition stage, we get the scene point cloud data from the *Kinect* sensor. The process starts by segmenting and extracting the scene. First, the end effector tool will be lifted to 80mm higher (the scanning position) from the operation plane to give *Kinect* sensor a more comprehensive scanning field version. The full-scale point cloud scanning results will be sent as meshes in *Grasshopper*. Second, the user needs to scan the AMs through the *HoloLens* from serial 1 to 4 to locate the boundary of our operation plane. Since the *Kinect* sensor is an external device, it is not easy to ensure the complete horizontal alignment physically of the camera. Therefore, the obtained scanning results must be further corrected for the alignments. To solve this issue, we combine the depth data from the *Kinect* sensor with the AR AM localization anchors to align the horizontal plane of the point cloud results and correct the mesh distortion in *Tarsier*. Last, we extract the RGB data from the *Kinect* sensor and use the RGB difference filter function to get the boundary of the operation plane with the synergistic correction from the AR AM (Fig. 2). In this way, the user can separate the operation plane mesh from the entire surrounding point cloud mesh and align the digital data with the physical environment.

At the analysis stage, the robot will remain at the scanning position. After the user places one brick on the operation plane, the *Kinect* sensor will be activated to scan. First, we analyze the RGB data to get the brick boundary point cloud. Second, we combine the depth data from the *Kinect* sensor with the thickness of the brick to determine the height and the brick top surface boundary from the scanned mesh in *Tarsier*. Next, we need to analyze the boundary results from both RGB and depth data to calibrate the tolerance, and determine the final digital corresponding minimum boundary of the top brick surface (Fig. 3). Last, the central point with related orientation for the top surface boundary will be uploaded to the robotic operation system as the picking point. In this way, the robot can recognize the centre point of the scanned brick as a picking point for the gripper in the following pick and place operation process.

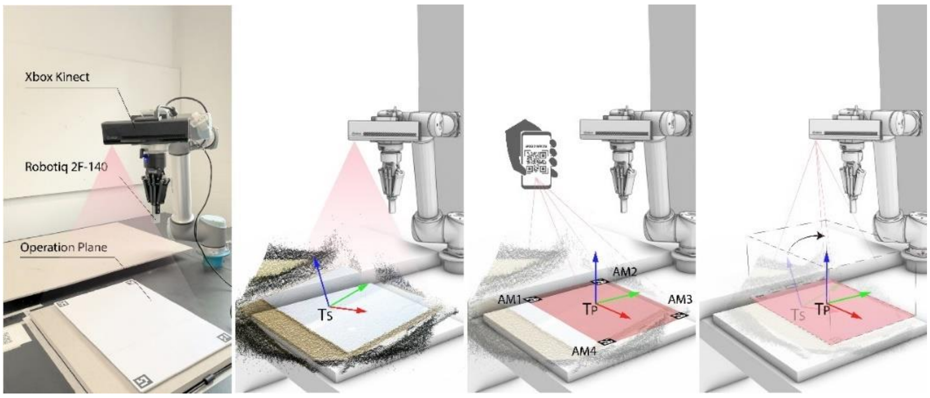

Figure 2. The figures from left to right are: a) the operation plane and device setting of the robotic object recognition phase, including a UR 10 robotic arm with *Robotiq* 2F-140 gripper and *Xbox Kinect* sensor; b) the point cloud meshes directly from the Kinect sensor, which is defined as plane TS and needs to be corrected horizontally and vertically; c) scan the AR AM in order (AM1 to AM4) from AR deceive to define the physical environment as plane TP and prepare to align the digital scanning results to the physical environment; d) rotate the plane TS to match with the plane TP in our calibration system to avoid problems such as inaccurate point cloud positioning and wide-angle sensor distortion. Source: Yang Song, 2022**.**

Figure 3. The figures from left to right are: a) put a brick in the operation plane for the *Kinect* sensor to scan and recognize; b) the point cloud mesh result from the *Kinect* sensor with RGB and depth data attached; c) using the RGB data to filter the boundary point cloud, using the depth data to remove other interference information and combine the boundary result to get the point cloud of the brick; d) using the minimum plane function in our calibration system to wrap the obtained brick point cloud to calculate the precise brick coordinate for the robotic gripper to pick. Source: Yang Song, 2022**.**

Phase A Findings. In summary, the object recognition method does fulfil our pre-determined assumptions. We successfully recognized and grabbed 400 bricks for the masonry column and wall, and each brick was placed freely at random angles and locations on the operation plane, waiting for the *Kinect* sensor to scan and the gripper to pick. Although not every grip is very accurate, and there is a tolerance of about 5mm relative to the brick's physical centre, compared to the length of the brick, the ±5mm tolerance is almost negligible. As a result, the robotic object recognition phase achieves accurate robotic object recognizing and grasping by the point cloud scanning method. This method frees the automated bricklaying from the fixed brick feeding position and cumbersome feeding installations and provides a more flexible on-site brick feeding method. Although the professional robotic camera can also provide corresponding functions, the high cost of the equipment and the complex computer science development environment are not familiar and friendly to architects. Our experiment achieved the same effect through an affordable device - *Xbox Kinect* and *Rhino/Grasshopper* & the *Tarsier* plugin, an architectural-friendly visual scripting environment, which saves the cost and allows users to manipulate object recognition by themselves.

However, the object recognition method still has some limitations. For example, the position of the *Kinect* sensor will shift after multiple physical robotic operations, which causes tolerance issues. Therefore, the user needs to repeatedly correct the physics environment with scanned mesh by AR AM. Moreover, due to the use of RGB data filtering, it is required that the identified brick and operation plane should be objects of different colours, and the greater the colour difference, the more accurate the result. Additionally, the size and shape of the scanned objects are also limited due to the tolerance. Therefore, extra sensors will be introduced into our system to improve the accuracy of utilizing multi-angle depth data detection from sensors, instead of RGB data, for the calibration system to reduce the tolerance and achieve the recognition of complex geometric shapes.

3.2 Phase B: the Augmented Human-robot Collaboration

The augmented human-robot collaboration is the second phase of the *Augmented Bricklayer* experiment, which contains an AR holographic guidance and an AR-assisted robotic operation method. The idea of proposing the augmented human-robot collaboration method is to utilize the advantage of human labour and robots respectively in the robotic fabrication process, and combine AR holographic guidance and AR-assisted interactive robotic manipulation to achieve a simple, efficient, flexible and low-threshold human-robot collaboration method for architects to control over the digital fabrication process.

In the AR holographic guidance stage, we use AR devices to align physical and virtual environments and enable data sharing for holographic adhesive application guidance. First, the user needs to scan the QR code with *HoloLens* to align the physical environment with virtual data. After that, the user can preview the robotic assembly process in real-time as the 3D holograms upon the site. The brick in the operation process will be shown in a white holographic border to highlight. Next, in our system, the overlapping part of the upper and lower bricks is automatically calculated, which means the overlapping area is where the adhesive needs to be applied. Last, the calculated overlapping area will be highlighted in red as a hologram upon the bricks. The user needs to follow the red holographic guidance, hold the mastic sealant gun, and apply the hybrid polymer adhesive at a constant speed until the virtual red holographic area is filled by the adhesive (Fig. 4). In this way, the user can apply the adhesive manually under the AR guidance on-site, which is a flexible method to avoid excess material waste and mess in the automated mortar application process.

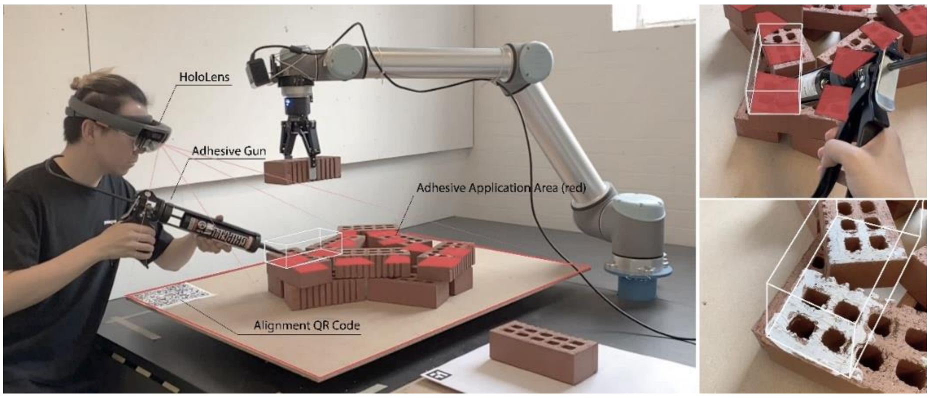

Figure 4. The AR holographic guidance stage in our augmented human-robot collaboration method. After scanning the alignment QR code through the *HoloLens* AR headset, the user needs to preview the adhesive application guidance upon the physical bricks through AR (red holograms in the picture above) and apply the adhesive through the mastic sealant gun to fill in the red holograms areas (left). The screenshots from *HoloLens* about the AR holographic adhesive application guidance upon the physical bricks and the bricks after applying adhesive (right). Source: Yang Song, 2022**.**

In the AR-assisted robotic operation stage, we use HMD (*HoloLens 1*) to achieve data interaction and send commands for robotic operation through gesture inputs. We have already pre-coded all robotic actions in *Grasshopper*, including choosing targets, setting trajectories, and gripper commands. We only use a few toggles in *Grasshopper* to control the entire coding system, and these toggles are mapped to our AR user interface (UI), which means the user only needs to point out the target and control the toggles in AR UI to send commands to the robotic arm (Fig. 5). First, the user needs to activate our AR UI, select the scanning position (details in phase A), operate the physical robotic arm there, and scan and get the position of the desired brick through AR UI. Second, the user can select the target in AR UI, preview the holographic trajectory simulation, and activate the physical robotic pick and place operation. After placing the brick to the target location, the robotic operation will be paused automatically, so that the user will have enough time to apply the hybrid polymer adhesive under the AR holographic guidance. Last, the user can return the robotic arm to the scanning position through AR UI, and repeat the above assembly loops till the whole structure is finished (Fig. 6). In this way, the whole process of human-robot collaboration can be realized through the easy interactions in AR UI.

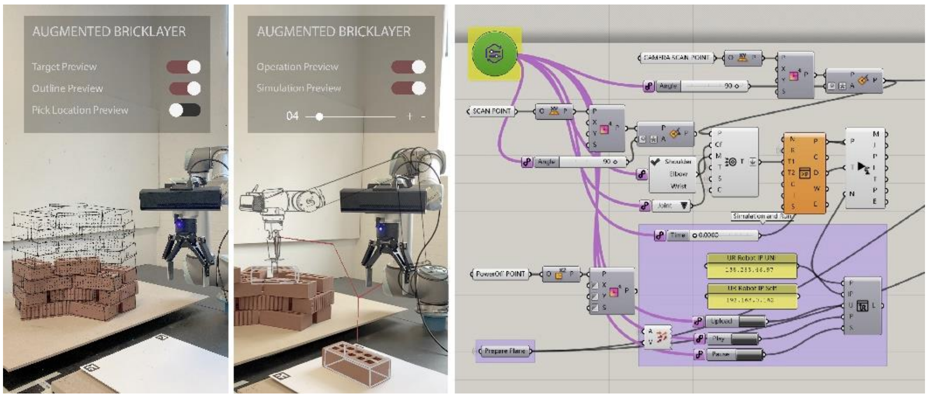

Figure 5. The toggles and the sliders in AR UI are mapped with the corresponding parameter settings in *Grasshopper,* which are colored and lined in purple in the *Grasshopper* processing file (right). The AR UI can achieve real-time visual programming modification for the robotic operation through the AR environment. Source: Yang Song, 2022**.**

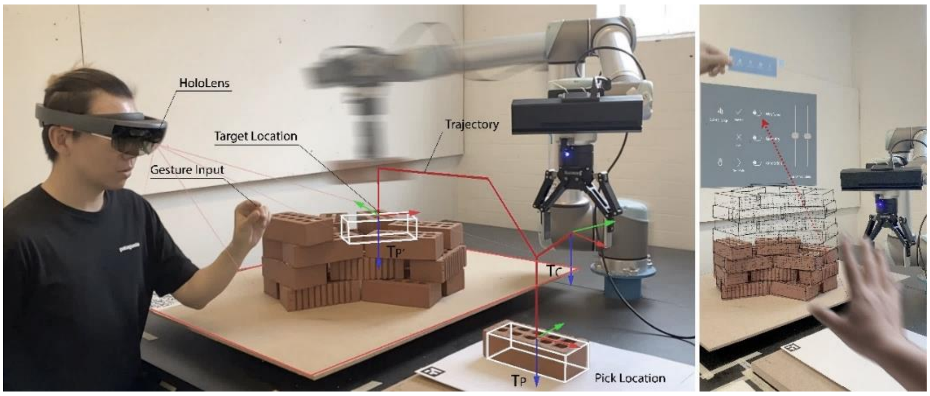

Figure 6. The AR-assisted robotic operation stage in our augmented human-robot collaboration method. The user can select the holographic targets in the AR environment through *HoloLens* through hand gestures, preview the robotic pick and place operation and trajectory as 3D AR animation, and operate the physical robot for the assembly process (left). The screenshot of our AR UI in HoloLens allows users to interact within the augmented human-robot collaboration process (right). Source: Yang Song, 2022**.**

Phase B Findings. In summary, augmented human-robot collaboration indeed achieves a more straightforward and accessible method for architects based on our pre-determined assumptions. We assembled 400 bricks for the masonry column and wall efficiently and precisely with the help of manual adhesive application in the AR environment (Fig. 7). As a result, the labour with considerable flexibility has an advantage over automated mortar applications when dealing with applying adhesive on-site, especially under the guidance of AR holographic instructions to improve the accuracy. Additionally, as a bridge between humans and robots, AR helped us to get rid of the constraints of coding skills successfully and control the robotic arm interactively in AR UI to realize the recognition, grasping and precise placement of 400 bricks. Moreover, we use HMD (*HoloLens 1*) as the AR device instead of smart devices (smartphones or tablets) because it can liberate the labourist hands for a more flexible operation.

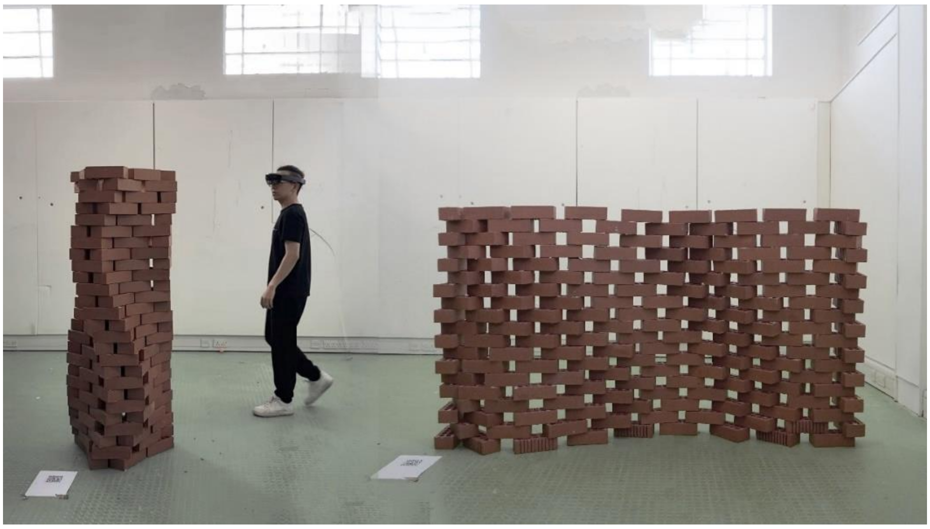

Figure 7. The validation of our augmented human-robot collaboration method for the robotic assembly of parametric masonry structures is achieved with the robotic assembly of two real-scale building elements, a parametric masonry column (left) and a wall (right). Source: Yang Song, 2022**.**

However, this method still has some limitations. Due to the interference of ambient light, AR holograms often drift throughout our assembly process. The user needs to scan the QR code repeatedly to align the physical environment. Therefore, more sensors or QR code grid networks should be added to our alignment system to reduce the interference of surrounding environments. Moreover, all the interactive information data and the display of 3D holographic animations are connected through one WIFI router with the same IP address. Therefore, the network speed and the wireless router data transfer rate directly affect the smoothness of information exchange. We use the 50MBpas transfer rate router, which causes the real-time preview intermittently to freeze or drop frames according to the size of our model or the data transmissions. To solve this problem, we need a good network connection with a high-speed router to ensure data transformation and holographic preview coherence during the augmented human-robot collaboration.

4 Conclusion and Discussion

The *Augmented Bricklayer* project developed and verified an augmented human-robot collaboration method for the robotic assembly of parametric masonry structures. This method takes advantage of the flexibility of humans and the accuracy of robotics. We assign each step of the robotic assembly process reasonably to humans and robots, including adhesive application, pick and place operation, and on-site error solutions, to maximize the use of their respective advantages. Moreover, the AR-assisted human-robot interaction and collaboration free architects from the need for cumbersome coding skills, and let architects control the robotic assembly of complex parametric masonry structures by themselves.

However, there are limitations and space for further improvement. The pros and cons of each phase have been summarized in the funding section above. In addition to these findings, there are future research goals for the overall macro augmented human-robot collaboration. This method has only been proven feasible in laboratory-based on-site environments with relatively low surrounding disturbances. For further research, we aim to repeat the experiment by mounting the robotic arm on the *MiR* mobile robotic platform, which would be better to test and validate our method in uncertain surroundings and natural on-site construction environments with movable robots. Moreover, during the AR-assisted manual adhesive application process, the pauses and restarts of the robotic arm make the entire workflow unsmooth and cause much wasted time. Suppose more sensors are added on-site, and the human body recognition function of *Kinect* is activated to realize the autonomous pause and restart of the robotic operation when it tests to detect if the user is in the operation area. In that case, it will significantly improve the user experience and workflow efficiency.

In conclusion, the *Augmented Bricklayer* project offers a more flexible, efficient, and controllable human-robot collaboration method, which gives a valid alternative to messy on-site adhesive applications and the limitations of non-professionals operating industrial robots, for improving the existing deficiencies in the conventional automated bricklaying process. This approach maximizes the strengths of human labour and robots through human-robot collaboration, and places high-tech manufacturing back into the hands of architects with the help of AR technology. Our final goal is to achieve the augmented human-robot collaboration method for robotic assembly in more architectural scale applications.

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