[AR]OBOT: the AR-Assisted Robotic Fabrication System for Parametric Architectural Structures

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Abstract. *[AR]OBOT* tries to assist the robotic fabrication process for parametric architectural structures with Augmented Reality (AR) technology to explore new possibilities for easy architectural robotic operations. Due to the lack of computer programming skills and the disconnection between design and fabrication, architects are hampered in the robotic operation process. As part of our project, we create a visualization prototype in which robotic and on-site related information is being shown through AR devices overlapping on the physical world; followed by a robotic trajectory planning method in which designers' gestures are being identified by AR as location nodes and calculated with the obstacle avoidance system; and an operation process in which robots are being controlled by human gestures and interactions with holographic simulation to enhance the robotic fabrication process efficiency and safety. In this paper, we share the preliminary results to demonstrate a new kind of AR-assisted workflow for the architects to perform the robotic fabrication of parametric architectural structures intuitively.

Keywords: Augmented Reality (AR), Robotic Operation, Human-robot Collaboration, Holographic Simulation, Design to Fabrication

1 Introduction

There is a historical connection between architecture and machinery for building construction. In particular, science the increased access to robotics, the architect's dreams of architectural mechanization and industrialization have recently again gained momentum (Retsin, 2016). Current technological advancements, combined with automatic renewals, are challenging architects, designers, and robotic engineers to seek novel solutions in making the architecture and construction industry more efficient, informed, and automated (Willmann et al., 2018). Therefore, architectural design and fabrication have opened up new aesthetics and functional potentials through robotics and computational information.

1.1 Robotic fabrication

Since the beginning of the 20th century, with such automated innovation on the rise in other industries, we can observe an increase in robotics research in architecture. Contemporary advancements in parametric design methodologies fueled the ability of the designer to generate complex structures easily. Correspondingly, we can observe a steady demand for some analogous assembly technology, such as robotic fabrication, to be applied to architectural construction.

Here to mention are several key developmental stages. The mobile robotic unit R-O-B, founded by Gramazio and Kohler in Zurich (developed in 2005), was the first attempt to implement an entire robotic crew on-site for non-standard brick walls (Gramazio, 2014). Along similar lines, KUKA robots introduced one of the early uses of a robotic pick-and-place assembly unit, entitled *The SequentialWall* project, where timbers are laid down on top of each other (Gramazio, 2010). Gandia et al. presented work demonstrating the integration of automatic path planning into the design environment to enable the multi-robotic assembly of spatial structures (Gandia, 2018).

While enjoying the efficiency and accuracy of robotic fabrication, this method still has exposed several shortcomings and problems that need to be improved and solved. For instance, firstly, the lack of an end-to-end solution between designer and robotic fabrication. The use of industrial robots in architectural projects is considered to be high-end that usually depends on robotic engineers instead of designers to realize. Due to the disconnection between designer and robotic engineer, uncertain situations often appear in the robot manufacturing workflow (Devadass, 2019). Secondly, architectural practitioners generally lack professional programming and operation skills. The robotic operation process requires specific expert computer science knowledge and skilled programming code workers, which is an expertise that is traditionally not found in the architectural design industries (Schmidt, 2017).

1.2 Augmented Reality (AR)

AR technology provides humans to sense or interact with a computer-generated virtual world integrated with the real world by overlapping the holograms on the real objects and spaces (Chen, 2009). AR technology offers today a more feasible proposition to bridge the virtual and real-world gap than ever before. In fact, it could be argued that it offers today and in the near future a fleet of new kinds of interaction scenarios that could also be harnessed in the fields of architecture and construction.

Multiple studies have shown that AR has the following characteristics and functions that could help to improve the above shortcomings in robotic fabrication and human-robot collaboration areas. For instance, AR techniques have been used to superimpose virtual objects or information as 3D holograms with location recognition and environment identification in the real world. Jahn et al. confirm that using AR 3D holographic guidance with related digital information on the construction sites could save time and improve the accuracy compared to a traditional process, which caused errors and is inefficient in translating information from 2D drawings to on-site construction (Jahn, 2019). Furthermore, Ong et al. demonstrate that AR can make robotics operations simpler and safer with intuitive on-site 3D hologram stimulation, thus providing a faster and more intuitive gesture-based robot programming method than conventional techniques (Ong, 2020). We see here that AR technology uses its power in terms of user-interactive performance, which helps to replace earlier mentioned technical limitations of robotics that normally require programming skills. Compared to such earlier methods, this clearly indicates an AR-assisted workflow improvement and is more user-friendly to potentially lesser-skilled workers.

2 Research methodology

This research will elaborate on the process of AR-assisted robotic fabrication for parametric architectural structures. Our research demonstrates the potential of AR during the robotic dynamic holographic information, on-site environment recognition, robotic fabrication process, and other human-robot collaboration processes in architectural construction projects. In this case, we provide some insights into a potentially new AR-assisted method for the parametric architectural robotic fabrication process (Fig.1).

As for the material and geometry system, we were looking to find a material that is easy to be controlled and recognized in the AR environment as well as achievable for the robotic arm to operate. Furthermore, the geometry shape should match the parametric design logic in *Grasshopper* because both the AR system and robotic fabrication process work well with similar and repetitive geometry. We choose foam brick (50*50*150mm) as the main material.

About the AR and robotic device, we choose a commonly available handheld device - iPhone 11, and a head-mounted display (HMD) – Microsoft *HoloLens 1* for AR, as well as a Universal Robots UR 10 for the robotic device.

In terms of software and plug-in, the AR-assisted robotic fabrication workflow of *[AR]obot* project was mainly designed in *Grasshopper* with *HAL* robotic, *Fologram* plug-in, and *Fologram App* in both iPhone 11 and *HoloLens* 1. The *Fologram* plug-in allows visualising the related digital information by on-site holograms; interacting with the digital models in Grasshopper; scanning and recognising the surrounding environment; and converting The *Fologram App* recognises human gestures, screen taps, device location, and editable interface on mobile phones and *HoloLens* to achieve the AR experience and interaction. We combine HAL robotics plug-in to fulfil the AR-assisted operation commands, immersive robot trajectory planning, obstacle avoidance, collision preclusion, and on-site virtual simulations for robotic fabrication to complete the whole workflow.

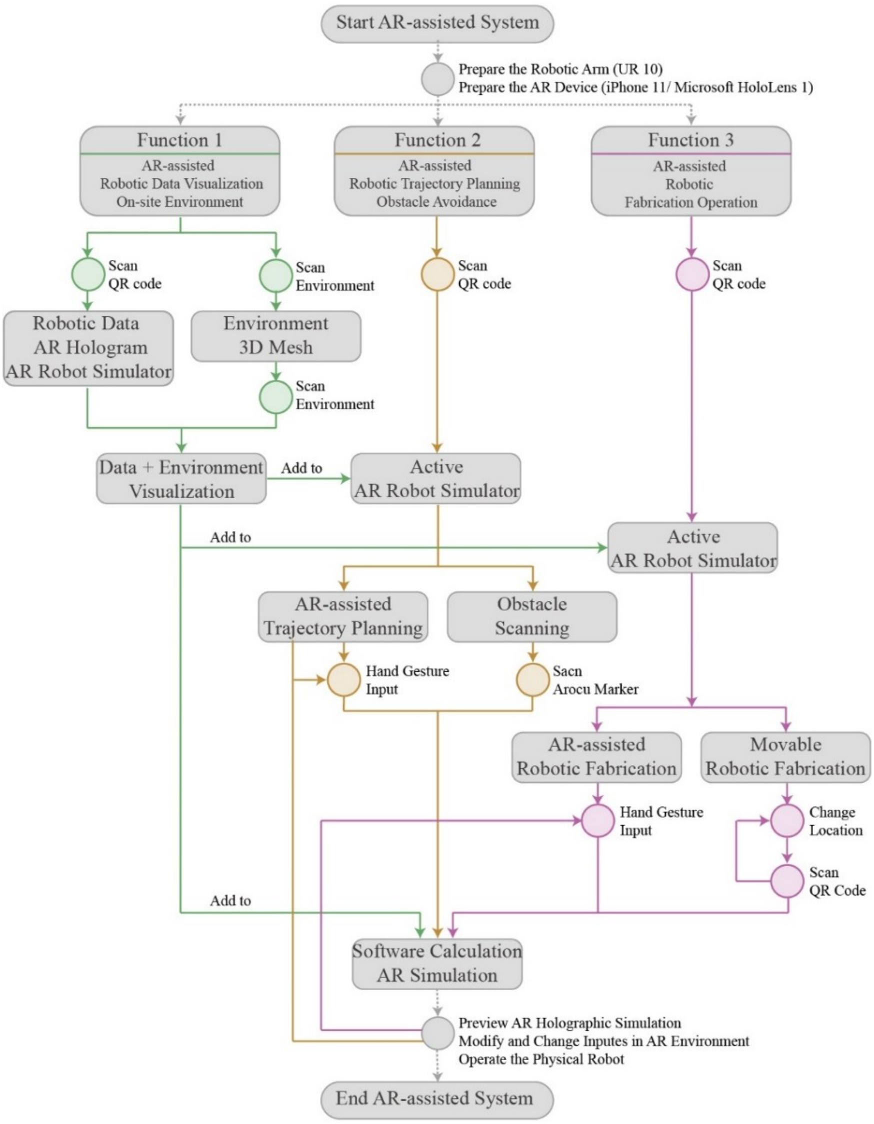

Figure 1. The workflow of *[AR]OBOT* project, an AR-assisted robotic fabrication method for parametric architectural structures, is divided into three function tests. Source: Yang Song, 2021.

Above all, we developed a multi-stage methodology that would allow us to develop, test, and refine the AR-assisted robotic fabrication system for parametric architectural structures into the following three tests.

3 *[AR]obot* project tests and outcomes

3.1 Augmented Visualization of Robotic Data and On-site Environment

Test 1 explored the possibility of using the AR to visualize the corresponding holographic information of the on-site robot by superimposing virtual holograms upon real objects; as well as the opportunity of using the AR device to recognize the uncertain on-site environment by scanning 3D space in real-time and spatial mapping the location information. Besides, we used device location recognition, on-site holographic information, and QR code identification methods to give designers or inexperienced operators more intuitive information and experiences about the robotic arm operating.

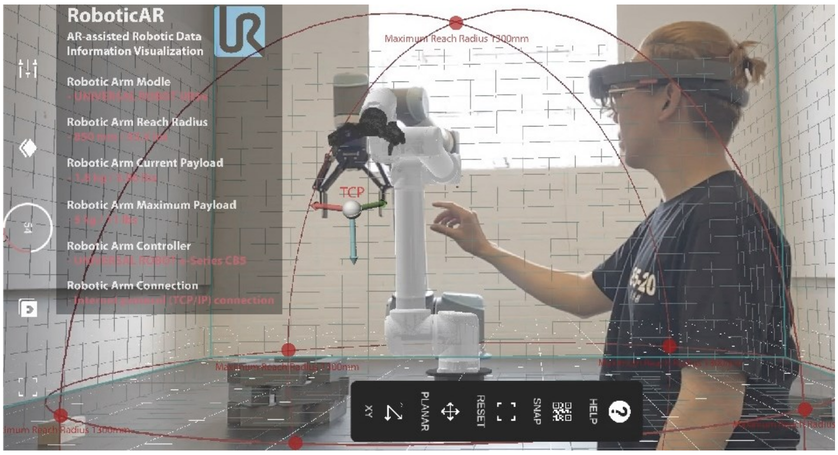

Figure 2. After scanning the QR code through AR devices, the dynamic digital data visualization will be shown as holographic information in *[AR]OBOT* user interface overlapping the physical robotic arm and the real world. Source: Yang Song, 2021.

For visualizing robotic data, we digitalized the robotic arm console table into a 3D model in *Rhino* and stored it in the QR code. To begin with, the user could scan the QR code through their AR device camera with *Fologram App* built-in to read and preview the virtual simulated robotic arm model and its related information as holograms. After that, the user could selectively visualize the robotic data, including the operating reach radius, available operation area, real-time payload, and robotic arm conditions in the AR user interface (Fig.2).

Also, this method supports multi-users to visualize the data through different AR devices simultaneously to share the information.

Test 1 used the real-time spatial mapping function of AR technology to visualise the on-site environment to convert the on-site robotic operation surrounding environments into 3D meshes in *Rhino* and *Grasshopper*. After that, digital mesh data informed the calculation of the robotic operation simulation to warn the user about the areas where the robotic arm might collide with the physical environment or other dangers caused by the uncertain on-site surroundings (Fig.3). As a result, the spatial 3D mesh model of surrounding on-site environments from iPhone 11 has relatively lower accuracy compared with the one generated by *HoloLens 1*. The iPhone device is suitable for digitizing a common shape space, while *HoloLens 1* can detect more complex spaces. Moreover, both of the above AR devices can assist the robotic arm in recognizing the uncertain on-site environment in real-time to avoid collisions.

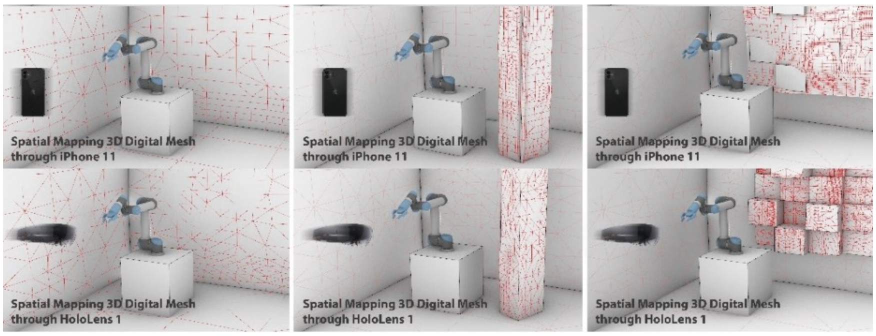

Figure 3. The digital 3D mesh results of the spatial mapping about three different surrounding environments through the handheld device and the HMD device (Microsoft HoloLens1). Compared with the spatial mapping reduction from physical to digital, the HMD device is more accurate than the handheld device. Source: Yang Song, 2021.

Test 1 shows that this AR-assisted robotic data information visualization could help designers, especially the unskilled users who lack the corresponding operation experience, understand the robotic arm better, including its corresponding information dynamically. Furthermore, the AR-assisted on-site environment cognition method could help the robotic arm recognize the reachable surroundings to its data information to avoid collisions and dangers while taking actions in uncertain on-site environments.

However, the accuracy of the holograms in AR devices depends on the appropriate lighting and background environments. If the ambient light is too bright or dim, it will make the sensor difficult to align location overlaying on the physical objects and cause the AR holograms to drift, which needs to restart the AR device. Furthermore, the spatial mapping 3D meshes from AR devices still lack precision. To solve this problem, we might need to use professional space detection and scanning sensors to assist robots in translating and recognizing the uncertain surrounding environments.

3.2 AR-assisted Robotic Trajectory Planning and Obstacle Avoidance

Test 2 based on the 3D scanned mesh for capturing the surroundings in Test 1 and explored the feasibility of using the AR technology to realize the robotic trajectory planning and obstacle avoidance, instead of using the traditional method, programming by computer science language and demonstration, for the architect who lacks the corresponding knowledge. To do this experiment, we used device location recognition and the Aruco marker tracking method to digitalize the physical obstacle for the robot to avoid and generate a new path.

For this AR-assisted robotic trajectory planning experiment, test 2 provides a robotic programming method by converting the location nodes in the real physical world into digital operation node commands for robotic trajectory programming in AR. The user could point out the location along the trajectory in the entire operating area. Moreover, the physical location nodes would be converted into digital commands. This digital command would be translated as a tool central point (TCP) for the robotic plug-in to identify and calculate the operation routes. Also, the user could change the trajectory mode between “linear mode”, “joint mode” in the AR interface sliders. After the trajectory was set, the user could preview the operation routes. The virtual robotics arm simulation animation will be shown as holograms through the AR environment overlapping the real machine. This AR-assisted virtual-gesture robotic trajectory programming method enables the non-coding users to command, plan, modify, and simulate the robotic trajectory (Fig.4).

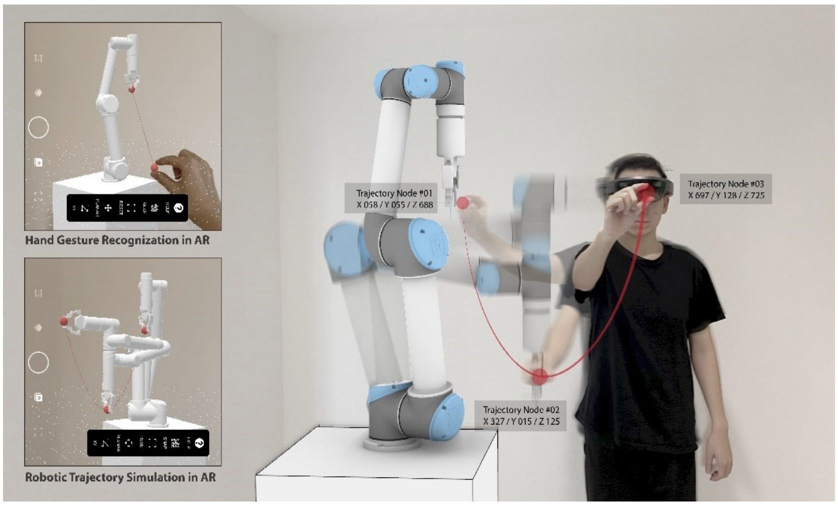

Figure 4. The AR-assisted robotic trajectory planning method requires the user to point out the TCP along the operation trajectory in the physical environment. TheseTCPs will be recorded as coordinate data for trajectory planning. Source: Yang Song, 2021.

It is difficult to 3D scan the foam brick volumes using the AR spatial scanning sensors in Test1. For the foam brick obstacle avoidance, we started to test the ability of the AR-assisted system in the robotic collision avoidance process. For example, we treated the obstacles as the built bricks along the trajectory of robotic operations. First, the user needed to digitalize the physical obstacles into digital models. The digital brick prototype was stored as a 3D model in the Aruco marker. The user should put the Aruco marker on the top of the obstacle brick in the right orientation and scan the Aruco marker by AR device. Second, the physical obstacles were converted into digital data for the user to visualize them through AR and the robotic plug-in to calculate the collision-avoid robotic trajectory. Last, after the new trajectory was set and shown in AR, the user could preview the hologram of robotic simulation and operate the physical robotic arm in the AR interface (Fig.5).

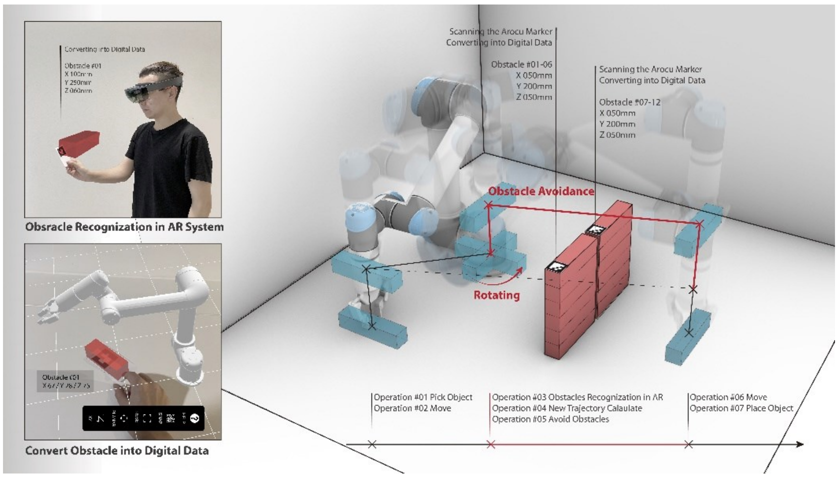

Figure 5. The AR-assisted obstacle avoidance method provides an Aruco marker recognization-based system for AR devices to scan and convert physical obstacles into digital data for robotic operation plug-ins to calculate and generate a new path for the robots. The path will be shown as a holographic trajectory in AR overlapping the physical robotic arm and operation environment. Source: Yang Song, 2021.

Test 2 demonstrates that this AR-assisted robotic trajectory planning method provides the unskilled user with intuitive simulation in robotic path planning and translates human actions directly into a robot programming language. Moreover, the AR-assisted obstacle avoidance system can digitize the physical obstacles along the robotic trajectory and send them to related software for real-time trajectory calculation to avoid the physical collisions and dangers during the operation of the complex construction process.

However, the accuracy of physical and digital trajectory node conversion in this method needs to be improved. Furthermore, this AR-assisted obstacle avoidance mode is only suitable for regular shape obstacles. This method should be generalized to more complex shape obstacles during the uncertain on-site robotic fabrication process.

3.3 AR-assisted Robotic Fabrication Operation System

Test 3 chose the parametric foam brick column for AR-assisted robotic fabrication workflow. Robotic operations, traditionally, need specific expert computer science and programming knowledge to program the complex movement. Even though robotic errors occur beyond simulation occasionally in physical operations, the screen-based simulation is out of touch with the real physical world. This process is dangerous because workers are in the same space as the moving robotic arm. We use the AR-assisted robotic operation method to reduce the complexity of the traditional coding-based operation method and avoid the dangers in the physical operation.

For the AR-assisted robotic fabrication part, we started with a simple robotic operation – “pick and place”, and we chose to stack a foam brick column from bottom to top. First, the user could scan the QR code to locate the physical robotic arm and the console desk with the AR hologram. Second, the user can scan the Aruco marker to digitalize the physical brick, which needs to be operated into the virtual environment in the preparing area through the AR device. Next, the user is required to “tap” the virtual brick hologram in the preparing area and the target location where the user wants the robotic arm to place the physical brick. Next, the command would be sent from the AR device to the robotic plug-in. The virtual on-site holographic simulation would be sent back to the AR device, and the system will be ready for physical operation. At the same time, users could preview the whole robotic holographic simulation and the safety area that needs to be maintained from the robotic arm operation radius in AR to keep it safe in the later physical operation process. Last, after all the simulations run safely and successfully in AR, the user could start the physical robotic operation process through the AR interface (Fig.6).

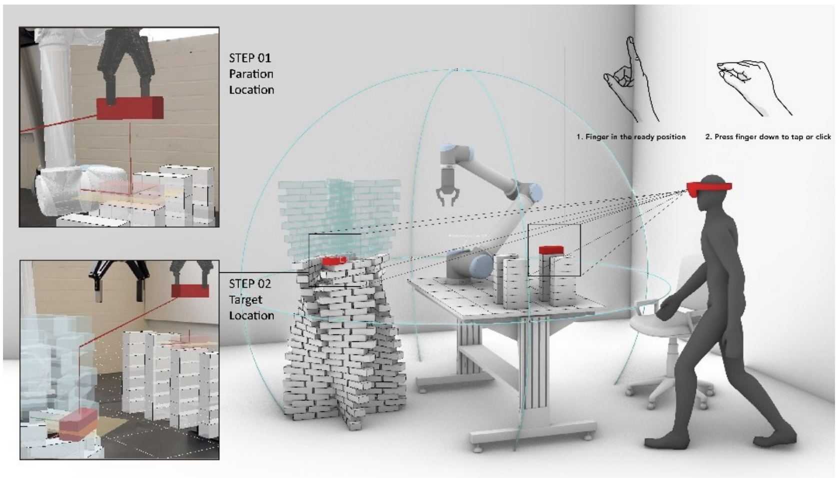

Figure 6. The AR-assisted robotic fabrication workflow visualization in AR. Users need to point out the virtual bricks i respectively in order. Source: Yang Song, 2021.

Test 3 shows that it is a safer and more effective process to operate robotics through AR-assisted method with on-site gestures command and holographic trajectory simulations. All the computer science programming technics have been pre-coding in Grasshopper. The user simply needs to point out the "preparation" and the "target" location instead of programming in computer science language (Fig.7). Moreover, we also provide a prototype for the AR-assisted moveable on-site robotic arm operation. When the position of the physical robotic arm changes, the user just needs to scan the new QR code based on the new location to update. After that, the user just needs to repeat the "tap" command in the AR environment to continue the operation.

However, the current functionality of test 3 is very limited. We only use the foam brick column as the prototype test. Other materials and shapes have not been tested and confirmed that they work well with AR-assisted robotic workflow.

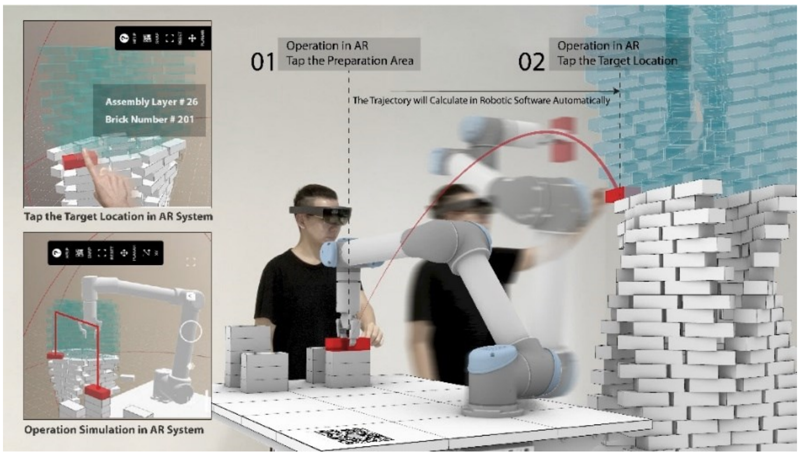

Figure 7. The AR-assisted robotic fabrication operation. The user can operate the robotic arm by tapping the preparing area hologram and the target location hologram. The computer will send the AR device a holographic operation simulation after calculating a trajectory. Source: Yang Song, 2021.

4 *Conclusion*

The *[AR]OBOT* tests give an overview of using the current state-of-the-art AR technologies, such as AR holographic information, AR spatial mapping method, AR identification of virtual information from QR code or Aruco marker, AR user interface, and AR immersive gesture-based interaction, to assist robotic operation for parametric architectural structures. The *[AR]OBOT* tests exam the practice and the running-in situations of these key factors and fundamental requirements in this AR-assisted workflow. In addition, the above-described three tests answered and solved the research questions about how to use AR technologies to assist the traditional robotic fabrication process and what will happen to the AR-assisted robotic fabrication system.

- For **Augmented Visualization of Robotic Data and On-site Environment**, our research has shown that with the ability to overlap the holographic data on the real physical world in AR, *[AR]OBOT* provides a method for unskilled users to visualize the corresponding robotic information and to understand robotic arm comprehensively and dynamically. Furthermore, our research shows an AR-assisted method to avoid real-time interference from the unstable environment for on-site robotic fabrication. This method gives a friendly way for unskilled users to get familiar with the robotic system and on-site surroundings in the AR-assisted environment.
- For **AR-assisted Robotic Trajectory Planning and Obstacle Avoidance**, it has been shown that with the AR immersive gesture-based interaction function, *[AR]OBOT* provides an intuitive robotic trajectory planning method by translating human actions directly into a robotic programming language through AR. Moreover, with the ability of AR to identify virtual information from QR code or Aruco marker, our research provides a way to digitalize the physical obstacles for robotic operation software to calculate, generate, and simulate a new obstacle avoidance trajectory. It gives unskilled users more opportunities to operate a robotic arm safely through human-robot collaboration in AR.
- For **AR-assisted Robotic Fabrication Operation System**, it has been approved that with the ability of AR user interface and AR immersive gesture-based interaction, *[AR]OBOT* offers a safe robotic fabrication operation method by on-site gestures commands and the interaction with the holographic user interface. Furthermore, our research proposes a prototype for the multiple and moveable on-site robotic fabrication operation methods by scanning the updated QR code, relocating the on-site robot, and operating robotic fabrication by human gestures in AR. This method simplifies the traditional operation method and replaces it with a user-friendly AR-assisted gesture-based system for the safe human-robot collaborative process.

In conclusion, the *[AR]OBOT* project bridges the gap between architects and robotic fabrication. This AR-assisted system makes design and robotic fabrication in the hands of architects who lack computer programming skills and experiments but are full of architectural inspirations. Getting familiar with AR operating systems and learning to use QR codes or Auco markers to convert between physical and digital are the required skills and knowledge sets in this AR-assisted system, which are substantially simple for architects to learn compared with computer science skills. This AR-assisted method allows designers to interact with the robotic fabrication process in AR and get the enormous advantage of feedback through AR in real-time in human-robot collaboration. On the contrary, in this system, the AR interaction function is very limited. The limited AR-assisted functions which have shown in this paper are based on the cooperation of plug-ins and grasshopper functions will be realized, and other custom operations need further development. What's more, designers can only make modular modifications and designs in this system, and the design results must conform to the parametric design with repeating units as the main element. Not all the design types work to this AR-assisted design to robotic fabrication system.

Further work will take in premeditation the additional development of using more professional space detection and scanning sensors to assist AR to translate and recognize the uncertain on-site environments for robotic software calculation. Through the AR-assist real-time environment, multiple robotic arms and operations will be developed for the human-machine collaborative fabrication part. More complex forms of obstacle avoidance and more complex robotic operations will be created and completed during the whole AR-assist system. The final goal is to make the AR-assisted robotic fabrication workflow simplified and modified for architectural scale elements and applications.

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