AR DIGI-COMPONENT

AR-assisted, real-time, immersive design and robotic fabrication workflow for parametric architectural structures

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Abstract. This research project, entitled AR Digi-Component, tries to digitalize the traditional architectural components and combines Augmented Reality (AR) technologies to explore new possibilities for architectural design and assembly. AR technology and Digitalize components will help to achieve a real-time immersive design and an AR-assisted robotic fabrication process through the augmented environments. As part of the AR Digi-Component project, we created an experimental design prototype in which designers' gestures are being identified in AR real-time immersive design process, and a fabrication prototype in which traditional 2D drawings are being replaced by 3D on-site holographic guidance, followed by an assembly process in which robotic operations are being controlled by humans within an AR simulation to enhance the assembly efficiency and safety. In this paper, we are sharing the preliminary research results of such AR-assisted tests, for which we used a UR10 Robotic arm in combination with Microsoft HoloLens as well as in terms of software Rhino, HAL Robotics, FURobot, PX Simulate, and Fologram plugin in Grasshopper, to demonstrate new kind of applications and workflow of AR technology for real-time, immersive design and robotic fabrication.

Keywords. Augmented Reality; immersive design; holographic assembly instruction; robotic fabrication; real-time interaction.

1. Introduction

Since the introduction of technological innovations such as the internet and mobile computers, including our mobile phones, we have seen substantial changes to how we see and engage with our surroundings in our everyday urban life. Yet, more recent AR technology seems to create new crossroads for which we are just beginning to understand. AR is a relatively new technology field that produces a virtual model and information that can be viewed and interacted with in the real world (Do Carmo, 2007). In other words, AR technology offers a way to bridges the gap between the virtual and the real world, offering all kinds of new interaction

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scenarios in the near future that could be harnessed in the fields of Architecture and Construction. Let's look at some common design workflow models today and see how AR technology has the potential can change it.

1.1. PROBLEM 1 - DESIGN PROCESS

In the current design process, architectural designers and off-site technicians are using 2D plans, 3D models, and renderings to understand the complexity and to make partial modifications to improve their design drafts. These methods are conveyed through paper and screen which provides off-site flattened previews. Designers do not have immersive possibilities which means they can't experience their parametric structure spaces before they were built and they can't modify and preview the draft on-site according to the actual space experience during the traditional design process.

AR offers a new tool in the design process, where designers can show their visual drafts in an on-site space and can use direct hand-based gesture recognition and paddle-based inputs to interact with (Sheldon, 2016). The nature of the AR - easy, user-friendly, little room for errors, and intuitive interactions - can support the design process. AR technology promises to have a series of unique benefits compared to simply working in a non-AR enhanced real environment. We would like to propose creating an immersive design process by combining the above characteristics of AR. Could indeed AR provide designers an immersive adjustment and preview methods during the design process, allowing for an on-site preview and real-time input interactions?

1.2. PROBLEM 2 - ON-SITE ASSEMBLY METHOD

The traditional architectural assembly process requires skilled labors and complex equipments to locate and transform highly detailed 2D drawings to physical on-site construction. It is commonly applied in many areas of architectural construction, but there remain a series of problems. This includes that the current workflow is not particularly time efficient and is open to human error; all of which is caused by translating information from 2D to on-site construction in the assembly process especially for complex structures (Jahn, 2019). As for the construction site, labors working on the assembly of building components have largely relied on 2D construction plans. The more complex the structure, the more time-consuming and error-prone will happen during the construction information translation process.

To reduce the gap between 2D graphic instructions and 3D assembly actions, the use of AR technology applies a method that is based on high precision and detailed AR 3D on-site holographic drawings and instructions in the architectural assembly process (Tsai, 2020). The holographic instruction in scale 1/1 enables the user to walk through the project before the actual construction and teaches unskilled labors step-by-step during the assembly process (Imani, 2017). This potentially opens up a new field of intervention for using AR digital instructions in the assembly process, especially in complex and atypical structures. The research question emerging from here is to find out whether AR technology can replace the traditional 2D detailed drawings in the assembly process?

1.3. PROBLEM 3 - ROBOTIC FABRICATION OPERACTION

Although digital fabrication is widely used in many fields of architectural construction which materials or components are not suitable for manual handiwork, there are still a series of issues that currently exist. 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 offices and industries (Schmidt, 2017). Moreover, most robots are controlled by teleoperation and have screen-based simulations before operation. Despite this, it still involves inaccessible, dangerous, or remote locations during the traditional operation process (Olar, 2019).

AR makes robotics operation simpler and safer with intuitive on-site 3D hologram stimulation and provides faster and more intuitive gesture-based robot programming method than conventional techniques (Ong, 2020). We would like to propose that this visualized property could give users intuitive gesture-based input for robotic trajectory plan through AR instead of computer programming requirements, as well as proposing the possibility of on-site virtual robots operation simulation to predict dangerous or error more intuitively before physical operation. The research question is that how will AR technology improve the traditional robotic operation in the assembly process?

2. Research Methodology

This project will elaborate on the workflow of AR-assisted design and assembly for parametric architectural structures. We hope that our research can demonstrate the potential of AR, in the sense that it could be applied at a full architectural scale, such as during façade constructions or other highly labor-intense installation processes. In doing so, we hope to provide some insight into a potentially new workflow model for human-robot collaboration using AR technology (Figure 1).

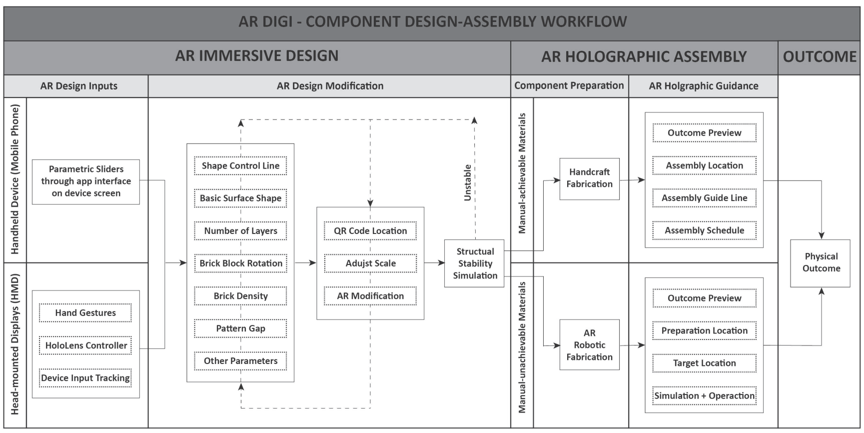

Figure 1. AR Digi-Component design-assembly workflow.

To test such immersive design and robotic fabrication workflow scenarios, we were looking to find a material that relies on manual labor in the current construction process which is easy to be controlled in an AR system and easy to connect with parametric design in a software, such as *Grasshopper*. After several trials, we choose to run our tests using standard UK brick as the main design and assembly material for all the *AR Digi-component*. UK bricks are mated to a standard size of 215 x 120.5 x 65mm, which are easy for AR device to track, recognize, and preview. They also can be re-used and re-design at any state. It innovates how to apply new technology for traditional architectural materials to achieve unique outcomes.

As for our AR device, we choose a commonly available handheld device and a head-mounted display (HMD) from a leading manufacturer, yet not their latest model, Microsoft's *HoloLens 1*. For handheld devices, the ARKit for iPhone allowed us to achieve a screen-based AR experience. For the HMD, Microsoft *HoloLens* gives user a hand-free AR experience and enables the user to engage with digital content and interact with holograms in the real world (Song, 2020).

In terms of software and plug-ins, our *AR Digi-Component* workflow was mainly designed in *Grasshopper* with *Fologram* plug-in and applied to *Fologram App* in both iPhone 11 and *HoloLens 1*. The *Fologram* plug-in provides the possibility to interact with the *Grasshopper* parameters in the AR environment, as well as the *Fologram App* provides the recognition of human gestures, screen taps, device location, and editable interface on mobile phone and *HoloLens*. To integrated the function of *Grasshopper* and the third-party API - *Fologram*, we created a unique AR design and assembly workflow. In our example, we set up different parameter variable inputs that will affect the result of the outcome. These variable inputs are connecting with parameters in *Grasshopper* and shown on the *Fologram App* as parameter sliders for designers to interact with. To complete the whole workflow, we also combine the *Fologram App* with *FURobot* and *HAL robotics* plug-in to fulfill the AR gesture-based operation commands and on-site virtual simulations for robotic fabrication.

In summary, we developed a multi-stage methodology that would allow us to develop, test, and refine the AR-assisted real-time, immersive design and robotic fabrication workflow for parametric structures into the following three tests.

3. AR Digi-Component Tests

3.1. TEST 1 | AUGMENTED REAL-TIME MODIFICATION AND ASSEMBLY

Test 1 is to explore the feasibility of AR real-time modification and assembly process through an augmented environment with virtual information on handheld devices - iPhone 11. It is used to receive the real-time modification input from designers and to illustrate the 3D virtual model for labors in the assembly process.

For the AR real-time modification part, test 1 sets up different parameter variable inputs that will affect the result of the outcome. The adjustable parameter sliders are divided into different parts which cover the entire design process such as basic layer shape, the number of layers, column rotation degree, column deformation control line, and the pattern gap distance. These sliders are connecting with the parameters in *Grasshopper* directly and showing in the *Fologram App* interface on the mobile device's screen in real-time for designers to modify with by using actions on the mobile phone screen such as "on press", "on drag", "on hold", and "on release". The outcome is then shown dynamically on the iPhone 11 according to the real-time inputs after scanning the QR code for on-site location confirmation (Figure 2). This on-site dynamic design method gives designers and participants an intuitive view of outcome preview and a new interactive method of real-time modification. After the shape is designed without further modification, the digital model will be sent to *PX Simulate* plug-in in *Grasshopper*. The designer can preview the on-site structural stable simulation in AR after calculation.

Figure 2. Interactive AR immersive design process through mobile device screen inputs.

For the AR assembly process, test 1 provides a step-by-step virtual guidance assembly instruction. The user can switch the toggle on the *Fologram App* interface from "AR Design" to "AR Assembly". When the assembly interface is activated, the user will first preview the number of bricks to be used and will then be guided to the place of each brick, using the virtual instruction shown on the mobile device. The user can, for example, see the red target lines of the location of the brick in the first layer virtually and place the brick one by one to align them with the red target lines of the first layer. After that, the user can change the sliders through the app to continue the following layers of assembly. The virtual model of the layers that are already finished will be blocked. Only the layer that is in that moment under construction will be highlight and displayed in red target lines, which is relatively intuitive. All the user needs to do is following the on-site red assembly target lines and complete the assembly according to the virtual model shown on their mobile phone device step-by-step (Figure 3).

Test 1 demonstrates that AR real-time modification can give users the possibility of stimulating creativity and an intuitive method to modify on-site design drafts. Although we have not tested the time needed for the assembly, it seems obvious to suggest that the guided AR virtual assembly has the potential of reducing the time normally spent when translating 2D documents to 3D real projects and as such improve the efficiency of the entire construction process. This AR assembly guidance no longer requires skilled construction workers, it creates a new method that the designer and the worker can be one and the same person in this design-assembly system. The communication speed between *Grasshopper* and mobile device in real-time is 2.863 Mb/s, which is fast enough for the real-time modification of simple brick columns.

Although the result of this test 1 is quite successful, it is considerably limited by the fact that the designers can only import parameters by adjusting limited sliders. Mobile AR experience is in parts also impractical and relatively non-immersive, and as such is currently not ideal for an immersive design experience at a full scale. This is of course the case because the preview of the virtual on-site models and all interactive inputs are happening on the device itself, meaning that interacting with a small screen will naturally lack a more integrated experience. Furthermore, the human virtual recognition of the hologram that is displayed on the small mobile screen will cause accuracy errors when the image is overlayed on location on the site. Due to the insufficient accuracy of the space environment perception by mobile devices, errors always occur between digital models and physical outcomes, which are between 1 to 2 cm. Besides, the construction workers would need to use one hand to hold the device and the other hand to carry out the assembly process, which would bring safety hazards and operational inconvenience during construction. Therefore, it seemed that the natural next step would be to try to find a more integrated AR method, which would offer instructions for the assembly through a holographic headset instead of with a handheld device.

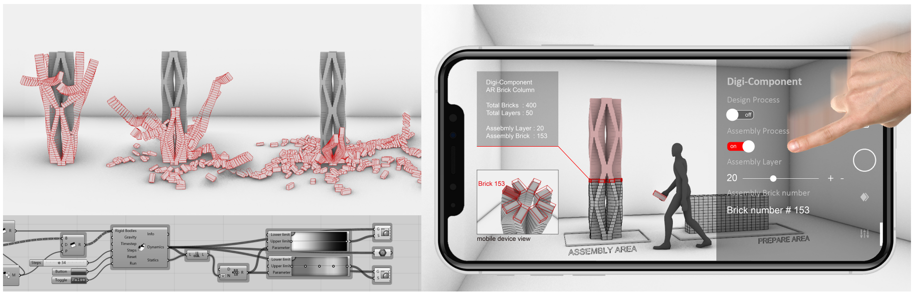

Figure 3. Structural stable simulation in Grasshopper and AR (left), and AR visual assembly guidance on iPhone and the mobile view during assemble (right).

3.2. TEST 2 | AUGMENTED IMMERSIVE DESIGN AND ASSEMBLY

Test 2 explores the possibility of an AR immersive design and assembly process with a head-mounted display (HMD) that is capable of projecting digital information and 3D objects, such as holograms, directly in the workers' field of vision. To do this experiment, we decided to use Microsoft *HoloLens 1*, which uses a sensor-based technology that seemed suitable for our work.

We have used hand tracking, gesture identification, and device location recognition methods to give designers more possibilities and the experience of a more realistic, unobstructed, and more intuitive AR immersive design experience. To begin with, the designer can scan the QR code for on-site location confirmation by *HoloLens*. After that, the designer can "draw" the virtual control baseline of the brick wall on-site in AR environment by "tap and hold" hand gestures. As in the previous scenario, the user can preview the shape of the design, this time however in the form of a 3D hologram that is overlayed directly onto the site, and adjust the control baseline in real-time. Following on from this, the designer can modify the shape by "tap and hold" the virtual control points shown on the surface (Figure 4). After the shape is determined, the designer can preview the brick wall as an on-site holographic model in *HoloLens* and can adjust the numbers of bricks, the angle of bricks, the brick structure density, and the brick pattern arrangement by interacting with the AR sliders through real-time immersive design process.

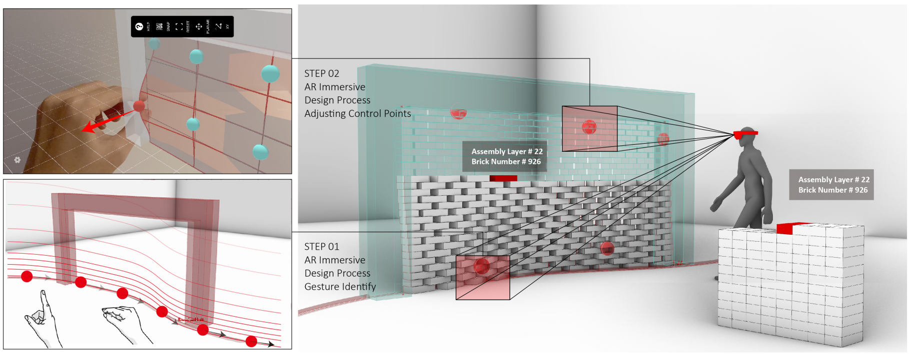

Figure 4. Identify hand gestures inputs and adjust parameter controllers in immersive design.

For the AR holographic assembly part, test 2 provides the users with the same intuitive immersive holographic assembly guidance as test 1. Instead of using iPhone 11, test 2 chooses *HoloLens*, so designers can walk around the on-site holographic model and use hand gestures to operate the assemble process state. The main difference is that test 2 is a hand-free workflow that gives users more flexible manipulation and a more immersive AR surrounding experience.

Test 2 shows that this approach is more immersive and indeed more intuitive. The higher degree of immersion assists the designer who is wearing *HoloLens* to modify and translate an on-site digital model into a physical structure. The input is more intuitive than using handheld devices, since hand gestures and even voice commands are recognized by the HMD.

However, such systems also have technical problems. The sensors in *HoloLens* are affected by the surrounding light condition. If too much or too little UV light is occurring in the natural environment, for instance, the holographic model has sometimes difficulties to lock a model in a specific place. Besides, the communication speed between *Grasshopper* and *HoloLens* in real-time is 4.136 Mb/s. Science this process requires more calculations than Test 1, the holograms have a little lag compared to real-time. The virtual information transformation from *Grasshopper* to *HoloLens* requires an internet with good connection and speed, such as wifi and 4G. If the internet connection is poor, it will cause a delay in hologram and real-time modification. As a consequence, it is sometimes necessary to restart the device and re-scan a QR code for correcting construction location.

Moreover, for the large-scale architectural assembly projects, the material might beyond the range of manual handiwork, such as concrete blocks, large-scale woods, metal blocks, etc,. For large-scale architectural structures, this AR-assisted design-assembly workflow will need the intervention of robotic fabrication.

3.3. TEST 3 | AUGMENTED ROBOTIC FABRICATION

Test 3 chooses the same brick column design as in Test 1, but this time adds robotic fabrication to the workflow of an AR/HMD-assisted design and assembly process. Robotic operations, traditionally, need specific expert computer science and programming knowledge to plan the movement of a robotic arm. For physical operation, robotic errors occur beyond simulation occasionally. This process is not without dangers if we imagine workers being in the same space as the moving robotic arm. AR provides us an interactive virtual robotic control methods and an on-site holographic robotic trajectory simulation to avoid the defect caused by the traditional robotic workflow. To do this experiment, we decided to use Microsoft *HoloLens 1* and a UR10 Robotic arm.

For this AR robotic fabrication experiment, we started with a simple robotic operation - "pick and place". First, the user can preview the brick location in the material preparation area and the target location in the assembly area through *HoloLens*. After preparing a physical brick in the preparation location, the user just needs to "tap" the virtual brick hologram, which is recognized and transformed in AR version through *HoloLens*, "drag" and "release" the virtual brick hologram to the highlighted target location. Next, the command for the robotic arm will be sent from the *HoloLens* sensor to *FURobot* plug-in in *Grasshopper*. The virtual on-site holograph simulation will be sent back to *HoloLens* and be ready for physical operation. Last, the user can preview the whole holographic simulation and switch the toggle to "Operate" to complete the robotic assembly process (Figure 5).

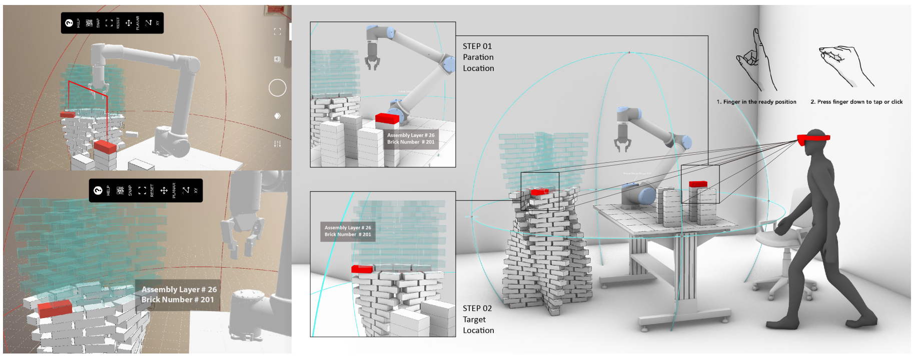

Figure 5. AR Robotic assembly process: view robotic operation maximum reach, preparation area, target area, and robotic operation trajectory.

Test 3 provides that it is a safer and more effective method to operate robotics through AR 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. In this way, the robotic fabrication workflow will not require specific computer science knowledge and skilled programming workers.

This last experiment also highlighted certain problems for us. The current functionality of test 3 is very limited. We only use brick-shape as the prototype material for tests, other kinds of materials have not been tested and confirmed that work well with AR/HMD-assisted robotic assembly workflow. But more architectural materials will be testing in future research.

4. Conclusion

The above-described three *AR Digi-Component* tests give an overview of the current state-of-the-art AR technologies, such as AR real-time modification, AR immersive design and holographic assembly, and AR/HMD-assisted robotic operation. Our research leads to three key recommendations in the fields of architecture and construction and in regard to the assembly of building elements at full scale (Figure 6).

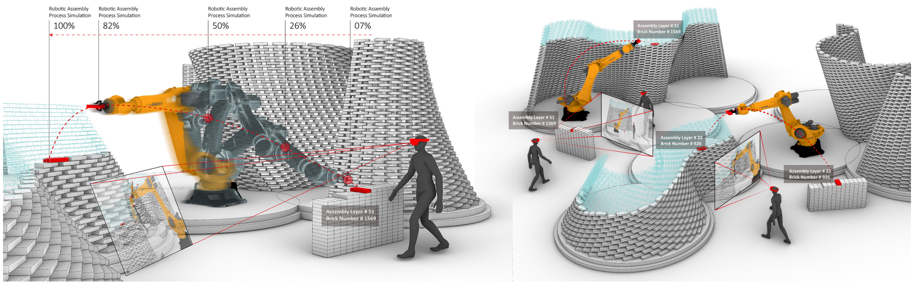

Figure 6. The holographic of robotic trajectory simulation in AR-Robotic assembly workflow for man-machine collaborative fabrication process in large scale architectural application.

In terms of **AR real-time modification and immersive design**, our research has shown that AR technology can translate the designer's gestures into corresponding parameter adjustments in *Grasshopper* to preview the immersive generated design. This method gives users a new way to modify design drifts and preview on-site locations through the AR environment in real-time. We hope that our research shows that, under certain circumstances (e.g. complex and labor-intense designs), a more intuitive and dynamic AR-assisted workflow could assist or replace the more conventional approaches.

For **AR holographic assembly**, it can improve the efficiency and accuracy in the assembly process, especially for unskilled labors to follow the stey-by-stey virtual instruction. This method can arguably also save time that is normally needed when translating 2D information into 3D on-site location design and built. Although there are still tolerances that occurred during transforming the assemble commands by the surrounding environment, devices, and labors, this situation will be improved by adding multiple AR devices for all assembly workers.

For **AR/HMD-assisted robotic fabrication**, it has been shown that modifying robotic movement trajectory plan and operating virtual holographic simulation is safer for human operators compared with the traditional industry robotic operation method. It offers the designers, who do not have special computer science or programming knowledge, a convenient way to operate the robotics for the construction of manual-unachievable materials directly through AR.

In conclusion, the *AR Digi-Component* project bridges the gap between digital design and physical outcome by designing a workflow that includes AR immersive design, AR holographic assembly, and AR robotic fabrication. Using this workflow, the AR device can detect and identify the designers' thinking and idea at any time; transform their gestures and reactions into digital outcomes calculated by parametric rules in *Grasshopper*; preview the hologram overlapping on the real world in real-time through AR device; and get the physical outcomes either in AR holographic assembly method or AR robotic fabrication method depends on the material behaviors. It brings the possibility to interact with AR and get the enormous advantage of feedback through AR to designers in real-time.

The further work will take in premeditation the additional development of involving multiple AR participants in the whole workflow to reduce the tolerance due to the command transformation. More sensors will be used to catch complicated human gestures in the immersive design part. Multiple robotic arms and operations will be developed for the man-machine collaborative fabrication part through an AR-assist real-time environment. Develop and complete the whole AR-assist design and assembly process as a *Grasshopper* plugin with the physical simulation of material properties for crash and collapse detection. The final goal is to make the whole AR design and assemble workflow simplified and modified for architectural scale elements and applications.

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