Augmented Construction

Impact and opportunity of Mixed Reality integration in Architectural Design Implementation

ABSTRACT
This paper discusses the integration of Mixed Reality in the design and implementation of non-standard architecture. It deliberates a method that does not require conventional 2D drawings, and the need for skilled labor, by using the aid of holographic instructions. Augmented Construction allow builders to execute complex tasks and to understand structural relations intuitively by overlaying digital design information onto their field of view on the building site. This gives the implementation system authors different levels of control. As a proof of concept, a group of non-professionals reconstructed the south wall of Corbusier’s Ronchamp chapel, the Notre-Dame du Haut, at scale 1:5 using no architectural 2D drawings but only custom-built Augmented Reality apps for HoloLens and mobile devices. This project focused on the assembly of non-standard prefabricated elements, based on an optimized parametric structure that enables designers to integrate imprecision within the construction phases into the design through a constant feedback-loop between the real and the digital. The setup was designed in a non-linear process that allows the integration of new information during the Augmented Construction phases. The paper evaluates applied Augmented Construction for further improvements and research and concludes by discussing the impact potential of Augmented Construction on architectural design, socio-cultural, and economical levels.
INTRODUCTION
Constructing complex geometries successfully “...requires some sort of construction machine that can efficiently translate the digital description of the shape into a tangible realization... Buildings were once materialized drawings, but now increasingly, they are materialized digital information” (Mitchell 2005). Augmented Construction allows non-standard architectural design to become more economical with the help of holographic manufacturing and assembly of custom-made parts and applications that do not necessarily require more time than modulated systems in small scale. Instead of visualizing 3D modeling information on a 2D screen, Mixed-Reality (MR) allows you to bring this information into the real world, in real scale as a digital overlay on top of real-world environment. Augmented Construction allows builders to execute complex tasks and to understand structural relations intuitively by overlaying digital design information onto their field of view on the building site. This gives the implementation system authors different levels of control. As a proof of concept, a group of non-professionals reconstructed the south wall of Corbusier’s Ronchamp chapel, the Notre-Dame du Haut, at scale 1:5 using no architectural 2D drawings but only custom-built Augmented Reality apps for AR-glasses and mobile-devices (Figure 1). This project focused on the assembly of non-standard prefabricated elements, based on an optimized parametric structure that enables designers to integrate imprecision within the construction phases into the design through a constant feedback-loop between the real and the digital. The setup was designed in a non-linear process that allows the integration of new information during the Augmented Construction phase.

Augmented Construction suggests future abilities to democratize skill through simple and intuitive holographic instructions that do not require professional training. Instead of deskilling human skill through automation in manufacturing, Augmented Construction enhances the human capacities to participate in complex building processes through simplified instructions.

BACKGROUND
The idea of using Augmented digital information for instructions dates back to the technology’s conception in 1992 (Claudel and Mizell 1992). Since then, Augmented Reality (AR) became popular through the gaming industry and social media face. The gaming engine Unity© in combination with its plugin Vuforia© allows users to build apps for bringing digital content into physical space by the use of image or object trackers that are detected and tracked by the device (mobile phone, tablet, etc.) to orient the holographic information in space. HoloLens, a head mounted...
display (HMD) from Microsoft® allows its user to display holograms by overlaying holographic information onto their eyes. “HoloLens is the first untethered Mixed Reality system. HoloLens includes precise head tracking, gesture sensing, and depth mapping allowing for accurate 3D world locking,” which is crucial in Augmented Construction (Kress, Bernard and Cummings 2017). Building apps for HoloLens through Unity® with Vuforia® combines the exact placement in space with the depth mapping of the surrounding to have the most applicable result for Augmented Constructions. Software development kits for mobile platforms like ARCore® and ARKit® have made the development of AR applications increasingly easy and the tracking of the holograms in space progressively stable, making them a relatively cheap alternative to head mounted displays, however without a depth of view.

Augmented Reality applications have been implemented on construction site by smart helmets and tablets, primarily for helping engineers “to make more accurate and more rapid judgments” for construction review tasks (Ren, Ruan and Liu 2017). User experiences for AR systems in industrial settings have been well accepted. They have shown that they have the potential to reduce errors in assembly and improve the quality of the maintenance work (Aromaa et al. 2018).

METHOD
Proof of Concept
To have a comparison between a project executed by 2D drawings and by Augmented Construction, a piece of iconic architecture was selected to be reconstructed. Using iconic architecture made it clearer for the team to follow the setup and compare the structure, built by holographic instructions, to its archetype, and we could focus more on the method and the design of the setup. The complexity of the south wall of Notre-Dame-du-Haute by Le Corbusier, lies in its convex and concave curvature, the variation in height, and the different-sized windows which are scattered in an irregular pattern (Figures 2 and 4). In its time, it was a masterpiece of architectural fabrication. The south wall was executed using concrete columns that were connected by a wire mesh that was sprayed with concrete onto the interior exterior surface of the façade by means of a cement gun (Pauly 2008, 81-82) (Figure 3). The reconstruction within the project does not aim for a replica in materiality of the monolithic and sculptural wall, but rather uses a cladded light weight mesh to come as close as possible to the exact shape of the wall, as well as to the exact location and size of the windows. The choice to do a reconstruction was to give the observer a well-known architectural piece, so that the evaluation of the execution of an Augmented Construction can be validated against a familiar example, rather than against a personalized design.

Tectonic System
For this Augmented Construction, we looked for a tectonic system that is flexible and adjustable—welcoming an exceptional tolerance of imprecision without the need of sophisticated tools—and that could be assembled with mediocre skills, embracing a high level of improvisation. For the reconstruction of the south wall in scale 1:5, we chose to fill the volume of the wall with a three-dimensional triangulated beam structure clad with tailored panels. This technique suited the convex and concave curvature of the wall and the different sizes of the windows and allowed sufficient anchor points to fix the cladding panels.

Digital Design
To find the optimal discretization of beam length and position, the setup was parameterized in a digital design software. Karamba3D® and Octopus® plugins for Grasshopper® and Rhinoceros® were used to optimize structural characteristics such as utilization and...
displacement against low material cost (less beams), and enough anchor points to fix panels to the beams. During the Augmented Construction phases, this data was updated through new as-built information onsite. Once the beam structure was completed, the new information of the scanned and AR-measured built structure was again digitized to update the size of the panels. These were optimized to cover the most area possible—without affecting the curvature of the wall—by finding a minimum of two possible anchor points on the beam structure (Figure 5).

App Design
The apps were designed in Unity© and used the plugin Vuforia© to place the digital model in the real world by the help of an image tracker that is used by the app to locate the model in space, at the same place in the same scale, each time you start the app. Each beam in the digital and holographic model had its length written as a text in its center. In combination with its color code, it was easy and fast to find the right beam (Figure 7 and 8). Also, the panels were all unique in shape and numbered in the app. To reduce the information in the digital and holographic model, layers were used to turn parts of the model and digital information on and off either by voice command in the glasses or by buttons in the mobile version (Figure 1). The apps were updated continuously with the new building information.

Holographic Fabrication, Prefabrication and Materialization
427 PVC pipes of 3m length and 16mm diameter were cut in 1275 correct sizes for the beam structure. There were two ways for the cutting: the conventional way of prefabrication by a list of elements; and cutting by the aid of Augmented Construction, which means to Augment the beam on site and to cut it according to the holographic template. Both methods are useful depending on available tools. The second method was used by integrating new beam lengths quickly on site. For the connection, a hole was drilled on both ends of each pipe. 1400 cable binders (5x250 mm) were used to fix beams to each other in space. A total of 36m² polystyrol sheets (1000x700x15 mm) were used to cut out the 348 panels on site by Augmented instructions and holographic templates. For the connections between the panels and the beams, 675 PVC clamps for 16 mm pipes were used, hot-glued on the Polystyrol panels and clamped onto the pipes.

Assembly Setup, Time
The assembly and fabrication of the elements was done without the use and need of conventional architectural 2D drawings, but only by the aid of Augmented Reality (Figure 6, 9-12). For this, the HoloLens was combined with a mobile device, an Apple© I-PhoneX©, in combination with the developed apps. A container was built to sort and hold the beams, which were color coded according to the length shown in the apps. An A3-sized image tracker was taped to the ground, fixing the position for the digital Augmented model. The beam structure was finished within 42 hours with 1 to 4 people and the panelization within 38 hours by 1 to 4 people.
RESULTS AND REFLECTION

Final Built Outcome
The spaceframe structure had a deviation of about 6% in total length, 2% in width and 4% in height from the 3D. The percentage of deviation constantly increased and decreased by the integration of imprecision. The panels that were tailored for the built spaceframe had an additional overlay of 4 cm, allowing it to respond to slight changes of angles of the beams that resulted in a rotation of the local panels depending on the position and number of possible connections to the beam.

Cause of Error
The beam connections were the main driver for observed imprecision. The holes drilled into the beams were of slight difference to the planned position and the overlap of the beams was not digitally integrated. Up to three connections were manageable, but as soon as eight beams hit one connecting point assembly became difficult. For a perfect solution, a 3D printed connection was tried, but it was deemed not economically suitable. The integration of the imprecision was much easier, cheaper, and faster than the execution of precision by a “perfect” system. Allowing the system to be imprecise was also a main driver for the overall concept of this project.

Hierarchy on Site / Number of Devices
The project was executed with one HoloLens and one mobile device only. Hence, the hierarchy on construction site was clearly defined, as the person wearing the HoloLens or using the mobile device was automatically the instructor to the others, as he/she was the only one having an overlay of holographic information. This slowed down the process and led to errors in communication since the assistants had no knowledge of information and had to rely on verbal instructions. To have more HoloLenses on construction site would be a great advantage and, at the same time, would present a challenge in managing multiple devices at the same project. The setup has to be designed so that the work field is clearly divided, or so that the holographic information is constantly updated corresponding to the construction partners wearing the same device.

Digital Setup
The holographic setup could be improved as well. Built parts could be blended out digitally after having been constructed physically and parts of assembly could be highlighted to improve the workflow. One issue faced onsite was that people needed verbal instructions on how the apps work. Making the instructions clearer by displaying them inside the app as a digital/holographic manual would

Feedback Loop
During the Augmented Construction phases, uncertainties and imprecisions occurred mostly by the connection between the beams by cable binder. To integrate this impression and to have a constant exchange between the digital and real model, the physical model was remeasured through the app AR-Measure© by Apple© and through 3D scans during the construction phases. To adjust information, the updated digital model was rebuilt into the app. Thus, updated holographic instructions were available right away. The hologram instantly shows you when you deviate, allowing easy identification of spots that do not match with the 3D. Thus, in what Crolla calls a Post-Digital architectural context, “...the case is made for the use of more democratic epistemic models and more intelligent structures of approximation than (common) deterministic approaches in digital design would allow for” (Crolla 2017, 1-2).
make the app more accessible to people without the need of verbal instruction from the author.

Surrounding
The project was partly executed in an outside area as a public event. While space and a free field is great for holographic displays, sunlight is unpractical as it easily outshines the hologram. Improvised shadowing constructions had to be built, like hats or paravents, to prevent the sun from interfering with the holograms. Hence, ideal sites for Augmented Construction would be large indoor halls with controlled lighting.

App Design vs. Live Streaming
At the time of the project execution, there was no access to the recently developed software Fologram©. This software makes it easy to concentrate on the setup, as it requires no coding or app development and allows geometry, text, and selection data from the Rhino and Grasshopper document to be live streamed to the HoloLens (Jahn et al. 2018). There is no need to update the app with new information, which makes for an even workflow between the digital model and the holographic display. The only disadvantage, however, is the need for a Wi-Fi connection and a computer from which to stream rather than only the HoloLens or a mobile device with a built-in app.

Feedback and Live Tracking
The feedback loop that was used during the project was based on 3D scanning and AR measuring. The HoloLens 3D scanning by itself does not differentiate its surroundings between the environment and the project. It would have been beneficial to have had a direct feedback between physical build elements, the digital model, and the holographic display. Fologram© allows for this direct feedback—by tracking and tracing markers position with HoloLens—to have a live display of physical built elements in 3D by digitalizing the marker positions and rebuilding the elements based on the location of tracked points.

Further Applications for Augmented Construction
“A strong dichotomy exists between the increased architectural design agency offered by digital tools today and the affordances given by many construction contexts, especially building environments in developing countries with limited available means” (Crolla 2017). As demonstrated by the project above, Augmented Construction enables a broader public without architectural knowledge to participate in the act of building through holographic instructions. “...[O]nsite affordances can be increased in parallel with the expanding virtual design solution space” (Crolla 2017). Using computational design tools and making them accessible through Augmented Reality applications has the potential to increase limited affordances on site for complex solution spaces.

Architectural Design
Augmented Construction allowed for the construction of a customized spaceframe and panelization that would have been extremely challenging with conventional 2D
plans. Even to construct the piece with a 3D model next to the construction site on a screen would be very time consuming and complicated. This paper claims that it would not have been possible to construct the same piece of architecture in the same time frame under different conditions than by Augmented Construction.

CONCLUSION
The project has shown that it was possible to construct a complex spaceframe structure with a tailored cladding without the need of 2D drawings, but only with the aid of holographic instructions in a Mixed Reality environment. Augmented Construction allows an architectural design process during the construction phases through a constant feedback loop between the digital and the built. It enables a broader public to participate in building by encouraging untrained labor force with intuitive holographic instructions. Augmented Construction is economical as it is low in cost; and it uses humans, rather than machines, to execute complex digital information. It enhances customized design and complex geometrical arrangements as it is comprehensible on a building site through holographic instructions and displays. Augmented Construction simplifies digital complexity in physical fabrication and construction and, therefore, has the potential to change the way we will design and construct our future spaces.

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REFERENCES


IMAGE CREDITS

Figure 2: The Chapel at Ronchamp drawing © Le Corbusier; from Le Corbusier, Princeton Architectural Press, 1999
Figure 3: Ronchamp: Lecture d’une architecture © Daniele Pauly, Strasbourg, 1980
Figure 4: © Wayne Andrews, Estate of Wayne Andrews, New York: Artists Rights Society, 2009
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