AUGMENTED ACTIVE-BENDING FORMWORK FOR CONCRETE

A Manufacturing Technique for Accessible Local Construction of Structural Systems

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Abstract. This research introduces Augmented Reality (AR) for manufacturing concrete structures through an open platform for autonomous construction. The study was developed under the following scopes: computational algorithms for bending simulations, materiality tests, system implementation, and a set of Augmented Reality (AR) tools. AR devices offer a technological tool that allows for a self-built environment through holographic guidance, allowing the untrained workforce to participate in the process. This technology can help users select the system to construct through an Open-Source platform, reducing the gap between complex computational geometries and construction processes. The research aims to investigate a building system that could benefit the UN Objectives SDG 10 by increasing the access to technology in undeveloped communities, SDG 11 and SDG 12 by promoting a self-sustainable method of construction based on local resources and material efficiency. In conjunction with the development of the AR Platform and augmented manufacturing, a 1:1 prototype was built in Quito, Ecuador, with the help of seven people with no previous knowledge of digital tools or construction. Presenting a novel, fast, and affordable concrete formwork connected with AR assisted assembly methods that facilitate access to more efficient and advanced building technology.

Keywords. Mixed Reality; Distributed Manufacturing; Online Platforms; Affordability; Local Communities; SDG 10; SDG 11; SDG 12.

1. Introduction

Augmented Reality is a group of technologies that belongs to a spectrum called Mixed Realities. This set of technologies allows for different interactions between humans and machines. A variety of media can be used to achieve this, as long as they fulfil the requirement of altering the typical understanding and perception of the real world by

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humans. (Milgram, 1994). Augmentation devices will soon become mainstream media for future workers (King, 2016), and with the use of these devices, users can have easy access to skills-enhancing technology.

1.1. ARCHITECTURAL CONTEXT

The development of assisted manufacturing is not new. Several projects have been testing the capabilities for AR to help with the building process. From an assembly perspective, "Real Virtuality" project (Retsin, 2019) presents the design of modular timber blocks that can be assembled in a discrete manner using AR through Hololens. The model itself could be changed in real-time due to its non-fixed design. Similarly, in regards to AR assisted manufacturing, the Steampunk pavilion, designed by Jahn, Newnham, Hahm, and Pantic, proposes an alternative to automation and robotic production. This project explores the production and assembly of steam-bent timber elements coupled with steel sections for joints. Both of which are formed into place following holographic guides projected through Microsoft Hololens (Pantic, 2019). As a result, unskilled workers were able to build the pavilion, demonstrating the skill-enhancing capabilities of AR technology.

1.2. OPEN PLATFORM FOR AUTONOMOUS CONSTRUCTION.

Technological devices such as smartphones or tablets have exceeded many predictions. The implementation of such devices is now mainstream and is evident even in the most undeveloped areas (King, 2016). Countries like India have doubled their user base within six years. There are more smartphone users in India than in the US (Newzoo.com). This trend generates a significant opportunity to open and modernise the building industry in rural or isolated areas. With the smartphone as a mainstream tool, local communities have access to various platforms to increase participation in the building environment. Projects like WIKI House (2012) or the work developed by AUAR in London (2018) could exemplify how the implementation of the platform performs a more participatory workflow allowing for community involvement.

1.3. AUGMENTATION FOR IMPROVED REMOTE SKILL ACCESS.

Access to some technologies or construction techniques is an extended issue in remote or underdeveloped areas. The difficulty of finding qualified technicians is an important matter. Usually, this is why design and construction techniques are limited among these contexts (Auwalu et al., 2018). Augmentation could be one of the most accessible options to improve skills access (Coppens, 2017). Using computational design and platforms, simple systems can be computerised and managed by a non-expert user through a simplified interface where the user selects and defines the building needs, after which the algorithm proposes the best solution. This shift on the typical workflow increases the user's autonomy, facilitating advanced design for areas traditionally isolated from the latest technology. Here, the use of AR during the construction process and access to such platforms instantly skills up the builders to the needs of the applied construction system (Goepel, 2019). Using AR manufacturing, workers can access a more varied range of building techniques and technologies, facilitating more efficient or versatile design ideas in inaccessible or remote areas (Hahm et al., 2019).

1.4. ACTIVE-BENDING STRUCTURES.

The main structural principle is bending deformation and force transmission to neighbour elements (Lienhard et al., 2013). Most of its use has been recorded worldwide in various vernacular architectures, demonstrating that this structural principle is familiar to most cultures (Suzuki and Knippers, 2018). The primary process of bending active structures is generating a 3D curve geometry from planar 2D compositions (Nicholas and Tamke, 2013). As an illustration, the AA Hybrid project presents a plywood structure, incorporating analogue and digital parameters to rearrange local behaviours (Laccone et al., 2020).

1.5. COMPUTATION AND CONSTRUCTION IMPLEMENTATION

Most bending-active structures present unpredictable bending events within their compositions. As Lienhard explained, it is due to the high resilience of the material used because of the elastica law presented when actively bending (Lienhard et al., 2013). To reduce this gap, Suzuki and Knippers's research presents a recalculation of unpredictable fabrication irregularities by incorporating the Iguana software, reducing the gap of computational geometries and physical models (Suzuki and Knippers, 2018). Something that could be connected with AR to promote a higher precision when fabricating. AR introduces a novel method for better accuracy in fabrication and construction by translating 3D geometries to the real environment, avoiding 2D drawings that might be inaccurately reproduced due to computational geometrical complexity (Goepel, 2019).

2. Design Methodology

This project explores Augmented Reality's boundaries to reduce the complexity of fabricating active-bending structures, promoting an autonomous execution aided by holographic visualisations. The novelty relies on using these structures to create inhabitable spaces and test its capacity to generate long-term compositions by using them as concrete formwork. The design incorporates an experimental formwork system to build complex concrete small-scale structures that can be constructed without expensive machinery and can prove the versatility to adopt any design solution.

The polygon system implements a generative solution for straight curve positioning, where each curve is attached with its neighbouring vertex as a single closed bending iteration, as shown in Figure 1. The design strategy is based on polygons based on 3D polyhedrons inside a single voxel. The straight lines of each polygon are constrained by length and attached using vector points and curve self-attraction. To avoid inaccuracies in the translation of the computational active bending simulations to the physical models, the bending behaviour is controlled by tangents, not allowing the curve to have closed angles that could not be replicated in physical models.

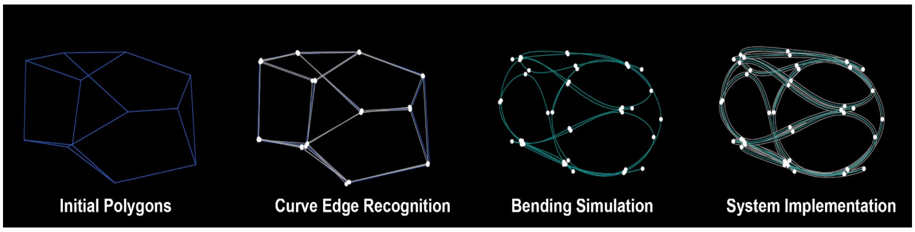


Figure 1. Curve bending from control points within polygons

The extension of this system acknowledges the difficulty of producing a large-scale proposal, considering the workforce and the number of people building a single compound space. Therefore, it incorporates chunks of concrete from several components that function as formwork. These chunks represent a part of a whole, which means that the different sections can be constructed separately and built-in situ, creating small-scale structures with a minimum length of 1.85 m.

2.1. MATERIALITY

This project aims to use locally sourced materials that are globally found for easy experimentation to follow the SDG12. Although the PVC's sustainability is not optimal, in this case, it was selected as an accessible material to test the concept, and further research will explore more sustainable materials like bamboo or other natural fibre-based pipes. PVC Pipes were also selected due to the ease of purchase worldwide and thickness needed for concrete spraying. The properties of these elements vary depending on their use and Size; therefore, 20 mm hollow PVC pipes were selected due to their physical bending performance and malleability, following Georgiou's 'God's eye' pavilion structural implementation with these types of pipes (Georgiou et al., 2014).

2.2. DIGITAL DESIGN AND CONSTRUCTION SYSTEM

The physical performance for active-bending and the structural behaviour is also tested and analysed to ensure a correct transition from the virtual model to the actual prototype using Grasshopper and Kangaroo Plug-ins. The explorations showed that each time a composition reaches a high displacement, more elements need to be added, forming a packing system of pipes. The structural simulations also predicted the displacement within large-scale compositions, allowing the re-adaptation of the components for structural optimisation.

The need for a more resistant and stable structure was solved by integrating a reinforcement strategy based on bundling several pipes on the weakest areas and reinforcing the future concrete by installing steel rods along the curves attached with 3D printed TPU brackets as described in Figure 2. This system increased the rigidity of the formwork and allowed for easier spraying of the concrete.

Figure 2. Construction System - PVC Pipes/Rebars/Joins

2.2. CONCRETE SPRAYING

The first small series of explorations were tested with different types of concrete mixture to assess its addition capability onto the PVC pipes. We determined that Glass Fibre Reinforced Concrete (GFRC) was optimal due to its high malleability due to the fibreglass elements within its mixture. The first layer of concrete did not attach continuously onto the surface; therefore, it was decided to spray glue on the pipes, which solved this issue. It was established that the number of layers directly relates to the amount of bending stress of the geometry, determining a minimum of three layers for simple shapes and a minimum of 5 layers of GFRC for demanding areas, the results of the system are shown in Figure 3.

Figure 3. System Implementation with Concrete

3. The Augmented Reality Platform

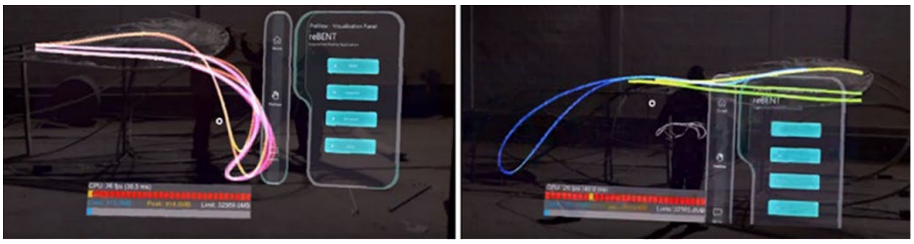
With the idea of promoting the SDG 11 goal for a more accessible quality housing with the inclusion of local communities, a bespoke software application was developed in Unity© for the Augmented Manufacturing to be used with Hololens and supported by Windows Mixed Reality Toolkit (W-MRTK). The Microsoft Hololens application processes the model from the design development logic and transforms it into building data to generate the construction sequence that any individual can easily access and use.

Starting with a home screen to choose between a new project or a work in progress, the AR platform is then reduced to a single menu for project interaction. As shown in Figure 4, this menu can be found the primary information about the project's construction, the quantity of elements specification, fabrication steps, and component assembly. Through this display, the user can easily prepare and program every section of the assembly process, knowing in advance the number of elements and the types needed.

The holographic visualisations facilitate a tutorial-like interaction on a step-by-step process. The user interacts with the holograms to replicate their shape with the different pipes, introducing an efficient self-assessment process. Each component is represented by different colours, where the final input shows the coloured components altogether. To reduce time in constructing or reviewing a work in progress, the app allows the user to go back, visualise the final composition, or skip steps if the user decides to build a different iteration. The AR Platform adapts to different scenarios where the user is the one who manages the operation and construction of the pre-designed systems. It promotes the autonomous and efficient construction of complex concrete structures, eliminating the need for printed plans or constant laptop screen checking.

3.1. AR APP IMPLEMENTATION AND TESTING

The test of the platform and the construction of a prototype were both tested in Quito, Ecuador. The pavilion design comprises a stable core structure with wings extending to both sides. The geometry was designed to test complex cases and test-proof its versatility. The composition was divided into three sections for assembly, one roof and two walls. With the help of 5 people, the 7m long by 2m high prototype was built within two days, working 5 hours each day. The people involved had no prior knowledge of the technology used or previous construction experience. All of the components were assembled using AR visualisations. The initial architecture was divided into three large sections, as mentioned above, fabricated on the ground. Then, AR visualisations were used to guide the assembly order, direction, and casting to enhance the stability of the structure portrayed in Figure 5.



Main Structure Holograms **Components Aggregation Sequence**

Figure 5. Platform Mock-up and Real Implementation

3.2. IN-SITU BUILDING TEST

The bending of the PVC Pipes for component construction was easily replicated thanks to the holographic visualisation. Only one Hololens device was available; therefore, Fologram©, a Grasshopper© plug-in for AR visualisation, was used in two mobile devices, one iPhone X and one iPad Pro as shown in Figure 6. The team was formed by people from the local area that participated voluntarily and whose professional background was not related to the architecture or building industry.

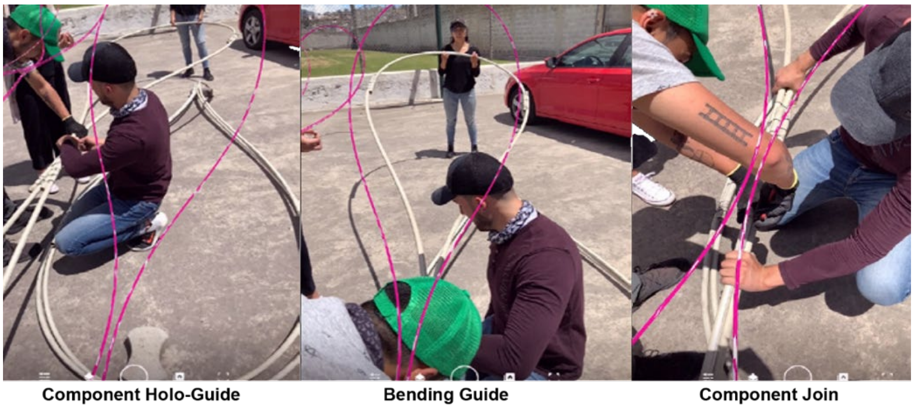


Figure 6. Fologram Implementation

The people in charge of the AR guidance marked specific points in the ground to follow the bending sections of the pipes. Then after bending them, the rest could see the visualisations inside the iPad to check its intended shape. The components then were constructed easily, efficiently, and with precision.

The inaccuracies mainly occurred in the connection of the components. Even with the pre-established bundling system, the expected flimsiness was higher than projected. The rebar diameter was not enough to add stiffness to the structure, re-designing the packing system to the following elements: 1 PVC Pipe of 20mm requires 4 x 6mm rebar, 4 PVC Pipes 20mm – 8 x 4mm rebar, and 10+ PVC 20mm – 12 x 4mm rebar, where most compositions should have at least four pipes as packing system. An additional 4 mm rebar was placed inside the main pipe for a stable bending moment, avoiding the pipe's rupture in stressed sections. Once implemented, the flimsiness reduced significantly, although still presenting some stagger level. After the assembly, the PVC + Rebar skeleton was sprayed from bottom to top in several layers with GFRC to complete the structure. The result was satisfactory as the model was fully achieved as well as fully functional and stable, portrayed in Figure 7. The fact that all the people involved had no prior experience in construction was also a remarkable fact.

Figure 7. Pavilion test results.

3.3. AUGMENTATION AND ACCURACY

The use of Fologram© was necessary for fast changes within the pre-designed components. Some of them did not work correctly for the structural stability of the pavilion. Therefore, changing them in real-time for physical reproduction was highly efficient. The pavilion presented a deviation of around 0.21m in length from its right side compared to the left side and 0.08m in height from the original model. The use of the Hololens App was essential but limited. If a pre-designed object did not work correctly, changing this takes more time than pre-loaded inside the app. A small but noticeable difference in accuracy was shown in the process between Hololenses sections and other devices sections. That was due to the fact that Hololenses have a more accurate set of cameras and sensors than an average iPhone or iPad. Still, the precision was sufficient to achieve a correct construction process.

The holographic visualisations were easy to follow for construction processes, but the mentioned difference between devices also slightly slowed the assembly. It is significantly more practical to work with a HUD while assembling than a handheld device. Also, the assembly process was done at night because of the sun's glare, which impeded the correct visualisation of the holograms.

4. Conclusions

The extent of opportunities and social applications of an Augmented Reality (AR) platform allows effective communication of pre-designed components. It provides an opportunity for users to self-build pre-designed objects, transforming simple archetypes into systems that generate other systems. This research tests the boundaries of AR fabrication for construction without using expensive machinery such as robotic arms for 3D printing, and the use of prefab architectural elements, promoting an autonomous work interface.

The research presented here was conceived as an early approach to how the XR can influence the future of manufacturing and construction in architecture. The prototype experiment shows that Skills Augmentation and deployment into undeveloped communities is possible. The volunteers could achieve a prototype of a new system for flexible formwork for concrete without any previous experience. Also relevant is that only a single AR Head Mounted Device (HDM) was necessary for the construction, which shows the excellent synergy between the experimental system and the guided assembly from the AR HDM. Regarding the concrete formwork technique, it is clear that further improvements must be made to make it viable for a more mainstream application. In the same direction, additional research will be needed in the material aspect. Although GFRC and PVC were selected for their ubiquity and easy access, more sustainable and locally sourced materials have to be explored in the future to guarantee that the project improves its alignment with the SDG goals. Materials like bamboo or the use of natural fibres and concrete replacements will be analysed in future iterations. However, the prototype was stable and can be considered a success. Finally, we can also conclude that Augmented Reality creates new opportunities for the building industry, in alignment with the SDG 10 and SDG 11, therefore, having the potential to bring digital technologies to remote areas facilitating access to technical skills for unskilled workers broadening access to a more efficient, collaborative and technological architecture.

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