Reusable Augmented Concrete System

Accessible Method for Formwork Manufacturing through Holographic Guidance

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Reinforced concrete has been one of the essential materials for modern architecture for the last hundred years. Its use is entirely global, having been adopted by all cultures and styles since its invention in the late 19th century. Although its value is excellent due to its low cost, durability and adaptability, its environmental impact is significant, being, in fact, one of the most polluting industries in the world (Babor et al. 2009). This experimental project will research a more sustainable use of concrete, exploring a new form of reusable concrete formwork that will ideally reduce the CO2 footprint by removing wood waste in the casting process and replacing it with adaptable metal components. The modular part-based system for the concrete casting also attempts to simplify one of the current complexities for concrete construction, the Skilled-Labour shortage. (Yusoff et al. 2021). To mitigate this problem, the project also proposes using an Augmented Assembly logic for the casting parts to guide the ensemble and dismantle the formwork through an optimised algorithmic logic. The use of Augmented Reality as a replacement for traditional paper instructions will facilitate access to more workers to this construction art and potentially improve access to optimised use of concrete in developing communities with restricted building technological resources.

Keywords: *Mixed Reality; Distributed Manufacturing; Augmented Manufacturing; Sustainability; Computational Design; Concrete Casting.*

INTRODUCTION

The use of hardware devices to enhance the capabilities and performance of a particular worker through digital guidance is called Augmented Manufacturing (King 2016). This digital guidance, also called Augmented Reality, is part of a broader spectrum named Mixed Realities, which contains all the different interactions between sense interactive devices and humans (Milgram & Kishino 1994). As is theorised by futurists like Michio Kaku, the use of augmentation devices will be of everyday use in the future, and the augmented human will be the norm in the working force (Kaku 2014).

The Concrete Problematic

The use of reinforced concrete in architecture in the last few years has been questioned due to its significant negative cost to the environment (Babor D. et al. 2009). From its production to the in situ casting. This factor, combined with the waste in wood and other formwork materials, results in a very polluting yet essential building element. Another negative factor is that the assembly of the formwork and the reinforcements require a costly and complex process that has to be achieved by highly qualified professionals that are not always available in every location (Auwalu, S.S. et al., 2018). To face this problem, the project presented here tries to overcome part of this situation by proposing an Augmented Assembly Metal Formwork that is reusable and adaptable, easy to pack and transport, can be managed by unskilled workers, and is optimised for “Glass Fibre Reinforced Concrete” (GFRC) to reduce complexity. Therefore, this approach would cut waste and time for the “in situ” casting to reduce the CO2 emissions in the concrete manufacturing process (Bahar, A. et al., 2021).

Augmented Manufacturing in Architecture

The use of Augmented Reality for manufacturing in architecture has recently been developed from several perspectives. Whether it is used for complex assemblies like the ‘Real Virtuality’ project, developed by Gilles Retsin (Retsin, G. 2018), or to enhance traditional crafting methods like the steamed wood bending in the ‘SteamPunk’ pavilion, designed by Jahn, Newnham, Hahm, and Pantic, the overall approach is to facilitate the access to a broader range of labour into complex manufacturing projects. Both proposals rely on using Holographic guidance to help unskilled workers produce a complex and digitally designed project. Further than just creating complex architecture, the real advantage analysed here is if Augmented technologies can help close the gap and solve the lack of skilled labour in the building industry (Yusoff S. et al., 2021).

Metal Manufacturing with AR

The use of alternative casting materials to the traditional wood formwork that can be reused is an essential keystone in the development of the project. Several materials were considered, from plastic to wax or fabric. The necessity for a robust and versatile material that could be reused or implemented on the final piece as part of the architectural design was paramount. That led to the selection of metal as the most suitable material, thanks to its tenacity, reusability capabilities, and easy global access.

Metal manufacturing is traditionally a complex process that requires skilled labour to be completed. With the inclusion of AR techniques, some projects have shown the potential to change this issue. The Woven Steel Pavilion team (Jahn.G. et al., 2018) had built Mixed-Reality applications bridging the Hololens and McNeel & Associates Rhinoceros 3D©. Under the interactive holographic instructions of the platform, a pavilion structure consisting of 92 unique parts and 560 individual bends was accomplished within three days by two teams of two people without any prior related experience in construction or metal-making. Also very relevant is the great precision achieved in the prototype. The structure was made from a 16mm radius pipe. The final physical model deviated from the digital model by only an average of 20mm across all parts on a 6m+ prototype. This project seems to prove that, when dealing with relatively complex architectural fabrication and assembly, augmented fabrication has the potential to reduce the skill requirements of operators while maintaining the efficiency and relative precision of construction. Based on this precedent, This project will implement this idea to research and develop a ‘skill-accessible’ and sustainable AR integrated concrete metal formworks system.

THE PROJECT

This project explores the boundaries between augmented reality technology and architectural computation, introducing and understanding the mechanism of mould manufacturing and casting techniques for users without previous construction experience by reducing and simplifying the fabrication process with augmented holographic visualisations. The generative design focuses on an experimental geometry system for the formworks to build small-scale structures with necessary construction components that can be fabricated and cast without heavy machinery while equipped with an AR device. The challenge lies in creating inhabitable structures with limited constructional components due to the cost, control and labour force factors and testing its life-span capacity to achieve long-term composition flexibility and a reconfigurable formwork system to reduce material waste.

METHODOLOGY

Generally, AR-assisted manufacturing and assembly workflow relies on the designers' pre-designed construction modules and structures through architectural computation. It then deploys the models within the Hololens 2© user-interface structure for manufacturing and assembly works. To make the approach of modular moulds repetitive and fabrication-friendly, the architectural computation practice starts with the study of geometry to investigate a suitable formwork system for both the prefabricated and the on-site casting construction components. There are two essential categories that contribute to the selection of geometry type: one is the overall area when it is being unfolded, which affects the amount of material used to produce the formworks; the other is the possibility of combinations or the number of growing directions which are determined by the number of surfaces that share compatible typology with its neighbour.

The generative logic is provided by the Grasshopper© plugin WASP©. Components can grow according to customised rules, including free-form growth, curve or surface constraints, and field-driven (point cloud) aggregation by defining the geometrical centre and two-directional vectors on one specific geometry surface.

Then a category with various basic components was classified into several layers according to the number of geometry used to form the basic components. Also, prototypes are fabricated using various materials, including different moulds panels and recipes for plaster and concrete casting for testing purposes.

The Hololens©, a Head-Mounted Display (HMD) system by Microsoft Corp., provided 'precise head tracking, gesture sensing and depth mapping allowing for accurate 3D world locking' (Kress et al. 2017). Hololens users could interact with holograms by the behaviour of their bodies, such as gestures and voice and develop applications for HoloLens© with the Unity© engine. On Mobile platforms, AR applications could be developed with software development kits such as ARCore© and ARKit© (Goepel 2019), making them relatively low-cost alternatives to HMD devices.

COMPUTATIONAL DESIGN

The trend of technological devices getting more intelligent and smart fosters a significant opportunity to stimulate and modernise the construction industry in remote or isolated areas where labour force and economic development are limited. With devices accessible to the Internet, local communities and citizens of various age groups can increase participation and efficiency in the built environment through different platforms. The scope of computational design is to equip the project for autonomous construction with multiple digital solutions of construction realisation while simultaneously making the information easy to get and to be understood by the user through a smooth human-computer interaction process.

The Space-Packing Geometries

The geometry study and moulding system were both investigated at the same time concerning geometry itself and the typology of unfolded surfaces. Inspired by the aluminium can artist Noah Deledda, whose artwork *'Traephexa'* (Deledda, N. 2018) with scratched and dented metal can indicate the relationship between spatial volume (the cans) and its skin patterns (moulds) who, have the great potentiality to simulate and perform the mould-casting construction process.

Geometry components were evaluated mainly in two aspects. One is the packing efficiency calculated by the value dividing the overall volume by its gross total surface area when being unfolded; the other is simulated via WASP© plugin workflow

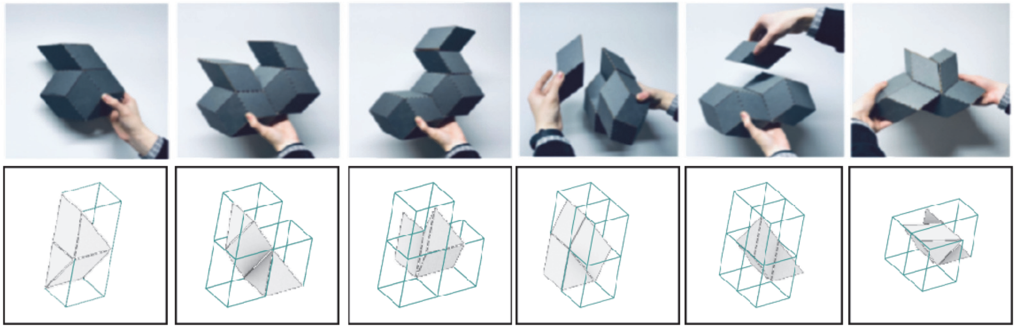

Figure 1
Geometry Grid
and Prototypes

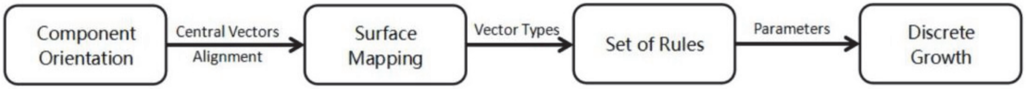

Figure 2
Generative Logic

to identify the space-packing grid (Figure 1). In order to make the geometry components capable of forming a tessellation of space, a collection of space-filling polyhedrons is necessary, which is usually accompanied by an identical spatial grid system, allowing geometry components to grow within. There are five space-filling convex polyhedrons with regular faces: the triangular prism, hexagonal prism, cube, truncated octahedron and gyrobifastigium.

The results indicate that when calculated individually without any growth constraints, triangular prisms have a significantly lower packing efficiency than the rest of other polyhedrons but with very limited growing directions, resulting in the lack of variety of construction components. This limitation was also found in the gyrobifastigium family with only two surface typologies. Hence, truncated polyhedrons were the ones that have both the space-filling feature with a number of growing direction options, among which the truncated dodecahedron has a relatively high and stable packing efficiency when the number of geometry increases. Additionally, the packing efficiency of Parallelepiped takes only 25% of the one truncated dodecahedron has. In order to increase the complexity of growth direction and chunk variety, parallelepiped that shares the same size of surface typology was added as a transition geometry together with truncated dodecahedron to form the components.

The Generative Algorithm

The WASP© algorithm works based on predefined geometry that organises parts made by several elemental components. The surface determined the generation of growing geometry with its central point and the direction vectors. (Figure 2) The algorithmic generation can identify each surface by mapping the geometric centres and the direction vectors. What we need to do is to set the rules both vertically and horizontally by the expression:

Component 1|0 _ Component 2|0

This means that point 0 in the point list on the surface of component 1 could only be attached to the same point on the surface of component 2 when conducting the growth command, and vice versa. By applying these rules to the WASP© plugin, the structure could be easily generated by following the above rules.

Additionally, there are three additional parameters that the user could control: (1) the first one indicates the quantity of population in the form of an integer number; (2) the second one is a boolean input defining whether the components can be populated based on themselves or not

Figure 3
Pattern Study

(SELF_P); and (3) the third one shares the similar type of input with the second that whether it can be populated based on the attributes which have the same predefined ATTRIBUTE-ID (SELF_C). While the first parameter was relatively straight-forward, the latter ones are more detailed control parameters, especially when the components contain more than one geometry. By setting the SELF_P false and SELF_C true, the components will only connect with each other through the attributes that share the same predefined ID.

Based on this logic, components were not only able to grow within the specific spatial grid but also within the constraints of curves (curve-charged aggregation), surfaces and point clouds (field-driven aggregation). Therefore, design attempts like chunks, walls, and floor slabs were generated for the pattern study by populating components with proper constraints (Figure 3).

Two important factors were considered for the efficiency and variety of space-filler: one was that the component mould should be easily folded with as few boundaries that might cause leaking as possible. Another was that it contains reasonable options of self-extended directions. For the wall patterns, the logic with surface constraint was applied. The same growth logic with surface constraint was also applied in the development of floor slab and stair patterns, with shading slabs that contain skylights and typical solid floor slabs both with and without steps. The design attempt mainly focused on the basic shelter unit built via these construction components. This approach made construction components ready for more complex constraints, including field-driven aggregation with point cloud and curve-charged aggregation to formulate a pavilion, a villa, or even a high-rise building.

Then the challenge came to the configuration and reconfiguration of the formwork system. The initial plan of the formwork system was to use water-jetted metal moulds to cast concrete. Generally, any suitable and cost-efficient material to cast works within this formwork system. To avoid leaks, specific connections between moulds were also carefully studied. By analysing the surface, generative logic could identify the neighbouring ones which could possibly form a mould if they combine with each other. Then by unfolding those surfaces, users could get the moulds accordingly and start producing parts for future construction.

There are two ways for the moulds to configure and reconfigure, one is to be removed after the cast (reusable moulds), and another is to be kept on the surface of construction parts as decoration coverings allowing pipes, wires and other interior components to go underneath.

In the former case, the database will be informed of the number and the type of moulds being removed. Then, a variety of new attachment components based on the already-built one are generated by the algorithm and the input parameters, including the number and the typology of additional components for users to choose from following the moulds available to be reused for the next cast.

The latter case offers another option of mould aggregation, which allows more forms of tessellations and installations that are different from full space-packing to fabricate furniture and interior parts such as a lampshade, tables, ceilings, and baseboards (Figure 4).

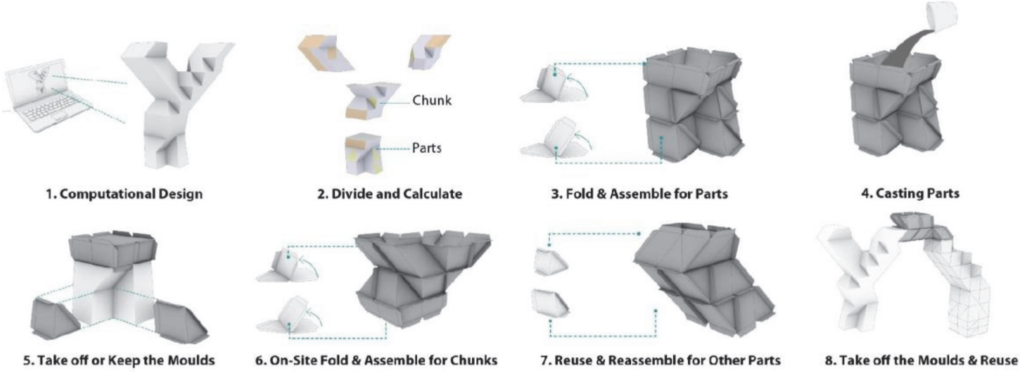

Figure 4
Implementation
Logic

Figure 5
AR Manufacturing
Implementation in Coal
Drops Yard, London

AUGMENTED MANUFACTURING

The HARI (Human-Augmented-Reality-Interface) development logic for manufacturing was categorised into several tracks for the UX design, taking individual construction experience into account to form an AR application loaded in the AR Headset for the on-site casting activities. The test of Augmented Reality Manufacturing Application implementation of a prototype was tested in an urban environment. (Figure 5). By adding basic components such as chunks, columns, wall patterns and floor slabs (stairs) into a collection of digital models in the database, the AR App was able to recognise and adjust the combination for both the moulds and the shapes. Furthermore, the construction steps are thereafter guided from the assembly to the casting process. Additionally, designers could check the status and real-time three-dimensional render through the augmented wearable devices while adjusting their models with real-time feedback.

The result of the App is a comprehensive system that guides the user through all the manufacturing steps, from the mould making and assembly to the casting process and the reconfiguration of the moulding components for a new segment, making the whole system accessible and intuitive. In order to further simplify the use of the Augmented Manufacturing app, the controls logic is based on a hands-free logic. By using an HMD and a series of gesture and voice controls, the user can easily interact with the physical components with both hands, facilitating manufacturing and assembly. The digital design outcomes with corresponding formwork combinations generated via algorithm

Figure 6
Fologram© Assembly Sequence

were imported into the application's database. Then the digital assets, including texts, static 3D models and simulated cast results, would be streamed to the AR devices and projected to the real world through space-aware deep mapping for holographic guidance. Simultaneously, FOLOGRAM© (Figure 6) embedded on smartphones provides an alternative when the amount of AR devices is limited or as well as secondary guidance.

Referring to the workflow, the AR guidance can generally be divided into four stages. However, it is worthwhile to mention that the Configuration-Cast-Reconfiguration procedure is not a single linear process but an iterative process through a constant feedback loop between digital modelling and in-situ manufacturing.

Folding Technique

Before the start of fabrication, the user chooses to import the architectural prototypes generated on the computer that is supposed to be cast. Then, the app will display the relative information, including the calculated concrete consumption, the catalogue and quantity of required mould pieces and the estimated completion time. In this step, the fabricator folds the water-jetted metal sheets to certain angles by aligning the hologram. Coloured overlays provide instructions for each fold. Additionally, individual decoration-oriented metal parts needed to create reconfigured interior components are also considered to enrich the database of the pre-designed model collection that was previously generated so as to respond to the ever-changing design needs from the users.

Assembly Technique

By taking advantage of the formworks' reversibility, the system will calculate and find a balance between the number of mould pieces and construction duration to maximise the benefit with the least amount of mould consumption. Therefore, instead of shaping in one pour, large structures are generally divided into several chunks to be cast. For each chunk, the fabricator will get formwork assembly instructions step by step. Holographic overlays with various colours are used to mark the corresponding mould types. Once the user placed the physical mould piece at an indicated position, a 'tap' gesture was performed to register the installation progress. When all the moulds for a chunk are in place, the program will indicate that 'It is ready to cast'.

Reconfigurability

The continuous development of AR technology has shown potential applications to the field of design and fabrication, especially the implementation of non-standardised architectural prototypes. This has extended the boundaries of the space-packing grid of the original geometry to a larger scale of reconfiguration possibility.

Once a casting chunk is finished, the Augmented Reality app will offer fabricator options for other aggregations with the removed mould pieces. Coloured overlays help distinguish the mould pieces to be retained in place for specific purposes or to be disassembled for reuse. When all the casting tasks are completed, the remaining mould pieces can be reassembled to the building as combined components such as partition walls or claddings for

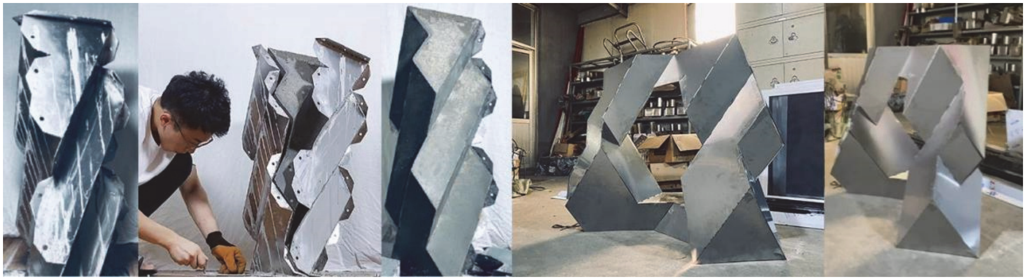

Figure 7
In-Situ Casting Test in Qingdao, China

mechanical facilities. Instructions as the light-weighted frames with generated mould combinations are after that projected as an attached asset if the new cast contains constructional components. Following the holographic guidance, fabricators can pick the ideal component and reorganise the removed moulds for a new cast. However, if the users choose not to cast new components, the system then searches the non-standardised model collection containing non-space-packing surfaces for interior components. Then, the guidance of the chosen parts shall be visualised through the headset showing the mould types and the connections.

In-Situ Casting Test

Parallelly, the in-situ casting test was implemented on the FOLOGRAM© platform with iPhone X© and iPad Pro© devices in Qingdao, China (Figure 7). After receiving the pre-processed metal sheets from the factory, the folding process was conducted by a two-person team operating on eight pieces of moulds with a MS HoloLens 2© and a folding machine that took an hour. These data were measured in a case where the fabricators had no experience with any of the manufacturing techniques required for this project, ensuring that only AR devices provided instructions in the entire process. The mould assembly process took three hours to complete by a team of three.

During assembly, the HoloLens© user led the installation sequence according to the holographic instructions and checked the shaping accuracy of installed parts. Two other fabricators followed the instructions to build the formworks in turn with bolts. To facilitate demolding, wax was applied to the inner surface of the formworks. When the formwork was settled, the fabricating team mixed sand, cement, and water in a concrete mix ratio of 2.5:1:0.6 and kept stirring with a mixer to prevent air bubbles from remaining in the cast. This prototype used traditional concrete to facilitate the test and reduce the risks.

The use of holographic visualisation was necessary for a quick reaction and response within the pre-designed construction components. Some errors were happening in the folding angle of moulds, and manual assembly may cause shape deviation. Reducing the folding steps of individual mould pieces may reduce deviation caused by multiple folding on one mould, requiring a larger unfolded surface when producing moulds. At the same time, the speed of the folding process can be improved. In addition, the horizontal pressure imparted by the liquid concrete to the formwork caused the formwork to deform slightly, which might be the reason for the more significant deviation happening in width. In response to this problem, we are considering perforating certain moulds and implanting lateral steel tie rods during the cast to provide tension for formwork and reduce deformation. Compared to the digital model, the one-metre-tall casting deviated by 2% in height and an average of 8% in width. Each mould was disassembled as planned and is competent for other aggregation.

CONCLUSION

There is exciting potential in finding more sustainable and accessible concrete uses in architecture. Since its use will not be replaced in the short-medium range, we should push for better solutions that will optimise its use for a better environmental proposal. Within this mindset, this project tries to explore the potential of Augmented Manufacturing to achieve this goal and propose a technology that can reduce its negative features by using reusable casting moulds and more sustainable concrete used through the GFRC. In the same direction, the project proposes a hybrid prefabricated and in situ workflow that could also improve the efficiency of material consumption. The third factor for better sustainability is the fact that the system aims for inclusive augmented reality guidance that can facilitate the use of local labour with no skills helping local communities and reducing the need for shipping expert working crews to develop the concrete formwork. By achieving these goals, the concrete use should reduce its CO_2 impact and therefore be less resource-consuming.

The Augmented Reality guidance app was used for the assembly of the prototypes, simplifying the process that was in fact conducted by students with no real previous manufacturing experience. That at least shows an actual use of it to include unskilled labour. Although the project presented here is still in development and more tests and prototypes are required, this technique has clear potential.

For the casting system, more precise and functional prototypes are needed. Although the concrete cast was within the standard concrete tolerance, it should improve to achieve a complete result. The assembly process can be improved for a faster and optimised system to prevent leaking or deformation during the casting step. A key consideration is to introduce lost connective brackets that will enhance the performance of the formwork and help mounding assembly.

The concrete formula will need to be adequately tested with the GRFC and a drier mix for even more efficient use of concrete. That should result in a more consistent and less leaky mix that should also save water and time in hardening.

These considerations and future goals should help to develop further the project and therefore achieve the main target of a more sustainable and accessible concrete casting technique, always keeping the technology open for future castable materials that could eventually replace cement for a more environmentally friendly solution.

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