Augmented Craftsmanship

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Creating architectural design and construction workflow by augmenting human designers and builders

ABSTRACT
Over the past decade, we have witnessed rapid advancements on both practical and theoretical levels in regard to automated construction as a consequence of increasing sophistication of digital fabrication technologies such as robotics, 3D printing, etc. However, digital fabrication technology is often very limited when it comes to dealing with delicate and complex crafting processes. Although digital fabrication processes have become widely accessible and utilized across industries in recent times, there are still a number of fabrication techniques—which heavily rely on human labour—due to the complex nature of procedures and delicacy of materials. With this in mind, we need to ask ourselves if full automation is truly an ultimate goal, or if we need to (re)consider the role of humans in the architectural construction chain, as automation becomes more prevalent.

We propose rethinking the role which human, machine, and computer have in construction—occupying the territory between purely automated, exclusively robotically-driven fabrication and highly crafted processes requiring human labour. This is to propose an alternative to reducing construction to fully automated assembly of simplified/discretized building parts, by appreciating physical properties of materials and nature of crafting processes. The research proposes a design-to-construction workflow pursued and enabled by augmented humans using AR devices. As a result, proposed workflows are tested on three prototypical inhabitable structure, aiming to be applicable to other projects in the near future, and to bridge the gap between purely automated construction processes on one hand, and craft-based, material-driven but labour-intensive processes on the other.
INTRODUCTION

It has been proposed that, after the Internet Age, we are now entering a new era of the ‘Augmented Age’ (King 2016). Physicist Michio Kaku imagines the future in which architects rely heavily on Augmented Reality technologies (Kaku 2015). Although Augmented Reality is not a new concept, it has been only in the last three years that the technology has broken into the mainstream with the development of consumer Augmented Reality devices (Coppens 2017). This is rapidly opening up possibilities in every aspect of our daily lives and is expected to greatly impact every field in the near future, including design and fabrication (Hahm et al. 2019). Therefore, the timing is ideal to think about the impact of Mixed Reality (MR) / Augmented Reality (AR) technologies on the building industry.

Contemporary research in computational design has seen great advancements over the past decade in automated construction and digital fabrication technologies, such as robotics and 3D printing. Digital Grotesque (Dillenburger 2013) [Figure 2] and MS3D Bridge (“MX3D Bridge” 2018) well exemplify the use of cutting-edge technologies in design and construction of algorithmically generated and digitally/robotically fabricated building elements. Although they demonstrate control and precision in distribution of material and execution of unprecedented complexity, these processes are highly dependent on expensive machines, highly skilled labour, and highly precise setups extremely limited in dealing with high tolerances and errors. On the other hand, projects such as Plex-e (“B.Pro Bartlett - RC6 Plex-e” 2015) and TecKnit (“TecKnit” 2014) (Figures 3) creatively utilize material behaviour to create relatively complex structures. Compared to earlier examples, they are similar in terms of formal complexity and in the way forms are generated and controlled by algorithmic processes (Figure 4). However, they are built based on material efficiency, using material behaviour and human craftsmanship in a creative way to achieve complexity as well as structural stability that would have been nearly impossible to execute by robotic processes. However, these project exhibit a fundamental lack of precision and accuracy control due to the lack of means to communicate these types of complex forms to human builders.

RESEARCH METHODOLOGY

Our research tries to bridge the gap between automated construction and human craftsmanship by introducing a workflow and tools that help transform humans into augmented designers and builders. To illustrate this approach, in this paper we are presenting three research projects that deal with MR- and AR-assisted fabrication. Each of the projects deals with a unique material

2. Digital Grotesque II, a 3D printed structure by Dillenburger and Hansmeyer (2017)
5. Demonstration of computer vision recognizing physical model using motion detecting system
6. Demonstration of computer vision recognition: Recognizing physical panel silhouette and showing label information
system which is highly dependent on Augmentation during processes of both design and making. Each of these projects tries to answer the following questions: (1.) how computers design differently from humans; and (2.) how humans can execute the computationally-generated models into meaningful physical structure which pose significant challenges to robotic fabrication processes? Regarding this, three key aspects have been identified within the research trajectory, as follows.

**Generative Design**

Generative design is still dependent on human-made commands, but the resulting products are generative non-manual (Conti 2017). Introduction of generative computation allows us to maximize the role of computer, unleashing creative potentials while allowing us to design structures which humans cannot imagine nor can manually design. From a design point of view, we are interested in generating formal outcomes that benefit from and are efficiently fabricated through AR assisted fabrication processes, not merely investigating only parametric or procedural modelling processes, i.e. parametrically panelised surfaces that can essentially be manually assembled without the need of digital guidance. For this reason we use techniques such as agent-based modelling, the products of which are typically either 3d printed or fabricated through complex digital manufacturing processes. Additionally, the use of non-linear design strategies also opens the possibility of interacting with models and virtual materials during the process of design itself.

**Execution of Complex Digital Models through Human Craftsmanship and Material Behaviour**

Different materials and crafting techniques have unique design languages and formal constraints. Therefore, finding the right material and technique for the right formal language is important. This is one of the key aspects required to execute computationally-generated models through human craftsmanship. Machines are usually good in dealing with repetitive, heavy, dangerous, precise job while humans are good in dealing with delicate crafts, adapting tolerances, and making intuitive decisions. Our design research challenges the typical setup of high cost and low tolerance nature of machinic processes. Within our research, we focus on materials and techniques which benefit from both aspects, human craftsmanship and machinic precision.

**Computer Recognition for Human-made Changes During Execution (Human-data Interaction)**

The nature of augmented fabrication is already allowing humans to make intuitive decisions during the making process and make real-time changes to the design. Thus, it is important for a computer to recognize these human-made changes (or changes made by structural or environmental reasons) and respond accordingly. However, although the current state of AR technology and devices does allow for real time environmental scanning, these are still typically very crude models, lacking in detail and precision, and are not yet able to reproduce digital replicas of intricate models to a satisfactory level. In order to overcome this limitation and create a streamlined feedback...
process between the real and the virtual, inclusion of real
time motion tracking cameras such as OptiTrack or Kinect,
as well as techniques for colour tracking, detecting, and 3D
depth scanning are needed.

Case Study 01 / BloomShell
Project BloomShell explores continuous double curved
surfaces assembled by a single type of component tile.
As the tiles are made from a synthetic custom material—
polyurethane foam board laminated by WBA sheets—each
tile can be bent to the desired curvature by applying heat.
Advantage of this material is that shapes can be heat-bent
without a predefined mould, avoiding the need for additional
joints for panel-to-panel connections. Likewise, opting for
a single type of malleable tile, enables creation of various
outputs while allowing the builder to change the design at
any point during the construction process.

Early BloomShell studies utilize unique tiles in order
to describe a given surface. This was later abandoned in
favour of a unified panel system to allow for greater flexi-
bility. However, it is worth discussing the initial approach,
as it required the use of computer vision in order to identify
different panels and provide builders with instructions on
labelling and positioning of a panel on the overall surface
(Figure 6). At this stage of development, a higher degree
of control in producing desired surfaces was achieved
based on a mesh relaxation algorithm. Further develop-
ment of digital tools focused on establishing a workflow
for penalization of digital surfaces and output of instruc-
tions for physical execution. An ‘auto labelling system’ was
established—an AR-based workflow which assists human
builders to identify each of the prefabricated panels using
computer vision analysis. Initially, the builder shows the
computer the panel which needs to be identified, after
which the computer analyzes pixel information of the
screen and detects the silhouette of the panel, identifying
the piece within the overall surface (Figure 6). Once the
piece is identified by the computer, all the necessary infor-
mation about the piece, including label number and panel
position on the overall surface, is sent back to the AR
device and communicated to the builder as a hologram.
The builder who is wearing the AR device can then custom-
bend the piece panel by panel following the holographic
instructions. Further, any other information, such as finish
type, etc., can also be embedded within this process.

This study tested the degree of accuracy of execution
within the AR-assisted assembly process. However, since
each part had to be custom-made with its precise position
within the larger whole, this resulted in a linear process
of fabrication, where adjustments during the construction
process were not possible without negatively affecting the
outcome. For this reason, a shift to a unified tile system was
made, allowing for a greater degree of freedom during the
assembly process, while compensating for any imprecision
and accumulated error during the construction.

Using unified tiles provides for greater flexibility in the
design outcome, allowing designers to produce different
design outcomes from furniture to building elements, etc.
In order to deal with this variety, an AR user interface was
developed, allowing designers to freely choose different input parameters to produce desired products.

As the material is lightweight, the direction of the panels on the desired surface does not fundamentally change the structural properties of the surface itself. This was turned into an intuitive design feature, allowing builders to make changes to the orientation of the panels on a local scale while maintaining the desired shape on a global scale. Once again, computer vision recognition modelling was used in order to achieve this local-global interface. Example of this is shown in Figures 7 and 8, illustrating a digital model of a self-standing wall that is initially suggested by computer calculation. However, during the assembly process, the builder decides to change the directionality of the next panel (as shown in the Figure 8), and accordingly, the computer recalculates the placement of the remaining panels, while keeping the initial global shape. This process can be done iteratively anytime during the building process.

Finally, an 1:1 physical prototype was produced to illustrate the idea (Figure 9), in addition of a larger scale architectural speculation, as shown on the Figure 10.

Although, the polyurethane foam boards can be understood as a proxy material, used to illustrate the concept, the proposed system is adaptable to any sheet material with enough flexibility, allowing it to be bent without the use of moulds (i.e. veneer, sheet metal, etc.).

Case Study 02 / iBrick

Project iBrick explored an assembly of simple three-dimensional timber blocks, with specifically designed joints, allowing for the whole system to be assembled and disassembled during or after the construction process.

A simple notched timber block and corresponding joint were designed to allow for assembly by interlocking, without using other tools such as nail or bolts. This system allows the overall structure to grow three-dimensionally but constrains it to x,y,z directions. More importantly, because of the fact that the system works simply with interlocking without additional mechanical connections, we could consider reassembly and disassembly processes as an important aspect of the project. As the components can vary in length, they are constrained to five different types for ease of prefabrication, although the variation does not necessarily need to be limited to only five types.

Although the overall design language remains constrained to a Cartesian grid, the rationality of the system simplified exploration into AR-guided assembly interface and machine vision/recognition, both fundamental components of the AR-assisted assembly process.

Similar to the previous project, a user interface was designed to help users choose the desired objects as the initial input, after which the users can fabricate these geometries following guidance from the hologram. More importantly, as the material system allows an assembled structure to be re-assembled to new shape, an additional
level of functionality was added, allowing builders to choose the next state of the assembly from an existing assembly. For example, as illustrated in Figure 11, the design interface allows builder to choose the current state of the assembly and the desired next state of the assembly—in this case from a chair to a table—and the hologram will guide the builder step by step through the assembly process while minimizing the number of operations. This is an extremely helpful guidance for builders because such information is difficult for a human builder to analyse especially within such complex structures.

Once again, the human-computer interaction presented an important aspect. Figure 11 illustrates how a human-made change to the position of the current component is detected (highlighted as yellow on the second image) and a new suggestion of model is generated afterwards (on third image). However, differing from BloomShell where 2-dimen-sional information was sufficient, for this demonstrator project, it was necessary to develop a way to identify the 3-dimensional structure. Thus, a Kinect motion-capture camera was used in this case to capture 3-dimensional data (Figure 12).

Technically, Kinect is a motion-capture camera whose main feature is to detect the distance between the camera and the ray cast of the camera pixel on the physical object. However, as the camera has limitations of pixel resolution, initial tests were conducted on a small-scale prototype. Firstly, a user places a physical component in front of the camera, after which the camera collects the pixel information of the physical model. New pixel information (with the new component added) is compared to the previous state of the pixel information, after which the computer can identify which pixels represent the newly added component, allowing it to record the made changes. After this, the computer can use this point information to approximate the component geometry. Thanks to the simple brick system with limited amount of component shapes, the approximation can be done quite accurately. However, due to the limitation of the Kinect device, this specific technique can be only explored within limited scale. Further development would include the use of larger and more sophisticated motion detecting system, such as OptiTrack, which would allow for larger scale construction within the same concept.

While exploring similar ideas to the BloomShell project, iBrick’s utilization of a simple joint system allows for exploration of disassembly and reassembly, which, in combination with the complexity of generated structures, consequently required us to overcome the challenge of real-time communication between the human team and the computer’s motion capturing system.

Case Study 03 / FlowMorph
Project FlowMorph explores the AR-assisted fabrication agenda from a slightly different angle. While the previous two projects deal with unified or simplified component-based systems, while focusing on assembly and computer recognition aspects, FlowMorth focused more explicitly on a hands-on approach, expanding the
showed that polymorph plastic achieves higher degree of strength and stability when formed through “stretching” rather than “accumulation” (Figure 16). The plastic was stretched into pyramid-like shapes, forming an interlocked pyramid grid system in order to achieve structural stability (Figure 16). More importantly, as the geometry is interwoven, it becomes clear that this highly crafted process requires delicacy of human hands.

With the complexity of the geometry and the material system, further technical development focused on two main aspects: (1) gesture recognition during design process, by influencing digital simulation through hand gestures, and (2) crafting of complex structures, purely relying on hand craft.

Part of the design process included hand gesture input by a designer, paired with fluid simulation. While the designer “draws” in physical space, the gestures are recorded and translated into a digital model that affects a running fluid simulation. The fluid simulation calculates input vector directions and forces global creative impact on the base vector field (Figure 20). The resulting overall geometries can be used as base data to form desired design products. In this case, the resulting vector field is translated into a simplified geometry set that becomes a guideline for the physical model (Figure 17).

As illustrated in Figure 18, an 1:1 physical prototype was produced as part of a larger scale proposal. For the purpose of fabrication, the piece is analysed and designed with the above-mentioned digital processes. The scale of the pyramid grid in this case is calculated from the maximum distance the material can stretch, which is about thirty centimetres. As the ultimate goal of AR-assisted fabrication is to enable unskilled builders, the whole process needs to be extremely user-friendly, meaning that the data communicated to the builder has to be simple and easy to understand, while providing the necessary minimum information needed to fabricate the piece. In this case, rudimentary information such as lines and points were sufficient to guide the builders, instead of superimposing the entire detailed 3D model (Figure 17). The finalized prototype was fabricated following a hologram of straight lines and points that represented the structure.

The production of an 1:1 physical model was impossible to do without the assistance of an AR devices. However, in case where a team of builders is working on the same piece, it becomes extremely important to accurately calibrate multiple holograms in same physical position. In order to speed up the process, increase efficiency, and avoid
mismatches occurring due to calibration, it is possible to work with several builders under the guidance of a “master” builder who is wearing the device and directing the rest of the team through assembly process.

Compared to earlier two projects, the value of FlowMorph lies in the delicacy of its making process, as well as the uniqueness of each product. As the project is not based on a component system, and both design language and material system allow high tolerance for errors and imperfection, it is generally more suitable to the augmented crafting method. Due to its “fuzziness,” scale of the elements, and adaptability of the underlying pyramidal grid, FlowMorph can absorb local imperfections while maintaining its structural integrity.

CONCLUSION
The above projects give an overview of the current state of MR technologies and the potential for their application in the fields of architectural design and fabrication, through the lens of augmented craftsmanship and real-time participatory design. By doing so, they outline an approach which integrates digital augmentation into the cognition models of making, challenging the traditional role of the artisan, while essentially democratizing the art of making.

The three studies showcased in this paper are just the beginning of our research, which tries to bridge the gap between automated construction and human craftsmanship by introducing a workflow and tools which help transform humans into augmented human designers and builders. This will be done through a combination of not only Augmented Reality technology, but also other technologies such as wearable robots, AI, computer recognition, etc., in order to advance the modes of human-machine interaction, while maintaining intuitive and creative component to an increasingly automated chains of production. The aim is to develop an adaptable workflow and toolset applicable to various design-to-fabrication scenarios.

Future work will take in consideration the additional development of the aspect of real-time interaction between the physical and the digital. We also envision the expansion of collaborative versions of the experiments and the formulation of collective behavioural models derived from the participatory observations and experiments.

Our final goal is to create an inventory of the culture of augmented making, identifying, and dimensioning the effect of the many emerging technologies in the critical production of design and in the collective engagement of the designer in the reflective practice of making.
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NOTES
1. Project BloomShell design credits: Soomeen Hahm, Alvaro Lopez Rodriguez, Yi Lin, Yushi Gao, Yang Song, and Jiayi Liu.
2. Project iBrick design credits: Soomeen Hahm, Alvaro Lopez Rodriguez, Kaijie Qian, Sheng Li, and Xiao Liu.

REFERENCES


IMAGE CREDITS
Figure 2: © 2017 Benjamin Dillenburger & Michael Hansmeyer; All other drawings and images by the authors.

Soomeen Hahm is an architectural designer and educator focused on the ecology of computational power, technology and human intuition, and ways in which they overlap and impact the design industry and physical environment. Working across multiple scales and perspectives, Hahm’s research interest involve the use of AR/VR-assisted fabrication, wearable machines, and human-computer interaction to execute complex digitally generated forms.