Digital fabrication with Virtual and Augmented Reality for Monolithic Shells

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Digital fabrication with Virtual and Augmented Reality for Monolithic Shells

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The digital fabrication of monolithic shell structures is presenting some challenges related to the interface between computational design and fabrication techniques, such as the methods chosen for the suitable parametrization of the geometry based on materiality characteristics and construction constrains, the digital optimization criteria of variables, and the translation of the relevant code used for digital fabrication. Specifically, the translation from the digital to the physical when a definite materiality appears during the digital fabrication process proves to be a crucial step, which is typically approached as a linear and predetermined sequence. This often-difficult step offers the potential of embedding a certain level of interactivity between the fabricator and the materialized model during the fabrication process in order to allow for real time adjustments or corrections. This paper features monolithic shell construction processes that promote a simple interface of live interaction between the fabricator and the tool control during the digital fabrication process. The implementation of novel digital and physical methods will be explored, offering the possibility of being combined with automated fabrication actions controlled by real time inputs with virtual reality [VR] influenced by 3d scanning and 3d CAD programs, and the possibility of incorporating augmented reality [AR].

Keywords: *virtual reality, augmented reality, monolithic shells*

VR AND AR IMPLEMENTATION

The implementation of several prototypes for monolithic shell construction has been explored with additive manufacturing techniques, by using deposition spraying with different paste like materials, such as clay mixes of diverse characteristics and performance ratios. The fabrication workflow includes traditional material practices by using branches that form self-standing peripheral and internal bending arches, from which an elastic membrane (Lycra) is stretched by hand to create a tense surface. A clay mix is robotically sprayed on top of this fabric and could be mixed manually with fibers in between layers that merge creating an assembly of interlocked materials. The temporary formwork is removed once the clay surface is dry and the structure is self-standing.

Preliminary experiments reveal that one of the most determining factors is related to the protocol established in a sequence to complete the process of 3d printing, which has been denominated "phasing".

The organization of this critical time-based sequence must be properly defined and formulated, following these steps:

1. Formwork setup
2. first scan
3. Material preparation [Mix - Type of sprayer - Trajectories]
4. Deposition [Robotic spray protocol]
5. Optimization [3d scanning - Export Scan to 3d model - 3d model optimization - Re-adjusted spray]
6. Curing time and formwork removal [temporary, or lost].

Despite some promising initial results, some of the key challenges observed during these experiments prove that additive manufacturing is far from being a linear and predetermined process, because during construction material properties and the structure in progress are constantly evolving. Some features observed include: the sagging of the temporary formwork due to the material weight; deformations or settlement of the supporting arches; the displacement of the structural elements due to shrinkage during curing time; some unexpected weakness areas around the supports, etc. These critical elements require immediate rectification while under construction, to avoid severe problems with the resulting structure, and to correct inconsistencies between planned and fabricated forms. To help resolve these issues, a singular digital fabrication process needs to be implemented to allow real-time adjustments between digital tools, structure and matter. The potential of carefully calibrating this phasing, in terms of the continuous optimization of materials and labor, and the feasibility of the builder to be involved during the fabrication phase, might prove critical for the renewal of shell construction processes. The interdependence between materiality and the fabrication methods has proven to require different tests and iterations, which has been implemented using two different protocols: virtual reality [VR], and augmented reality [AR]. AR is used for the constant readjustment of the fabrication process has been implemented, and VR tests were adopted to project optimization simulations on the physical as a live tool to fabricate directly on the physical structures. These steps required to take advantage of the recursive process involving digital modeling techniques, matter characteristics, shell structure behaviour during fabrication, digital tools using robotics (Block, Veenendaal, 2015), and real-time adjustments, will be further explored.

Figure 1
Off the shelf drones used for 3d scanning of structures at different stages of the construction.

VIRTUAL REALITY AND DIGITAL FABRICATION

Computational design techniques facilitate the implementation of design and optimization of possible solutions using Rhino 3dm, and Grasshopper plug-in, as well as providing the opportunity to make adjustments during the process of digital fabrication by using scans with Agisoft together with optimization softwares (Karamba) that are able to correct the robotic trajectories during the fabrication process in the Kuka PRC interface. VR proves critical as an tool to collect data and to make adjustments in the structure in progress, showing some potential to navigate into Rhino 3d space of the simulated structure at different stages of fabrication to better calibrate the robotic actions using Kuka prc interface.

Some relevant projects that use VR techniques include the Iaac seminar in Valldaura (Figures 1, 2 and 3) with drones used to test trajectories and collect data for mud shells. Another relevant reference was recently used clay wall (On Site Robotics, collaboration of Iaac, Tecnalia, and Noumena, at the Barcelona 20th. edition of Construmat 2017) using drones to monitor with multispectral cameras collecting thermal analysis of the structure in progress.

Of particular interest is the exploration in depth of the possible remote operator control of fabrication in Realtime using VR, revealing an unexpected degree of freedom and creativity such processes could bring to monolithic shell construction.

Figure 2
Kuka robot taking pictures of the structures from a minimum distance, different angles and in a logical sequence that can be at a later stage translated into a 3d mesh using Agisoft software.

Figure 3
Engineer Daniele Ingrassia from Fab Lab Kamp Linfort-Real time temperature 3d scanning of the clay wall being 3d printed

AUGMENTED REALITY AND IMMERSIVE ENVIRONMENTS

The use of AR for human machine interaction is also not common in architecture, although it has been a field of research for decades in other disciplines. Interesting examples, such as an augmented toolkit for robotic fabrication (Bard et al 2014) or hybrid digital / physical robotic plastering workflows (Bard et al 2015) demonstrate the potential of augmented and mixed reality for automation and assistance in human-machine creative interaction workflows, while recent examples of AR use in construction sites (Abe et al 2017) show the future possibilities of the technology in the building industry.

The distinctive use of VR and AR techniques can allow a constant recalibration of the spray at different phases during the fabrication progress, and could help to rectify or stop the process early if some part of the structures are revealed to be non-viable, or if they are subject to unforeseen dangerous conditions and efforts. For example, if some arches are deforming too much, the spraying should immediately stop and ranges of acceptable deformation are to be set after iterative physical experiments and precise mapping of the acceptable fluctuations. This step can allow the immediate re-adjustment of critical parameters, such as the angle of deposition, speed, pressure of spray, trajectories, distance to the structure in progress, and changes in the matter characteristics while being applied, such as the level of humidity, viscosity, amount of fibers, size of gravels, among others.

AR has already a significant amount of application in the construction industry as a control tool. It is used in construction site for the builders to have a better understanding of where errors can have some critical negative implications in the buildings. AR has not been significantly used yet as a design and optimization tool during the fabrication process. This is part of the challenges the 2 small scale case studies will highlight.

Real time drone 3d scanning is developing at fast pace especially in the precise agriculture domain.

Companies like yellow scan in Montpellier France in partnership with eca are putting in place 3d scanning devices that are not only based on photogrammy, but thermal data can also be translated in real time. This has recently been implemented in Iaac´s installation at Construmat in collaboration with Tecnalia and Noumena where custom made drones were developed. Such developments are of particular interest for the technique used in case study 1 and 2.

Some construction and material manufacturing companies are increasingly interested in bridging their knowledge with the academic digital fabrication and augmented reality research community to seek diverse objectives, such as to renew their business models, to learn more about the potential of different materials, to study the hybridization of matter performance, or simply to explore different techniques for digital fabrication.

An argument defending the importance of this set up will be exposed, to create a viable construction system incorporating the craftsmanship and the knowledge of the builder as an active input during the fabrication sequence, and its potential for producing unexpected novel forms. Therefore, it will highlight significant changes that digital fabrication can engender in the use and the resulting aesthetics (Huijben, Van Herwijnen, Nijsse, 2011).

IMPLEMENTATION (EXPERIMENTS / CASE STUDIES)

Recent academic experiments investigate new methods of using digital fabrication for raw materials, involving industrial partners (manufacturers, architectural firms) to provide a more realistic setup for the students towards patented fabrication techniques. Two case studies are featured, with solutions implemented with an easily mounted temporary or lost formwork, explaining the specific phasing loop related to the 3d scanning, the export scan to 3d model, the 3d model optimization, and the re-adjusted spray.

In general terms, a 3D scan protocol must be carefully established for all experiments. Some tests with off the shelf Parrot drones 3d scanning were implemented in the case studies but were not real time, and around 50 pictures from different angles were taken by the drones in a logical sequence around and on top of the shell in progress and then exported into Agisoft to generate a CAD mesh (Figure 4).

Figure 4
Parrot Drone performing the 3d scanning of the shell at its initial state by providing a series of photos around and on top of the structure.

The first scan is performed when the fabric and the formwork branches are mounted with a minimal fabric formwork pulled on the supporting arches, with a series of marks on the surface to facilitate the scanning process. A minimum of 50 pictures from as many angles as possible in a logical sequence are then exported into Agisoft to extract a 3d mesh, that can be exported as an OBJ file which can be opened in Rhino 3d. In Agisoft, the precision of the simulated mesh can be varied and the more precise definitions require a significant amount of computation power that not all computers can provide. Furthermore, rendering the textures help recognizing the shapes but contributes to the computational weight while performing the render.

During phase 2, a 3D scan of the shell is performed once the first layer of watery clay mix (“barbotine”) has been applied. The board on which the shells are attached can be used as reference to be able to superimpose the shells at different stages and be able to map their distortion precisely.

A protocol of 3d scanning it’s implemented with cameras or drones to collect images using Agisoft, a photogrammetric processing of digital images that generates 3D spatial data in McNeel Rhinoceros 5

[Rhino]. The raw scan was then simplified using principal curves (arches), after which the mesh was rebuild (Figure 5), deformations from previous scans were evaluated, and the resulting form was ready to run an optimization software using Karamba, a parametric finite element engineering tool.

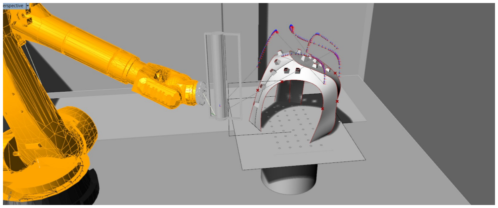

Figure 5
Initial Robotic trajectory set according to first 3d scan from the dry structure.

After the optimization is completed, the digital reconstruction of the form in Rhino 3d does allow implementing some tests using VR to navigate inside the constructed forms with the resulting optimization simulation embedded into the Rhino geometry. The potential of including AR in the mud shells experiments featuring Minddesk with HTC Vive goggles offers an immersive navigation inside Rhinoceros space that is recently being tested in public at the AWE Expo, featuring some of the experiment models included in this research. Another interesting method for the implementation of the mud shell is to superimpose the optimized geometry view from Rhino on the physical shell and perform actions on it accordingly. For example, stress lines can be generated on Rhino Karamba and translated into the design, projecting the image of the simulation on the physical shell can allow new design processes to emerge. These relatively new methods are not yet embedded in architecture, but have the capacity to provoke new design methods and aesthetics. For example, the location and type of perforations can be tested and decided upon using this virtual reality strategy. Very few recent architectural projects are investigating the correct setup of the the use of remote-control tools to facilitate this process.

Some deformations are predictable as they're part of the recurrent features offered by the technique: such as the sagging of the structure on both side of each of the ribs. On the contrary, some other areas of the shells will distort in an unpredictable way (as the experiment involves too many parameters for the result to be predictable: air humidity, clay mix invisible properties such as air and water, bending and rods and lycra formwork computing their own shape once the initial formwork is mounted). The non-predictable morphologies particularly happen when the span in between arches is relatively large (equal or superior to the radius of the arch). Unexpected form distortion also happens when the edges of the shell meet the support base, as significant amount of forces are applied on those junctions. The iterative 3d scanning has been implemented to readjust the trajectories and actions performed by the robotic arm.

CASE STUDY 1 - PHRIENDS FOR SHELLS.

May 2016; 25 hrs. seminar. First year master students. IAAC, Barcelona. PARTICIPANTS: 23

Seminar: "Phriends for Shells" ("Phriends" was defined as the safe interaction between people and robots during fabrication progress).

Tutors: Author 1, D. Stanejovic (robotic expert), Y. Mendez (assistant).

Five earthen vaults of 1m x 1m x 0.8 m in height with perforations were built during this seminar. Bending rods in clusters of 2 or 3 members bundled together by a rope were the supporting arches where the stretched lycra was secured. The openings for the perforations needed to be defined before applying the first coating of clay mix, and laser cut rings and triangles were mostly used to create those temporary formworks removed after the last layer of clay mix was applied, so that the holes could be formed. This phase of the fabrication was both digital and manual, as the study of the perforations that were tested in both digital and physical models appeared to lead to the most successful designs (Figure 6).

The 3d scan was performed using Agisoft, and the 3d scan protocol had the following phases:

- 1st. scan: After arches and stretched fabric were installed;

- 2nd. scan: After the first layer of clay spray was completed.
- 3rd. scan: After all sprays are completed and the structure is set.

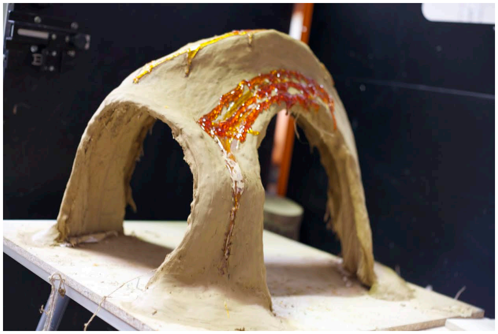

Figure 6
Robotic resin pouring while the upper mud layer is still wet.

Karamba was used to perform these structural analyses by applying the following criteria: 1) Displacement to verify areas that are most stable, that have the least displacement, and with the most deformations or buckling. 2) Utilization to detect compression and tension areas and concentration of forces. 3) Isolines to detect changes in the forces where most deformations were anticipated. The trajectories of the deposition were adjusted in the Kuka PRC interface to correct some potential problems with the structure in progress.

Case Study 2:

May 2017; 25 hrs. seminar. First year master students. IAAC, Barcelona. PARTICIPANTS: 12

CASE STUDY 2: EARTHEN SHELLS, MANUAL CRAFT AND ROBOTIC MANUFACTURING

Tutors: Author 1. Assistants: Abdullah Ibrahim, Noor El Gewely, and Kunaljit Singh Chadha. Augmented reality and CFD advisor: Angelos Chronis

During this seminar three 1 m x 1m x 1m earthen shells were constructed. The brief given to the students was to design with the earthen shells fabrication technique explored in various previous workshops (successive clay mix coating on fabric formwork performed manually or robotically) while designing with robotic natural resin pouring and perforations types variations.

The trajectories of resin pouring by gravity in continuous lines were implemented and varied according to the regions of the shells of distinct geometries. For example, in the more horizontal parts of the shells the resin doesn't pour down and some branching liquid patterns solidified just after meeting the edge of the peripheral arches. Temperature of both the upper layer of clay and the resin when the latter is robotically poured on the shell were to be explored aiming as highlighting different finish while varying basic parameters such as height of pouring and velocity of robotic pouring. (Figure 7)

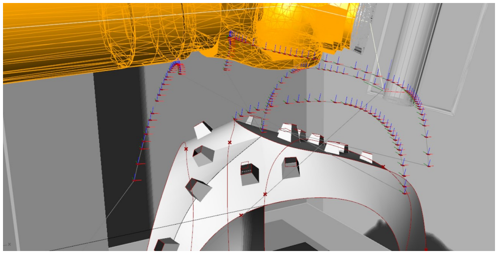

Figure 7
Robotic simulation of resin pouring on mud shell.
Close-up.

Figure 8
Robotic deposition of natural resin on the mud shell while the upper clay mix coating is still wet so both material adhere to each other. Different geometric areas of the mud shells are explored and chosen for the resin robotic pouring to test different finish.

The 3d scan process was identical to the previous case study, using cameras and translated to Agisoft, then converted to a 3d mesh in Rhino that was optimized. The 3d scan protocol has 3 stages: First scan after the supporting arches and stretched fabric are installed; Second scan after the 1st layer of clay spray is completed; and third scan after all sprays are completed and structure is set. Karamba was used to highlight different zones of the shells giving different colors ranges according to compression and tension forces applied. In addition, stress lines were highlights and a ride diversity of resulting stress lines configurations were given according to the resulting form found geometries (Figure 8).

For the development of the AR application, the Unity3D game development engine was used along with the Vuforia AR framework for image tracking. Unity and Vuforia were chosen as platforms as they are freely available, easily accessible and straightforward to implement. The aim of the AR application was to visualize the changes that happen to the structure during the various fabrication stages and thus to enable the user to understand the effect of their actions on the structure. At its current stage the AR application visualizes the 'before' and the 'after' states of the spraying process. A 3D scan of the structure with its arches and membrane stretched is compared with a 3D scan after the layering of spray and the openings are created and the structure is set.

Both 3D scans are optimized for 3D visualization and imported in Unity. The application is developed for Android devices and Android tablet is used to augment the structure over a target. Each state of the process is assigned to a different virtual button in the AR application so that the user can switch between the different modes (Figure 9). At a later state the AR application can be further developed to allow for augmentation over the structure itself, by superimposing a projected state of deformation on the physical structure, thus assisting the fabricator in the fabrication process and in real time. (see Figure 10)

Vive will be implemented at an international event on VR and AR California, the AWE expo where the Karamba simulation on the mud shells from this seminar will be used as demonstrators on how to navigate inside the simulation space in Rhino with the Vive Goggles and the 2 remote control in hands to move inside the optimized model.

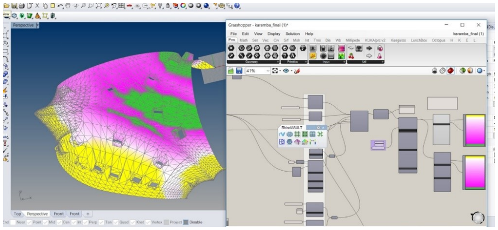

Figure 9
Karamba (Plug-in for Rhino developed by Clemens Preisinger) simulation on the shell in progress highlighting different compression and tension areas.

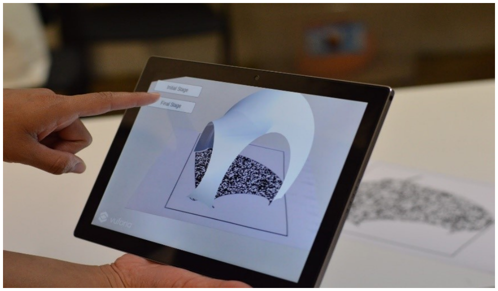

Figure 10
Augmented Reality application visualizing different states of the fabrication process.

CONCLUSIONS

The experiments featured in this paper have showed that superimposing a level of interactivity between the fabricator and the physical form under construction with the distinctive use of VR and incipient developments of AR proves to be beneficial for the integration of innovative design tools leading to the structural optimization and new resulting aesthetics. In addition, navigating inside the virtual reality space inside Rhino with AR helps changing viewpoints, unveiling design aspects that cannot be visualized with the naked eye.

However, this interactivity has been conducted using drones or photographs in a non-real-time manner, but could potentially include other devices using tablets and smart phones iteratively or in real time. The benefits of real time feedback loop between constant 3d scanning's can allow significant progress in the technique, making it more efficient in terms of timing and helping to minimize further errors. An opportunity is detected to incorporate the 3d scanning device with the actions performer tool, where for instance the robot depositing the material could as well be the scanning device by having a camera fixed close to the end effector. In this scenario, AR could be used to run the Kuka prc code to still have the control of the robot, so if a crack or a suspicious deformation is detected in AR, the robotic action can be stopped on time.

These examples feature the procedure of onsite fabrication of mud shells construction based on the iterative analysis and monitoring, allowing the final form to fit into a certain range of constraints for shells structures optimization, and will defend the thesis that a process of continuous adaptation might prove more suitable than pre-established forms. A complete parametric approach might be desirable not only for the design, but also for the fabrication protocols, allowing certain variables to fluctuate in importance according to the structure's development. The novelty of the resulting constructed forms lies in the input from both users and fabricators proved crucial for the possible -and multiple- outcomes of new fabrication and design techniques for shell construction, claiming that this process engenders forms and results that are different than outcomes from the same process done entirely by the machine.

Lastly, the digital fabrication of mud shell construction is currently carried out primarily in academic environments, and its immersion into the construction industry depends on the implementation of precise real scale prototypes, in the formulation of a suitable fabrication protocols, and in the wider and deeper integration between matter behavior, digital tools, and AR/VR devices.

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