IEREK PRESS
Academic Research Community
CrossMark
http://www.press.ierek.com
ESSD
ISSN (Print: 2357-0849, online: 2357-0857)
International Journal on:
Environmental Science and Sustainable Development

DOI: 10.21625/essd.v3iss2.382

# Adaptive Strategies for Mud Shell Robotic Fabrication

**Chaltiel Stephanie[1], Bravo Maite[1], Ibrahim Abdullah[1]**
[1] *Institute of Advanced Architecture of Catalunya*

## Abstract

The digital fabrication of monolithic shell structures is presenting some challenges related to the interface between computational design, materiality and fabrication techniques. This research proposes a singular method for the sequential robotic spray deposition in layers of diverse clay mixes over a temporary fabric formwork pulled in between peripheral and cross section arches. This process relies mainly on the continuity of the construction phases for stability and durability but has encountered some challenges in physical tests related to sagging, displacement and deformations during the robotic deposition of the material. Adaptive strategies during the digital fabrication stages are proposed for a sequential exploration of the geometry, structural analysis, and construction techniques. Iterative adjustments of protocols for the robotic material deposition include both predictable and unsuspected behaviors, preventing the structure to reach non-viable geometric thresholds. Two case studies of physical tests describe, analyze and simulate some of these strategies and identify specific parameters, inquiring the sequential adjustments of the robotic material deposition. These strategies will drive future full-scale tests within a sustainable use of materials, adaptive construction methods, seeking an optimized structural performance, that could open a new chapter for the digital fabrication of earthen shells.

***Keywords***

Digital fabrication; Monolithic shells; Robotic construction; Clay additive manufacture

## 1. References - Background of the Technique

### 1.1. Theoretical References

Some traditional mud shells can be found in vernacular practices, such as the Musgum domes, where curved geometries based on catenaries arches are used at suitable ranges to provide structural stability while allowing a proper construction technique provided by textures on the outer side of the shell to serve as scaffolding, while preventing negative climatic aspects such as rain and humidity. The construction of shells during the last century has been profoundly linked to geometry, structural performance and construction practices, and this intrinsic correspondence was explored extensively by some master builders such as Torroja, Candela, Otto, Nervi, Dieste, among others (Bravo, 2013). The appearance of computation in several realms, from design processes to performance simulations to digital fabrication, are opening new avenues of exploration of this topic.

### 1.2. Construction Advanced Practices

Construction practices exploring spraying concrete materialized in a technique called shotcrete, featured in a significant number of large domes built in the 1960´s using large inflatable domes such as in the Bini domes (Fig.1a), but this technique was not pushed further for different reasons including aesthetics (Huijben, Van Herwijnen, Nijsse & U-Bletzinger, 2011). Bini´s methods and techniques are considered suitable for future improvement if still fibres, prefabricated nets, or robotic mechanical spraying were explored to reach their full potential (Van Hennick & Houtman, 2008). Current shotcrete industry (sprayed concrete on preformed rebars) allows a degree of automation with the possibility for the builders to move the spraying pump at the end of a crane. However, the matter flow per second control remains incipient in most cases (Veenendall, 2017).

Figure 1. (a) Bini Shells withinflatables covered by a metal mesh as lost reinforcement to be sprayedmanually with shotcrete. 1(b) Spray ice on fabric formwork and active bendingmetallic elements. “Zero bending moment” Lancelot Coar Winnipeg, Canada2016.

Recent experiments involve spraying over light formwork including digital fabrication techniques can be found with spray ice on active bending shells and fabric formwork (Fig.1b) in the project Zero bending moment (Lancelot Coar, Winnipeg University, Canada, 2016). Other examples include large textile tensed over CNC cut wooden arches after optimization of the shell, then sprayed with concrete by workers standing on cherry pickers to reach different parts of the membrane (Block Group, ETH Zurich, Switzerland, 2017). These examples testify the relevance of this emergent agenda, and a growing interest in the protocols for the associated materials and methods.

### 1.3. Recent References

Several tests for monolithic earthen shells using robotic fabrication were conducted over the last four years by the authors, such as the *AA Visiting schools Lyon: “Synchronized Movements”* [2013]; “*Mud, Body and Scripts*” [2014]; “*Chocolate and Other powders*” [2015], “*Smart Geometry workshop in Gothenburg*” [2016]; and 2 seminars at Iaac Barcelona: “*Phriends for Shells*” [2016] and “*Earthen Shells*” [2017]. These experiments represent a robust body of examples where techniques are increasingly reformulated, adapted and improved.

## 2. Adaptive Strategies for Monolithic Earthen Shells

The experience accumulated during the monolithic shell workshops led to the formulation of a set protocol of adaptive strategies for mud shells, a process that includes the following steps:

- Geometrical shell formulation includes two approaches. The first is a given 5 peripheral arches vault geometry, and the second is based on a form finding strategy based on 3 peripheral arches and at least one cross arch to be met and the scanning afterwards produced a 3d model that was needed to map the robot trajectories. In this form finding the maximum height difference between the different arches was not specified. However, resulting structures have highlighted that certain thresholds must be respected to obtain a sturdy shell.

- Structural analysis using Karamba (FEA Finite element analysis tool plug-in for Rhino) was digitally modelled and defined by support points, load points (gravity and mesh load including self-weight), material (clay was not available in the plugin; therefore concrete was used as the only alternative paste like material), surface, providing results for the analysis of displacement, utilization and stress lines.

- Construction technique is defined by the iterative recalibration of the spray technique to include the trajectory, angle, and speed of deposition according to the form evolution and matter consistency trajectory, speed, angle, distance to surface, pressure, and material consistency according the evolution monitoring of the structure during construction.

Two case studies show the implementation of different workflows and protocols for the application of the steps described above.

## 2.1. Case Studies

### 2.1.1. Case Study 1 Synchronized Movements Lyon AA Visiting School June 2013:

Teaching team: S. Chaltiel, MP Placais, Suryansh Chandra, Zubin Khabazi, Chiara Pozzi. Earth architecture experts: W. Carazas, P. Doat. Participants: 40 Duration: 10 days

Location: The Grands Ateliers de L´Isle d´abeau France. Description: Construction of one monolithic earthen shell composed of 5 peripheral and 2 middle cross arches.

Size: 2m x 1m x 2m high.

The workshop started with the Rhino digital modelling of the shell starting with the geometric model of a shell with pentagonal base featuring five perimeter arches, together with cross arches so that each support point goes to the middle of the facing edge through the central point of the shell. Each of the peripheral and cross section arch varies in height within a 50 cm limit. The doubly curved resulting surface is defined by a peripheral arch and a cross section designed so that the span is never more than 70 cm to avoid sagging related to the weight of the wet clay mix being deposited. The digital fabrication of the temporary formwork is formed by 5 peripheric arches and 2 cross vault arches were CNC cut in plywood panels (Fig. 2a), secured and assembled in place to a wood base panel. To create a dry removable surface, elastic lycra was pulled and secured over different ribs using strong staples to tense the fabric over the arches (Fig. 2b & c).

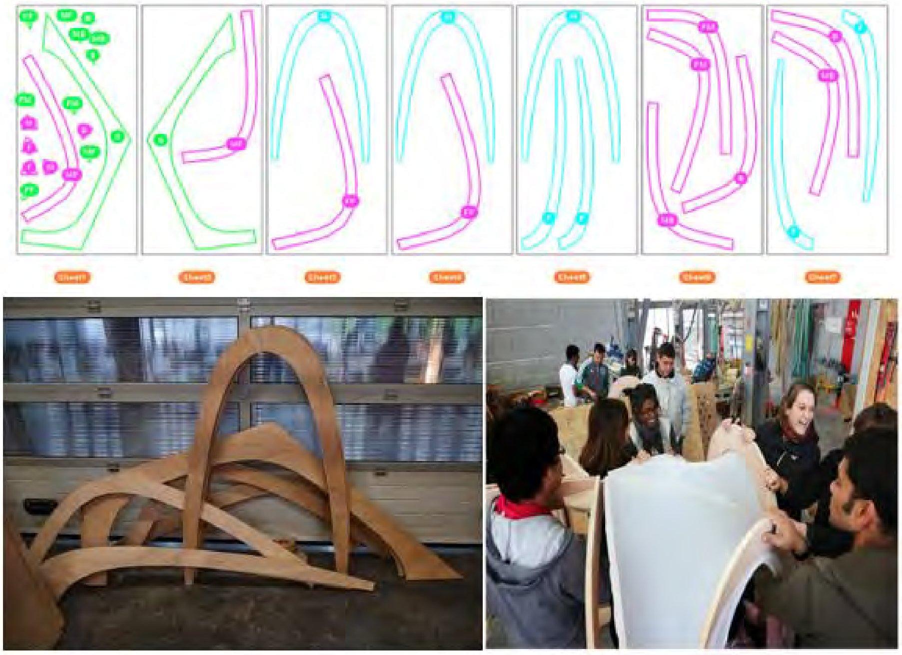

Figure 2. (a) Nesting of cutting filefor the plywood arches to be cut by CNC machine. (b) Use of CNC to cut theplywood arches forming the temporary formwork (left). (c)Placement of the elastic fabric over the wooden arches fixed by staples (right).

The deposition of clay mixes was performed by hand with a team of more than 5 persons at a time, following a precise phasing where each clay mix was carefully formulated. The structure was coated 7 times with different types of clay mixes in the following sequence: 1st layer or ¨barbotine (2 water Units (U) for 1U clay); 2nd layer (2U water for 1U clay + 1U hard sand); and from 3rd. to 7th. layer (2U water + 2U clay + 2U hard sand + 2U fibers of 3cm long straws). Each layer respected a crucial drying time, using devices such as large lights and hair dryers to speed up the process. Once the 7th. layer was applied, dried and reached a 3cm thickness, the temporary support of plywood arches and fabric was removed, a laborious step that required enough strength to remove the plywood arches without creating a crack in the shells, but the lycra fabric was easily peeled off.

The following problems and possible improvements were highlighted for further structures. To make the structure more stable and performative in terms of thermal comfort can be achieved by reaching greater thicknesses of at least 5 cm for a 3 m high shell that requires more time for more clay mixes to be applied. Different parts of the shell where difficult to reach and at least 5 people were required to work simultaneously to avoid a non-homogeneous deposition. After the completion of this first physical test, robotic spraying was identified as a possible solution to ease additive manufacturing performance and to increase thickness control.

Figure 3. (a) First layers of claymix applied by hand by more than 3 people working simultaneously. (b) Removal of the wooden arches and fabric formwork.

The necessity to work with a 3d model as an interface became evident during the construction stage, so after finishing this workshop, a fully parameterized model was constructed in Rhino 3D with Grasshopper plugin, based on the main inputs and parameters extracted from the construction experience.

1. Geometrical shell formulation was defined by:

1.a Curves defining the supporting arches were limited from 1.5m to 2m span, and between 2m to 3m height.

1.b The surface defined by the stretched fabric over different arches is generated as a mesh. Three options were explored in terms of geometry generation. one mesh with default subdivisions in Rhino 3D and the second one with evenly distributed subdivisions by grasshopper that yield a better resolution than the first one and lastly and the most accurate is using Kangaroo in Grasshopper a physics engine to generate the mesh and enhance the shell subdivisions as quads for the outcome which allows increased precision in extracting compression and tension values from Karamba.

1.c The support areas where the shell meets the ground were established based on the values obtained from physical tests to ensure the shells ‘stability (Fig. 4), to have a minimum 10cm for the support area at each arch base, legs meeting the ground at an angle rod/ground at a minimum of 45 degrees and maximum 90 degrees.

2. The structural shell analysis was defined in a Karamba script based in the following parameters (Fig. 5a):

2.a Geometry: Shell surface constructed by shell ribs (curves) in Rhino environment or a Kangaroo generated shell to obtain a quad mesh result which gives more precision in further Karamba Finite Elements Analysis results.

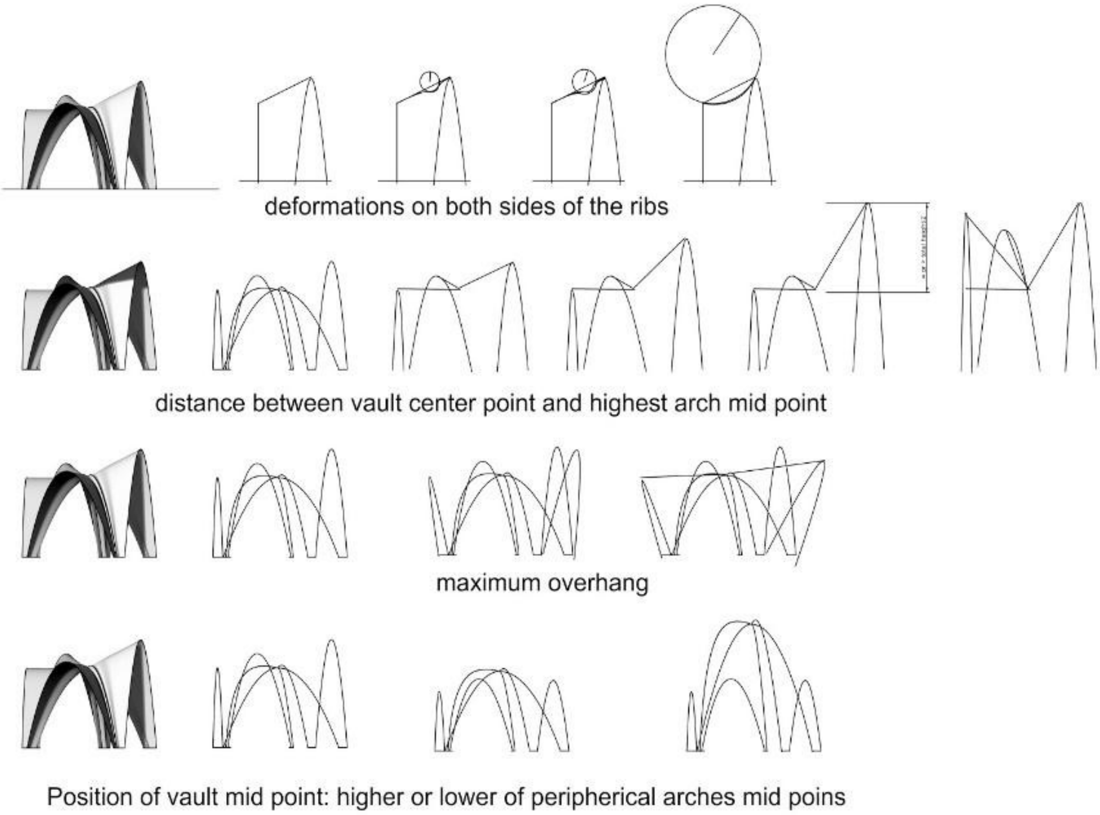

Figure 4. Diagram of considerations to determine viable geometry ranges: maximum sagging, maximum distance between lower and higher arch (convex and concave resulting surfaces) and maximum overhang. By the authors.

2.b Anchor points;

2.c Gravity load;

2.d Material selected is concrete (as the only alternative in the software with 1cm. thickness), therefore further tests must include the young modulus from the clay mix used to replace it in the software and get a result closer to the real material behavior.

The next step is to assemble these inputs and run the analysis to get the following outputs:

2.e Geometry displacement values are helpful to enhance the structure in terms of material thickness and adding membranes.

2.f Geometry utilization to identify areas of compression and tension by percentage of the material usage. As a result of how the geometry is constructed with different mesh subdivisions in Rhino 3d generated shell, structure analysis were run with completely different results *(Fig. 5b)* for two versions applied on both. Tension (blue with max. value of 16.8%), compression (red with -2.9% max. compression), maximum tension (green) and maximum compression (yellow). The first geometry is more unified and coherent showing a better structural performance because of the tension and compression distribution among the shell due primarily to an evenly subdivided mesh grid, meanwhile the second version is more random and unsystematic. The results of the geometry utilization shows that the load has been transferred from the centre point to the five cross arches and main support points, allowing stability, strength and stiffness. To achieve the desired performance, the material capacity must be able to resist the force or pressure and it provides enough stiffness to resist any deformation caused by an applied force.

2.g Geometry stress lines: Computationally, stress lines are a result of distributed shell points from the compression and tension values. The final stress lines analysis proved useful to verify tension areas, and will be explored in future experiments to direct the application of added reinforcement in the shells.

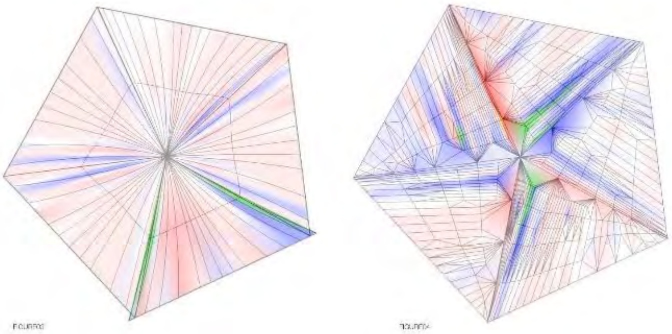

Figure 5. (a) and (b). Analysis of two different mesh subdivisions.

Figure 6. Karamba structural analysisshowing areas of compression (Red), tension (Blue), maximum tension (green),maximum compression (yellow), and neutral areas (white).

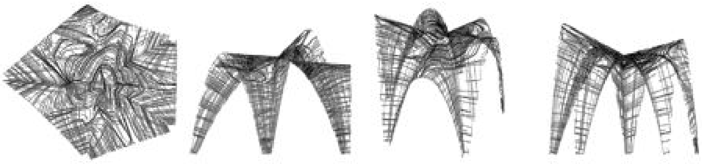

Figure 7. Karamba structure analysis of case study one from the AA showing the stress lines of the shell structure. ofthe shell structure.

Future digital experimentations involving the generation of a quad mesh from Kangoroo for Rhino optimized in Karamba explored further configurations of this 5 peripheral arches non regular vault.

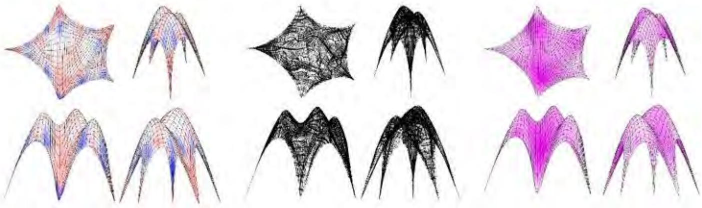

Figure 8. FEA Analysis generating stress lies and compression/tension areas of the shell was performed on an optimized shell from Kangoroo.

In conclusion, this workshop allowed the experimentation of the physical construction of earthen shells in an analogue manner, providing some key parameters, geometric criteria, and construction recommendations.

## 3. Earthen Shells Iaac 2017

Faculty: S. Chaltiel, A. Y Ibrahim, N. El-Gewely

Technical experts: A Chronis, K Singh Chadha

External advisors: Maite Bravo (IAAC), Amadeo Monreal (UPC), Verena Vogler (McNeel Europe)

Vincent Chavy (Universal Robots).

Number of students: 11

Duration: 5 days total.

Location: Iaac, Barcelona.

Description: Construction of three monolithic earthen shells composed of 3 peripheral and middle cross arches.

Size: 1m x 1m x 1m high.

The construction stage started by inserting in a pierced wooden board some clusters of small branches in clusters of 2 or 3 - 0.3 mm diameter reeds. Three peripheral and one middle arches were materialized and a tensed lycra surface was pulled over the arches (Fig. 8 a, b, c).

Figure 9. (a) Placement of the 3peripheral and one middle arch materialized by a cluster of 2 or 3 0.3 mm diameter reeds. (b) Placement of lycra fabric stretched over the different arches. (c) First liquid clay mix robotically applied on the fabric and reeds formwork.

Two 3d scans were performed after the fabric formwork is completed and after the first layer of clay application, by taking over 60 pictures around the structures and exporting them to Agisoft software to convert them into a mesh. Different layers of clay mix were applied following the same protocol as in the *Synchronized Movements* workshop (Chaltiel & Bravo, 2017), and the initial 2 first layers were robotically sprayed.

Figure 10. (a) Kuka PRC simulation of robotic trajectories after the first scan of the temporary formwork. (b) Middle layers of clay mix containing fibers applied by robotic spraying. (c) Close-up of the freshly projected fibrous clay mix robotically applied on the shell.

The robotic trajectory was adjusted respecting a distance of 30cm to the surface and a constant angle of 45 degrees spraying device. In addition, the speed of the robot was set at 2cm/sec taking advantage of findings from previous seminars (*Phriends* for Shells*, Iaac, 2016).

Geometrical experimentations with Rhino Vault and Karamba were performed as a shell study determining the type (sinclastic or anticlastic), the curvature (single or double), arches span, height (floor to mid-point arch), the degree (angle of curve from the support point to the arch midpoint).

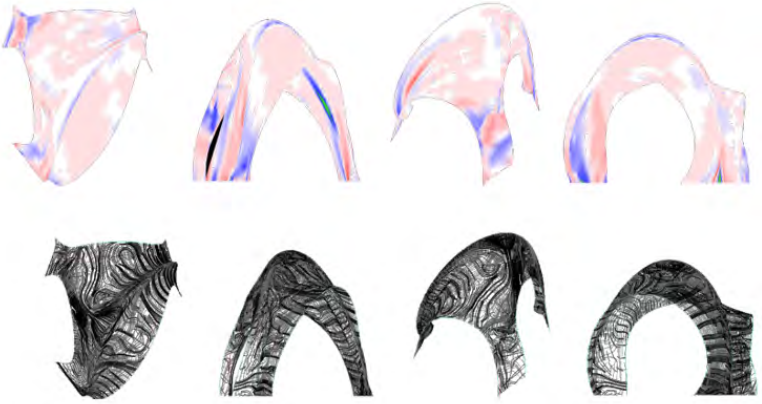

Figure 11. Karamba structure analysisof case study two from IAAC showing the compression and tension areas. Blue istension, Red is compression. / Karamba structure analysis of case study two from the IAAC showing the stress lines of the shell structure.

The results of this case study show areas of compression and tension. The size of the shell is around 0.5m in height from the central point with three different arches with a maximum height of 0.35m and minimum 0.3m height. This shell has a better stability because of the scale factor because it is almost half the size of the first case study. The forces are evenly distributed throughout the shell because of the number of support points and the small scale. Nine support points for a small scale give more strength and less displacement.

Some improvements for further structures are highlighted. Although the initial reeds and fabric formwork was easily mounted, some of the geometries resulting from this case study proved to be non-viable due to the extreme sagging of the fabric under the weight of the wet clay. Furthermore, the geometry control of the shells proved difficult to monitor, especially in between and in the main arches themselves, because surfaces deformed too much under the weight of the material as illustrated in the failed examples (Fig. 12). Those have proven that the difference in height of the different arches cannot go over a certain threshold (Height A + $^{1}/_{5}$ Height B on average for maximum height gap) especially during spraying of wet matter where excessive sagging can prevent the structure from resulting in a valid structure.

Figure 12. Failed experiment of ashell collapsed when applying different layers of clay mix, because the initial geometry was not matching the viable thresholds.

## 4. Conclusions

This paper seeks the implementation of adaptive strategies for the construction of earthen shells over easily mounted light formwork, allowing the structure in progress to be mapped and robotically sprayed.

The two case studies presented different sequences. The first features a process starting with a clear geometric definition in Rhino 3D, followed by a manual construction process, finishing with the digital reconstruction of structural analysis afterwards. The second case study started with a form finding experiment where arches and cross arches were arranged by hand, the fabric surface stretched, scanned, the deposition of material by a robotic arm meanwhile the structural analysis was performed during the fabrication process. A clear geometric definition proved critical for the shell stability and viability, as seen in CS1.

Two different kinds of easily mounted formwork where showcased: CS2 with light branches were easier than CS1 with CNC wooden panels to mount but displayed less geometry control and too much sagging. From the results of the featured case studies, one of the challenges to improve the technique is to explore other types of light formwork options, that are able to be easily mounted and removed once the shell is solid, but that do not deform significantly under the weight of the clay mix being applied. Some alternative solutions include exploring inflatable formwork that could help keeping its shape and provide most successful geometries that those developed in previous structures.

In terms of structural performance, simulations for tension and compression, displacement and stress line analysis prove to be critical to evaluate the fabrication process during construction. Because only small shells were constructed, the parameters extracted were limited in their application, and a full-scale prototype would allow to establish minimum and maximum thickness, protocols for reinforcement placement along the stress lines, acceptable loads, among many other considerations.

The material deposition technique could be improved with greater thickness control of the robotically deposited material and allow some variation in different parts of the membrane to follow the results obtained from the Karamba simulations. Iterative geometry analysis of the structure proves to be necessary, as the process embeds a degree of deformation that must be controlled and corrected. Karamba results before the fabrication process starts proves more efficient as the data can be fully integrated in the robotic control code.

Recent experiments have proven that drone spraying as an alternative to the robotic arm provide a significant freedom of reach at different heights and in challenging positions of the membranes such as cliff conditions. Furthermore, drones monitoring paired with drones spraying provide an opportunity to improve significantly a non-regular amount of material by varying the matter flow per second and controlling the number of iterations of each spraying round. Existing shotcrete equipment with a pipe connected to a matter mixer with water on the ground connected to the drone is to be tested in large scale earthen shells in the near future. the constant feed of material to the drone could help coat efficiently very large surface with a controlled thickness proportional to the pressure used.

Real time monitoring is recently being explored for the calibration of iterative digital tools according to the form in progress, including scanning and augmented reality, providing a constantly updated geometry to inform the optimization software, and consequently providing correct material deposition information during the fabrication process. An improved robotic spraying with UAV to reach different parts of the shell would allow less stress on the light formwork and an increased homogeneity in the material deposition. Some initial tests using HoloLens (Fig. 13) and some upcoming tests study full scale shell visualizations showing stress lines to serve as guidelines for the builder to inject reinforcement material, or to monitor in real time the shell's thickness (blue areas with 3cm. while red areas at 5cm.) because accurate thickness control would greatly improve this method. The potential is that builders could follow simulations such as stress lines to apply additional material, or real time monitoring of the shell being built from the distance, a rather difficult task to be performed with conventional methods.

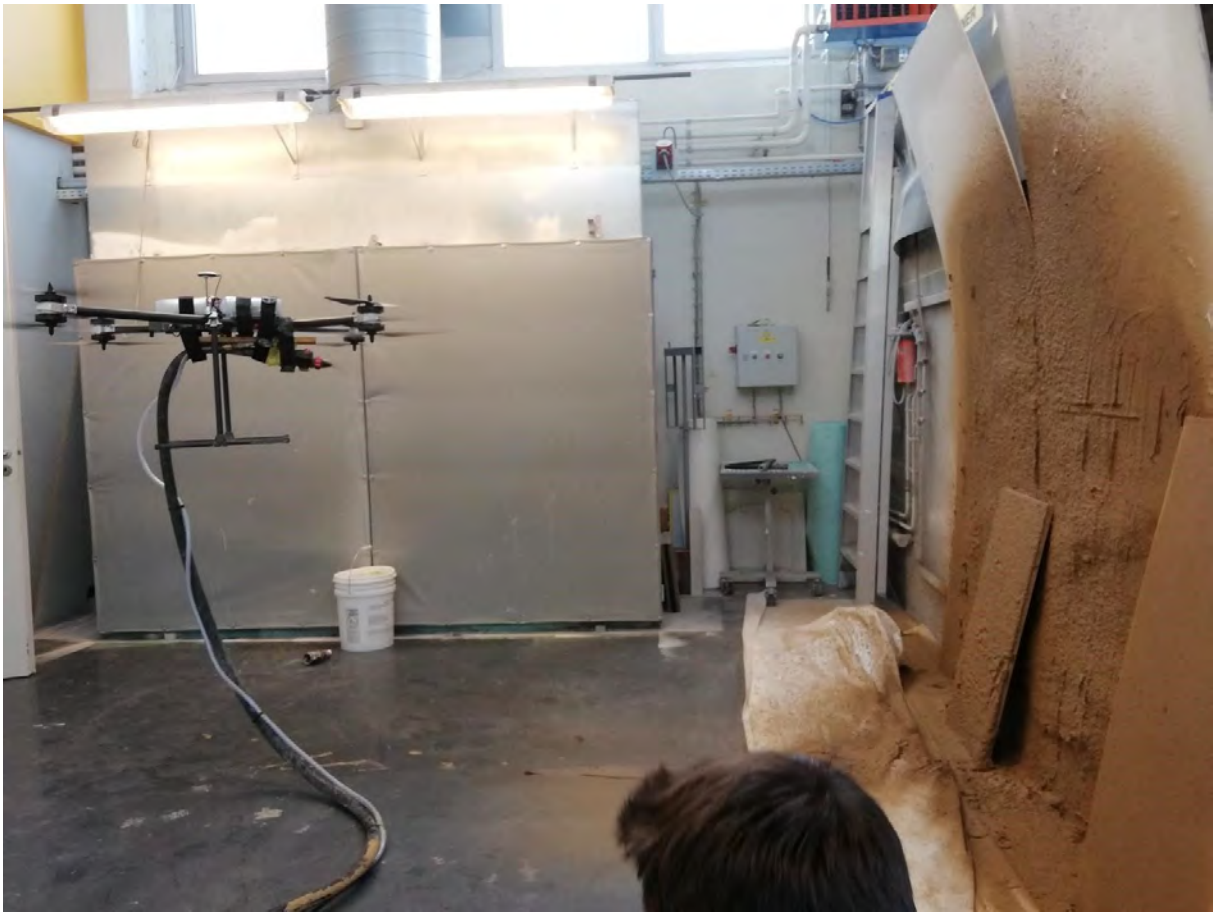

Figure 13. Drone connected to a continuous spraying industrial pump from EUROMAIR resulting in a homogeneous coating of clay mix on some wooden testing boards.

Figure 14. Mixed Reality Specialist Cameron Newnham (RMIT Australia) performing a full-scale visualization test ofan earthen shell using Holo Lens.

## 5. Acknowledgments

This project has received funding from the the “Marie Skłodowska-Curie Actions” Innochain grant: 642877 Horizon2020. The authors would especially like to thank all students who participated in the construction of many

monolithic earthen shell structures.

## 6. References

1. Bravo, M. (2013). Parametric Logics in the architecture of the XX Century. *Cutting Edge in Architectural Science: Proceedings of the 47th. International Conference of the Architectural Science Association.*(pp. 147-156).

2. Burry, J., & Burry, M. (2012). *The new mathematics of architecture*. London: Thames & Hudson.

3. Chaltiel, S., & Bravo, M. (2017). Monolithic Earthen Shells Robotic Fabrication. In *The proceedings of the ACADIA conference*. Boston.

4. Coar, L., Cox, M., Adriaenssens, S., & De Laet, L. (2017). The design and construction of fabric formed ice shells with bending active frames utilizing principle stress patterns. In *Interfaces: Architecture, Engineering, Science, Annual Meeting of the International Association of Shell & Spatial Structures (IASS) in Hamburg*. Retrieved from https://structurae.net/literature/conference-paper/design-and-construction-of-fabric-formed-ice-shells-with-bending-active-frames-utilizing-principle-stress-patterns

5. Costanza, D. (2017). *ACADIA 2017: Disciplines Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture: Massachusetts Institute of Technology, School of Architecture Planning, Department of Architecture*(p. 100). United States: Association for Computer Aided Desifgn in Architecture (ACADIA).

6. Galbiati, P.A., El Bahar, B., Slabbinck E., Solly, J., Knippers, J. (2017). Irregular cable nets: exploring irregularity as a driver for form and structure. In *Interfaces: Architecture, Engineering, Science, Annual Meeting of the International Association of Shell & Spatial Structures (IASS) in Hamburg*.

7. Huijben, F., Van Herwijnen, F., Nijsse, R., & U-Bletzinger, K. (n.d.). Concrete Shell structures revisited: Introducing a new lo-tech construction method using vacumatics formwork. (E. Oñate & B. Kröplin, Eds.). pp. 409-420.

8. Tam, K. M. M., Mueller, C. T., Coleman, J. R., & Fine, N. W. (2016). Stress line additive manufacturing (slam) for 2.5-d shells. *Journal of the International Association for Shell and Spatial Structures*, *57*(4), 249-259.

9. Van Hennik, P. C., & Houtman, R. (2008). Pneumatic formwork for irregular curved thin shells. In *Textile Composites and Inflatable Structures II* (pp. 99-116). Springer, Dordrecht.

10. Van Mele, T., & Block, P. (2011). A novel form finding method for fabric formwork for concrete shells. *Journal of the International Association for Shell and Spatial Structures*, *52*(4), 217-224.

11. Veenendaal, D., & Block, P. (2015, August). Design process of prestressed membrane formworks for thin-shell structures. In *Proceedings of IASS Annual Symposia* (Vol. 2015, No. 1, pp. 1-12). International Association for Shell and Spatial Structures (IASS).