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Robotic Fabrication of Segmented Shells: Integrated Data-Driven Design

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Abstract: This paper focuses on the robotic construction of segmented shell structures incorporating data from structural analysis and digital simulations into automated construction system. The research aims to provide a methodology of translation between digital and physical experiments through the stages of design development as well the assembly logic. Through an integration of structural analysis data force driven form-finding process is determined, accompanied by custom tessellation pattern. System stereotomy is developed as an integrated interlocking system, derived from material properties and robotic fabrication constraints. Assembly process is developed as an automated construction 'pick and place system' capable of customized on-site fabrication of architectural-scale structures. The system consists of multi robots, composed six-axis robotic arms, carried on mobile platforms with scissors lifts. The complexity of robotic fabrication is addressed through developing a custom robotic toolpath. Correlations between these steps are verified through developing a large-scale prototype, tested with proposed robotic assembly logic.

Key words: Robotic fabrication; Robotic pick and place automation; Segmented shells; Force-driven form-finding; Custom tessellation pattern, Geometry optimization; Digital workflow.

1. Introduction

This paper contains research from the thesis project 'Arctic Recalibration'. The thesis aims to provide a resource-driven fabrication system for the Arctic environment, addressing problems including lack of resources, harsh environmental conditions and the lack of human labour. The proposed site is located in Alaska, at the Seward Peninsula. The construction system for compound housing units is proposed to meet the problem of dependence on prefabricated, expensive solutions in face of predicted population influx in the Arctic territories.

The thesis consists of all the stages of the construction process: from material sourcing to global settlement strategies. This paper describes only a specific part of the thesis, dedicated to the fabrication and robotic assembly only. However basic points of the thesis worth mentioning to clarify this paper.

During the material experiments, the compacted peat-based material is invented and tested. Peat is beneficial as a construction material for the arctic environment due to the potential abundance of this material in the near future as a response to the global warming. This peat composite is used for the material system and fabrication processes described in this paper.

On the global scale, digital experiments are conducted to determine the topological relationships between the housing units, using computational tools, such as Genetic Algorithms. Objectives are:

- environmental conditions – maximisation of solar gain, minimisation of wind exposure
- fabrication requirements – minimisation of material usage and robotic toolpath length.

The overall appearance of the shell is predetermined by this global scale experiments earlier and is only optimized and altered in this research paper.

Therefore this paper inputs are: compressed peat as a construction material and predetermined shell morphology due to environmental factors and spatial requirements

1.1. Segmented Shell Structures Overview

Shell structures are widely used building type, which provides stable structures with large span. Shell structures are structurally efficient, because plane forces are transformed into membrane forces. However, continuous shell structures are rarely built today, due to high manufacturing costs.

Segmental plate shells, composed of prefabricated planar panels, might offer an interesting alternative. Unlike single layer grid shells, which usually need bending-stiff joints to stabilize the structure, segmental plate shells could generate local bending stiffness without the help of a bending-stiff joint.

When three plates meet at one point and are hinged along the intersection lines, each plate is constrained by the other two; they cannot have relative movements anymore. This property helps segmental plate shells to generate a relatively simple connectivity, which makes this type of structures more competitive. The pattern of segmental plates affects the force transfer also in the shell.

Since the material is not continuous at joints, forces will be redirected when they pass through the connections. The joint stiffness affects the force transfer as well, because stiffer connections attract higher forces.

1.2. Force Flow in Segmented Shells

The pattern of segmental plates will affect the force transfer in shell structures. It defines the locations of all connections, which are the weak points in the structure. Because the material is not continuous at connections, forces will be redirected when they pass through the connections. Besides, the joint stiffness also affects the force path largely, because when the joints are stiffer, larger forces will be attracted to flow through. The geometric pattern and the joint stiffness thus determine where and how the internal forces are transferred in segmental plate shells.

2. Digital Design

This section describes the sequential, but interrelated steps of the workflow from form finding to materialisation.

2.1. Fabrication Set-up

A key aspect is to define and develop a suitable and coordinated design and fabrication set-up for the production of the hundreds of individual voussoirs that need to be processed for a single vault design. Owing to the three-dimensional shape of the separate blocks and the geometrically complex fabrication constraints, the challenge is to coordinate the design of the individual voussoirs, in accordance with the technical machine set-up. Furthermore, the right balance needs to be found between form finding and fabrication constraints, in order to produce free-form vaults efficiently [1].

The first phase of the digital chain is the design process, which consists of three steps. The defining structural properties for the proposed material, are its low tensile and high compressive strength. Because of this, to span space in unreinforced masonry, the use of funicular form, acting purely in compression, is mandatory to ensure structural stability. Therefore, in the first step, an appropriate funicular form is determined [by using a RhinoVault plugin for Rhino].

In the second step, based on the results of the funicular form finding, a possible tessellation geometry is generated that defines the cutting strategy of the vault. This is an automated process, informed by structural and fabrication-related data, which is influenced or guided by the designer.

In the third step of the design process, the tessellation pattern is used to generate the voussoir geometry considering structural as well as fabrication and assembly constraints.

2.1. Form Finding by Manipulating Force Lines

The Rhinoceros Plug-In RhinoVAULT emerged from research on structural form finding using the Thrust Network Analysis (TNA) approach to intuitively create and explore compression-only structures [2]. Using reciprocal diagrams, RhinoVAULT provides an intuitive, fast funicular form finding method, adopting the same advantages of techniques such as Graphic Statics, but offering a viable extension to fully three-dimensional problems. The key aspects of the research is a comprehensible and transparent setup to complex freeform shells but also to give an understanding of the underlying structural principles (Figure 1).

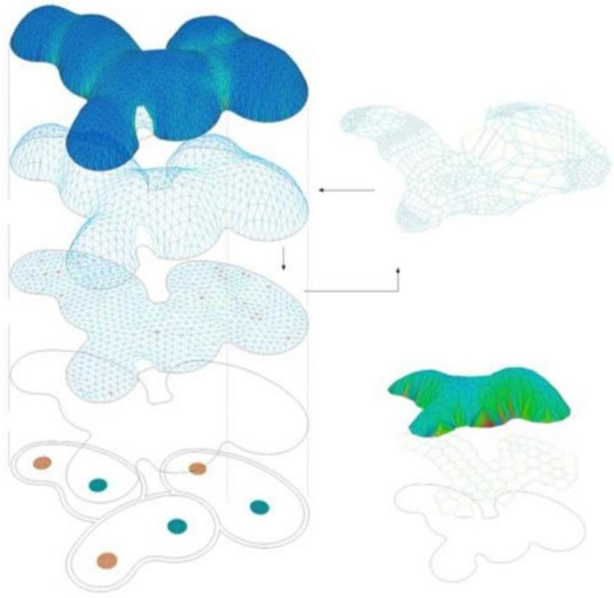

Fig.1 RhinoVault form finding process.

Objectives of this experiment were to provide required architectural qualities through spatial differentiation of the interior space of the shell, provide various program distribution with the input constraints of height (5m) and width (6.2 m). Keeping this parameters, structurally sound compression only shell structure is aimed to be achieved. A compression only structure is created with spatial variations that are controlled by the designer. The structure created has domed like variations, interconnected with vaulted transitional spaces into one complex shell structure. For the experiment the initial shell with equal forces and no spatial differentiation is modified through manipulating the force flow to achieve spatial differentiation (Figure 1). A comparative analysis of the input surface and the output surface is made. While the basic geometry and the footprint are kept intact due to alterations of force lines to create a funicular structure there is a slight change in the geometry of the shell (Figure 2).

Fig.2 Comparison between input and output shells.

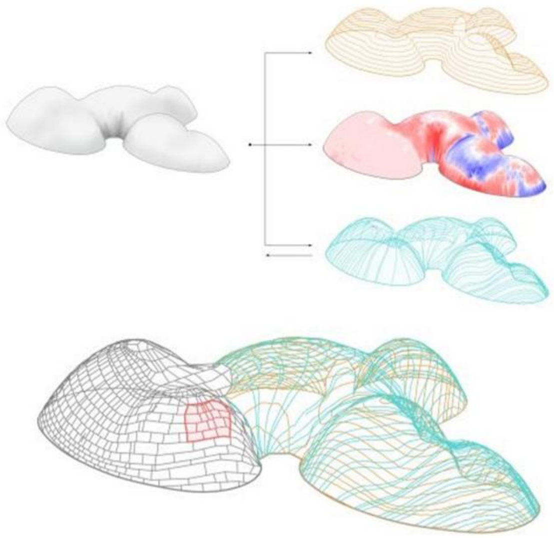

Fig.3 Karamba structural analysis

Structural analysis of the resulting shell in Karamba plugin for Grasshopper is conducted in order to evaluate the results of RhinoVault optimization (Figure 3). Left image shows utilization, red colour indicates compression forces, blue – tension. Right picture shows displacement, more saturated colour indicates bigger value, which is located on the top of the shell.

Therefore, complete compression only structure is created without compromising spatial requirements and architectural qualities.

2.3. Tessellation

In cutting lines generation data streams from several methods of structural analysis are used. Topological data of the shell is abstracted through series of equal-spaced isocurves. In parallel, utilisation values are extracted using structural analysis (Karamba software). The results of utilization analysis are informing the isocurves: their control points are moved down in areas of the shell which are utilized more, and are moved up if the utilization value is low. By doing so, horizontal direction of cutting lines is created.

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In the third step of the design process, the tessellation pattern is used to generate the voussoir geometry.

2.4. Planarisation

Individual voussoirs are generated from the tessellation, however these voussoirs are doubly curved. Due to properties of the proposed material [compaction] and the production of material being possible only in flat sheets the production of double curved panels is impossible. Therefore, the doubly curved panels need to be converted to planar panels. This step is computationally heavy and requires a sufficient amount of additional manual alterations. To ease this process a custom Python script should be explored (Figure 5).

Algorithm: Move points on the surface until planarity reached. Applying this planarisation algorithm creates a considerable change in panel's geometry however care is taken into maintaining the resolution of the overall structure.

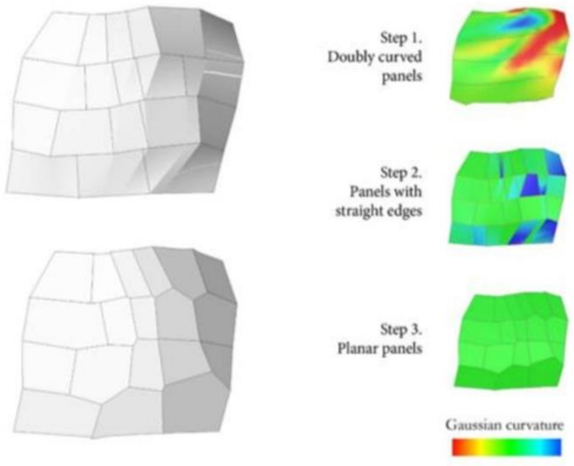


Fig.4 Planarisation- curvature analysis.

2.5. Stereotomy

The lack of materials onsite and the rejection of expensive and inefficient outsourcing of resources has been a key driver in this research. While analysing the fabrication system proposed the use of mortar was rejected simply due to lack of resources. This chapter explores the geometries required for a dry masonry system.

Physical tests were conducted and it is understood that the panels collapse due to the lack of interlocking [requires more friction forces] in the directions of voussoir collapsing through horizontal sliding and vertical flipping. To prevent these two methods of the system failing a stereotomy exploration are conducted.

2.6. Interlocking System Experiments

Iteration I. Multiple teeth

It is found that the number of perpendicular teeth are excessive creating complications in the assembly process. (Figure 6, I).

Iteration II. Trapezoid single tooth

The geometry evolved to one tooth per side with a trapezoid geometry instead of rectangular making it easier to slide into position. The vertical interlocking doesn't lock voussoirs in all the directions and the panels slide out (Figure 6, II).

Iteration III. Multiple teeth

A horizontal only tapered joint is proposed. It is observed that the panels slide in the horizontal axis, inside towards the centre of the shell and also [in the vertical direction] flip inwards. The occurrences of these failures increase with an increase in the structures increment (Figure 6, III).

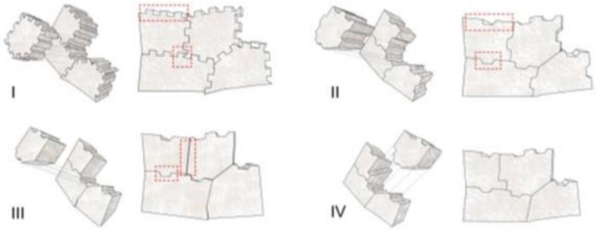


Fig.5 Interlocking systems experiment.

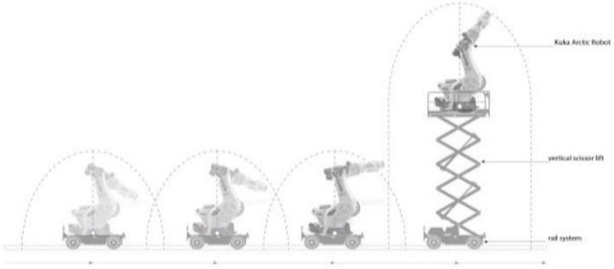


Fig.6 Robotic scissor lift system.

2.7. Proposed Stereotomy

Tapered horizontal joint

The horizontal interlocking tooth is tapered along the internal side of the panel to prevent the panel from sliding horizontally inwards. If there is an attempt to slide inwards, the tapered joint will prevent this movement and the panel will not be able to and will stay in position.

Angled vertical joint

The vertical joint is designed in such a manner to prevent vertical flipping. The side interlocking is redesigned in order to relate to the robotic pick and place toolpath. An angled plane is placed along the vertical sides of the panels, it is tilted against the direction of flipping. The interlocking system is designed to fulfil two contradicting criteria: No friction while the robot is placing the voussoir in order to not damage the previously constructed part of the structure, while also maximising friction once the panel is placed to prevent movement (Figure 6, IV).

3. Robotic Construction

The robot proposed to be used for the construction process is a KUKA ARCTIC QUANTEC KR240. Robotic arms have to be placed such that their workspaces overlap to avoid inaccessible spaces.

The approached proposed on site is a set of moveable robots on an external rail system (as structures are in compression the placement of aggregates must be externally) These robotic arms are guided by a rail system increasing its reach, simplifying the workflow and reducing the number of collaborating robots in construction thereby also easing the computational process. The maximum height reachable by a robotic arm is 3.2m; this limit the possible spatial morphologies too. This limitation is addressed by mounting the robotic arm on scissor lifts (Figure 7).

The system also proposes the use of moveable robots on scissor lifts with rails arranged in a fashion taking into consideration the requirement of the settlement pattern and overlapping workspaces. This arrangement helps encompass significantly larger areas with controlled number of robots decreasing the construction time when compared to the previous approach of numerous stationary robots.

3.1 ‘Pick and Place’ System

Robotic pick and place automation speed up the process of picking parts up and placing them in new and different locations, increasing production rates [3] With many end-of-arm-tooling options available, pick and place robots can be customized to fit specific production requirements.

The robots can be easily programmed and tooled to provide multiple applications if required. An increase in output with a pick and place robot system offers long-term savings to construction processes.

Local sequence A patch is selected from the total structure to analyse and perform physical tests to prove the ‘pick and place’ fabrication system. The toolpath followed at the local scale is a one following one direction, constructed row by row from bottom to top such that each panel is half locked by two sides and has two free sides also. However, once the successive panel is placed, the previous panel is fully locked thus creating a rigid compression-only structure.

3.2 Toolpath Development

The objective at this stage is to place panels with variations in dimensions with accuracy, so they don’t fall during the ‘pick’ process. The proposed automated feeder system requires guides to place the panel precisely as there is a great variation in dimensions of all the panels. However, the two largest surfaces of the panels are parallel to each other. Therefore, the feeder is transferring blocks in a conveyer belt with edges that are tailored to the thickness of the panels. Therefore, the supporting guides of the panels are the side edges and the starting edge of the panel is perpendicular to the surface.

However, the side of the panel to be placed on needs to be determined. This is done by calculation of the centre of gravity of each panel as well as area of each side surface. The surface with the biggest area, which is not outside of the projection of the centre of gravity once the panel is placed on it, is selected as a bottom surface. The gripper position adapts accordingly.

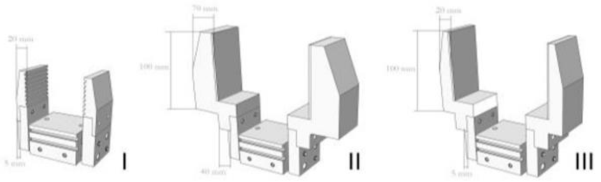


Fig7 End effector design.

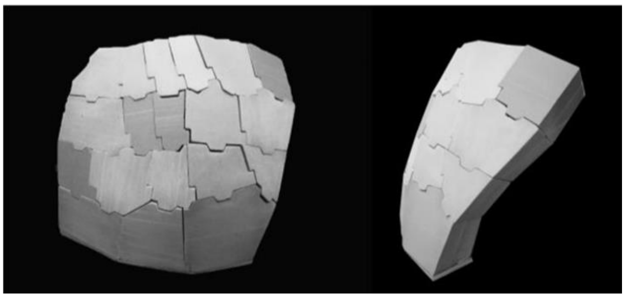


Fig.8 Physical model segment.

3.3 Gripper Design

The main aim of the gripper is to accommodate panels with various dimensions and grip the panel perpendicular to the planes. Since all the panels have different sizes and angles of side surfaces this becomes a challenging task. However, the two largest sides of all the panels are parallel, flat, and are located at the same distance in all the panels [due to a constant thickness].

As far as the pneumatic gripper construction requires two surfaces parallel to each other as if the surfaces are not parallel the gripper will not close properly and/or will cause a change in the gripping position [the flanges, trying to shut properly will rotate the panel and thus damage its surface]. Therefore, using the two largest flat surfaces of the panel [representing an inner and outer surface of the shell] is the optimum solution.

During this process, it was brought to notice that the system has two contradicting aims: to increase the strength of the grip and to decrease the length of the total system.

Extension of the 6 the axis increases the lever arm, therefore making the panels harder to lift as well as harder to manipulate in complex rotations. However, minimising rotations means minimising the risk of collisions and singularities. These two factors are kept in mind while designing the end effector through several iterations. The iteration III with 10 cm flanges is the selected option (Figure 8). 3.4 Gripper Position on the Panel There is great variation within the panels with all of them measuring different sizes and different angles of the side surfaces. However, the two main parallel largest sides of the panels are parallel, flat, and are located at the same distance in all the panels [due to equal thickness]. This is used as a benefit for the system; to utilise only one universal gripper design for all the panels.

One gripper design without the requirement to adjust flanges proves to be a simpler, more efficient and mobile [as there is no need for the end effector to be replaced during construction] design. As far as the pneumatic gripper construction requires 2 surfaces parallel to each other. If the surfaces are not parallel, the gripper will not close properly and/or will cause the change in the ‘pick’ position because the flanges while attempting to close properly will rotate the panel slightly and damage its surface or also potentially create a deviation. Therefore using two largest flat surfaces of the panel [representing an inner and outer surface of the shell] is the only appropriate method of picking the unit for construction.

In this case, the base point of the gripper [the tip that is predetermined and set up] constantly changes in order to pick up different panels. The 6 the axis of the robot, therefore, is no longer parallel to the side surface, only the flanges are parallel to the panel. There are 2 types of manipulating the robot in KUKA PRC software:

- Automatically by defining the position of the end-effector tip surface
- Manually by defining the rotation for each axis independently [4].

The selection of methods depends on the goal which is needed to be achieved. Therefore, for the start and end position of pick and place, the angles for each axis' are defined. This position is standard for all the pick and place iterations and prevents singularities. It is also used for maintaining the robot by putting additional rotations if needed.

The toolpath, on the other hand, requires custom, tailored to each block movement. Therefore, is the compiled of the sequence planes, where the origin defines the position of the gripper and the orientation defines the same aspect of the gripper accordingly. KUKA PRC software adjusts the position of all 6 axes in such a way, so the end-effector is positioned properly automatically.

During the research, the 1:2 scale polystyrene foam model was developed in order to test the fabrication sequence (Figure 9).

3.5 Gripper Relation to Panels

This step involves contradicting criteria where minimum friction is required so that the panels can be placed perfectly into position, however, for the panel to stay in position friction is required [in addition to the horizontal and vertical joinery developed] The only solution is to develop a toolpath that would allow the panels to fit perfectly into position with zero tolerance.

Fig.9 Pick. transfer and place end effector positions

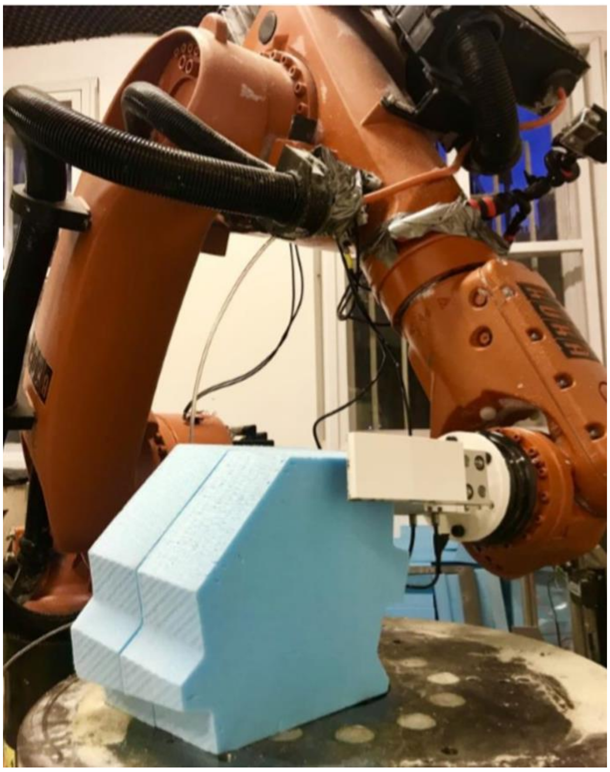


Fig.10 Robotic arm approaching 'Pick' position

The main challenge in placing the panel is to avoid friction. Therefore, the direction of the movement of the panel is always parallel to the previous side panel. The 3d position of the panel, however, is derived by the panel itself due to the fact that it needs to be parallel to the gripper flange's surface (Figure 10, 11).

4. Stages of Construction

The design proposal includes a 5 stage construction process, from the creation of peat harvesting basins to the construction of rail systems followed by the aggregation of the panels of the settlement. The rails of the robot in certain area that show potential for growth are proposed to be retained on site for future use as pedestrian pathways. The figure alongside illustrates the stages of construction and figure illustrates the construction process showing in layers the sequence in which construction process is proposed to take place.

4. Phasing

As multiple robots collaborate to fabricate the structure, it becomes necessary to phase the fabrication process. This process of phasing also allows for structurally sound fabrication. The basic subdividing for the phasing of the structure is illustrated in the figure [on the next page], this allows for organized work flow, constructing bottom up providing intervals for the robots to assemble the successive structures as required. The tolerance seams structures are assembled in a layer by layer manner and joined after the fabrication of the unit structure it supports. This process is illustrated in the figure on the next page.

The rails system as discussed earlier determines the positioning of the robot and the number of robots involved in the fabrication of a unit. Furthermore, the positions of the robots determine the role the robot will perform, be it a unit, tolerance seam or keystone caps.

For compression-based structures to be fabricated in most cases there is a need for temporary scaffolding to be constructed, over which the structures are built [5]. However, this stage proved to be a challenging aspect in this research. The proposed structure is a compression only structure and therefore, to be fabricated would generally require a temporary scaffolding. Most scaffolding over the world utilises steel frameworks or even low-cost timber. However, due to the remote location of our sites and its harsh conditions utilising foreign scaffolding was rejected. This was mainly due to lack of resources onsite and time constraint. In keeping with the concept of material autonomy and local resources, outsourcing scaffolding is a contradicting proposal. The proposal of essentially constructing a base dome geometry over which the proposed panels would fit in would mean double the resources, in terms of money, time and material and is a contradicting proposal to the ambition of this project.

Therefore, various methods were analysed to create a freemason construction system. Phasing of the construction sequence in such a way that freemason construction could be utilised is explored further.

4.2 Tolerance Mitigation

As multiple robots collaborate to fabricate the structure, it becomes necessary to phase the fabrication process. This process of phasing also allows for structurally sound fabrication by mitigating tolerances during the construction process. The construction phasing is divided into units, seam units, keystone cap units. The main units are constructed two at a time with successive units being constructed simultaneously. Once, a specific height is reached, which is predetermined from increment analysis, the connecting tolerance seam is then constructed taking into account any deviations that have built up in either units due to machine tolerances, thus, mitigating the deviation at this step. This iterative process is following a sequential path, such that any minor or major deviation is mitigated at every step of the unit construction thus, resulting in a precisely fabricated geometry (Figure 12).

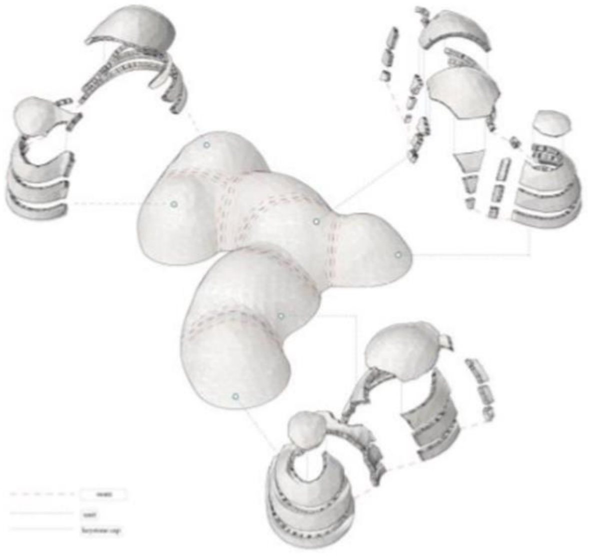


Fig.12 Global sequence- successive units

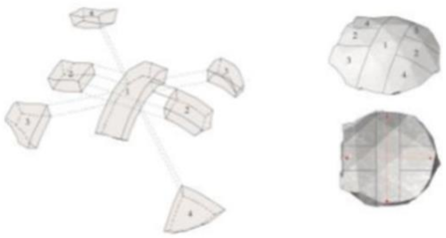


Fig.13 'Keystone cap' construction.

Once, the entire structure is constructed to a predetermined self-standing height, the final stage is the construction of keystone caps. These keystone caps must be constructed separately and then placed in their specific positions.

Keystone Cap Construction

The placement of the keystone cap unit is the last stage of construction. The keystone caps are constructed in several parts. A rough mound of unused peat is placed as a temporary support on the ground. The caps are divided into symmetrical arches. The arch 1 is first constructed over the mound of peat, followed by the two parts of arch 2 simultaneously which connects to arch 1. Following that parts 3 are constructed and finally part 4. The cap unit is held together with the help of cables to maintain its position as it is lifted off the ground and placed as keystones pieces into the existing construction. The cables are then removed. These keystone cap units act in a similar manner to keystones in arches, putting pressure into the existing structure and keeping the whole structure in complete construction (Figure 13).

5. Evaluation

Leveraging digital manufacturing techniques to create buildings enables novel structural designs, improved structural performance, and greater construction efficiency. Use of the proposed techniques would change the cost structure of buildings to be based on total raw material cost, rather than on geometric complexity. Automation of the construction process also simplifies logistics, reduces construction time, and decreases labour costs. Having a correct time prediction is valid in a taught time frame.

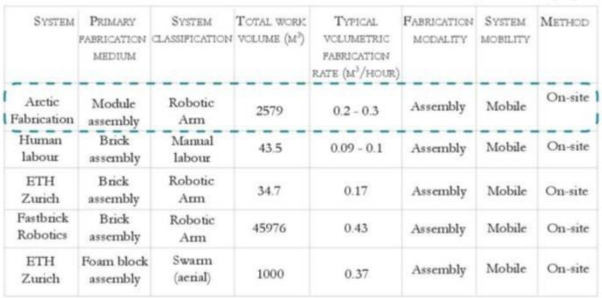
As an example, a preliminary financial analysis was conducted to compare the proposed fabrication system with traditional construction methods for an average-sized one-storey structure [6]. Estimates from construction workers were used to calculate costs for pre-fabricated aluminium construction and included human labour for the construction system. This analysis shows that the cost of the proposed system would be 27% less expensive than traditional prefabricated methods. While the initial investment of robots would be high, due to their continuous over time the investment would gradually pay off. These estimates strongly support the fiscal feasibility of the proposed material and fabrication technique, showing that it will not only save time and increase safety but also lower costs for a better more adapted building structure.

5.1 Comparisons with Existing Automated Construction Research

A basic analysis using two metrics that can provide insight into the relative performance of different automated construction systems. The first metric is the total work volume that the system can reasonably reach during a fabrication operation. The second metric is the typical maximum volumetric fabrication rate a system can achieve with its default fabrication process. (Table 12).

An important lens for evaluating the contributions of this research is in the context of other large-scale automated construction systems that exist today.

Together, these two metrics give a rough sense of a system’s overall performance in executing automated construction tasks [7].



SYSTEM	PRIMARY FABRICATION MEDIUM	SYSTEM CLASSIFICATION	TOTAL WORK VOLUME (M^3)	TYPICAL VOLUMETRIC FABRICATION RATE (M^3/HOUR)	FABRICATION MODALITY	SYSTEM MOBILITY	METHOD
Arctic Fabrication	Module assembly	Robotic Arm	2579	0.2 - 0.3	Assembly	Mobile	On-site
Human labour	Brick assembly	Manual labour	43.5	0.09 - 0.1	Assembly	Mobile	On-site
ETH Zurich	Brick assembly	Robotic Arm	34.7	0.17	Assembly	Mobile	On-site
Fastbrick Robotics	Brick assembly	Robotic Arm	45976	0.43	Assembly	Mobile	On-site
ETH Zurich	Foam block assembly	Swarm (aerial)	1000	0.37	Assembly	Mobile	On-site

Fig.14 Comparison with existing automated construction research

5.1 Physical Experiments – Problems Faced

Though the physical experiments were successful assembling the material along the designed tool-paths several issues were faced at the initial stages of the experiment.

Picking position

While an automatic feeder is proposed for onsite construction during the physical experiments manual placement of the panels is required. However, due to the proposed system of the automatic feeder, this problem will not be faced during onsite construction.

Limitations of the experiment (material)

The foam is extremely light when compared to the proposed material [peat] and sensitive to the slightest pressure variations caused the calibrated speed of the robotic arm. Due to the foams lightweight, there was difficulty in the panels staying in position as the centre of gravity did keep the panels in place at all times after being placed.

However, the weight of peat is much higher than the foam and thus it is concluded that this problem will not be faced on site due to the centre of gravity falling within the previous panels when the assembly is conducted in peat.

6. Conclusion

The digital design and materialisation chain for the development of this structure, allowing innovative architectural applications for a traditional material, has been discussed. The interdependent constraints, in particular, structural and fabrication requirements, have been discussed and associated with basic geometric constraints. Optimisation algorithms that deal with these constraints have been developed. The techniques for tessellation and for generation and optimisation of voussoirs have been integrated into the TNA-based form-finding tool RhinoVault. The result shows the efficient combination and integration of construction material and structural form.

Assembly logic was created by identifying geometrically feasible and structurally stable construction sequences during incomplete phases of free-form vaults. Robotic fabrication sequence is proven to be a feasible method for segmented shell contracture. However, the future investigation is required, first of all, with the proposed material in one-to-one scale.

Through the examination of the computational process, a complex architectural output was achieved. While integration of a compression-only structures and planarization helps simplify the overall physical fabrication process, it created an extremely computationally heavy system. Due to the highly interconnected data from micro, meso, to macro scales, the resulting output required increased computation time, the process becomes computationally expensive. The further development, therefore, is aiming to reconsider the complexity of the system.

The future goal of this research is to implement continues data feedback loop into the fabrication process, which can potentially increase the structural performance and accuracy in responding to the environmental data as well as serve as error tracking tool, helping to create structures with 0 tolerance. In terms of robotic fabrication exploration of multi-robotic system in physical experiments can bring intriguing opportunities to the architectural potential of the proposed fabrication system.

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