The Role of Parametric Design in the Robotic Assembly of Dry-Constructed Shell Structures

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Abstract. Architecture is going through major changes as automation in construction is radically transforming standard processing technologies and could lead, in the long-term, to disruptive technologies such as 3D-printing and robotics being applied to improve construction processes. This paper describes the adoption of a parametric approach in the design, fabrication, and assembly of dry-constructed, lightweight, wooden shell structures.

The design of the structure in a parametric environment simplifies the process of running multiple kinematic simulations of the construction sequence. These simulations are used to determine the feasibility of each simulated sequence and detect collisions and errors in the robotic arm path. The instructions from the simulation stage are passed through a series of steps to a single collaborative robotic arm that assembles the structure with minimum human intervention. The simulated tests are carried out using a single KUKA lbr iiwa R800 robotic arm equipped with a 2-finger parallel jaw gripper.

The complexity of the design requires a multi-disciplinary effort in the development of suitable systems. This research aims to show the potential that robotics and 3D printing could offer in terms of enabling the adoption of more complex and efficient free-form shell structures with decreased need for formwork and temporary supports.

Keywords: Parametric Design, Robotic Assembly, Kinematic Simulation, Shell Structures

1 Introduction

Shell structures are thin, spatially curved structures that transmit external applied loads through membrane actions. Shells are found abundantly in nature such as eggshells, seashells, turtle shells, and many other notable examples. The efficiency of natural shells is also found in artificial shell structures developed in ancient times, and increasingly more in modern engineering disciplines of civil, architectural, mechanical, aeronautical, and marine engineering. Shell structures are extensively used in civil and architectural engineering, examples include large-span shell roofs, liquid retaining structures, silos, cooling towers, and arch dams.

This paper addresses a solution for the robotic assembly and disassembly of a segmented dry constructed shell structure. Dry construction refers to the use of dry materials in the construction of the structure without the need for bonding agents like cement or mud. Dry structures can benefit from faster construction times, better insulation, better moisture resistance and fire safety. However, this type of assembly introduces a set of challenges that should be addressed in order to achieve a structurally stable, usable, and aesthetically appealing shell structure. Among those challenges is the need to connect the segmented modules in such a way that conserves the continuity of the structure and allow the shell to transmit the loads using membrane actions.

Membrane actions are the internal forces that act in compression and/or tension on the cross section of the shell. One of the significant advantages of shells is the ability to design a structure that minimizes bending moments and transmit external forces through the thin walls of the shell using membrane actions. Segmented shells offer an advantage for robotic assembly in that the size of the segments can be adjusted in the design stage to suit the capacity of the robotic system used. The process of creating a segmented surface is called tessellation. Tessellation is carried out in the design stage and results in segments that closely follow the original surface (Fig. 1).

Fig. 1. ICD/ITKE Research Pavilion, Landesgartenschau 2014 Exhibition Hall (Willmann et al., 2016)

2 Review

Robotics cannot replace skilled labour in the construction industry; however, robotics can complement the workforce. Faster and safer construction is a pressing need especially in an industry that have a high rate of injuries even in the most advanced and regulated economies. Robotics technologies have just started to realize commercial potential. A clear reason is that the construction tasks are notoriously difficult to automate. Research and development in this specific sector are much needed.

The use of robotics in the construction industry dates to the 80s of last century. Some processes were automated on or off-site, but the use of robotics was limited to experimental applications and the social and economic factors caused the progress to slow down (Bock, 2015). More recently, and due to the rapid development in computer software and hardware, robotics use in the construction industry is becoming more viable. New methods are being developed for dry construction, fabrication, and assembly of structures; however, robotic systems are mostly being used in fabrication of shell structures rather than assembly (Fig. 2) (Li and Knippers, 2015).

Fig. 2. Landesgartenschau Exhibition Hall in Schwäbisch Gmünd (Jian-Min Li, 2015)

Robotic arms have been used in the dry stacking of wall sections, and simple structures. Two papers by (Thangavelu et al., 2018) and (Bonwetsch, 2012) describe the vertical stacking of regular and irregular objects by a robotic arm, however, this method is only used in dry stacking where gravity provides the stability of the structure at all stages of construction (Fig. 3). This is not always the case for all types of structures and certainly not the case for most shell structures.

Fig. 3. "Structural Oscillation” Completed installation at Venice Biennale 2008 (Bonwetsch, 2012)

3 Methodology

The approach to this paper in software is a CAD method called parametric design. Parametric design refers to linking the geometric design to parameters. Changing the parameters directly or indirectly changes the linked geometry and ultimately the overall design. Parametric design is an algorithm-based process that uses parameters to define relationships between a set of inputs and derives a result from this relationship. The outputs of this process remain tightly related to the parameters. Changing parameters at any stage of the process affects the resulting geometry. The magnitude of this effect depends entirely on the implementation of the parameter in the system being designed. The fundamental design approach of the research is illustrated in (Fig. 4) to highlight key features of the design.

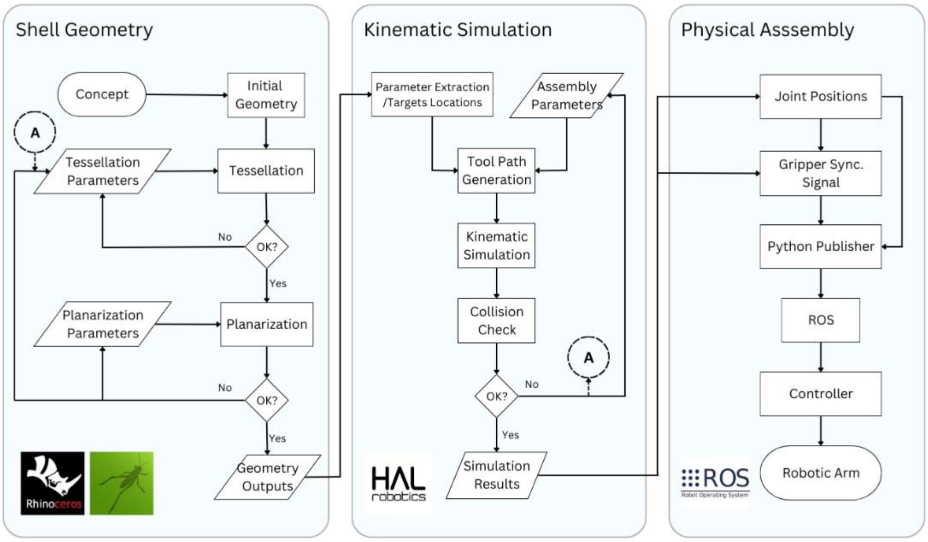

Fig. 4. The fundamental design approach proposed for this research.

3.1 Geometric Simulation

This approach contains three main conditional junctions where the design is evaluated. However, the actual design contains many more logical checks. The conceptual design is converted into a 3D design modelled in Rhinoceros/Grasshopper. The assembly of the shell structure is simulated in software using HAL Robotics plugin which offers great integration with Rhino3D and Grasshopper.

Setting up a simulation helps to identify problems and avoid most errors in the assembly sequence that could lead to crashes, unexpected behaviour of the robotic arm, damage, or injury. The simulation aims to investigate the possibility of automatically generating a path for the robot to follow, after the tessellation and planarization operations are completed. Extracting the parameters from the design will allow the code to adapt to different initial geometries and generate a new path for assembly. A robotic arm is used for this method, developed, and manufactured by KUKA robotics, the LBR iiwa collaborative robot is a 7-axis collaborative robotic arm is a lightweight manipulator with a very high repeatability and accuracy.

Geometric simulations are powerful tools to help designers make decisions on planning, analysis, and design in different areas of research and development. Different simulations are designed depending on the required model. For example, an assembler robot simulation is mainly concerned with the motion of the robot and the motion of the surrounding environment. A kinematic simulation is used in this case. On the other hand, a simulation of actuators mainly focuses on the dynamic models rather than kinematic models (Zlajpah, 2008).

3.2 Shell and Connection Design

The parametric environment was used to design a parametric model of a segmented shell structure supported by 4 pillars. An example of segmented shell structure is shown in (Fig. 5).

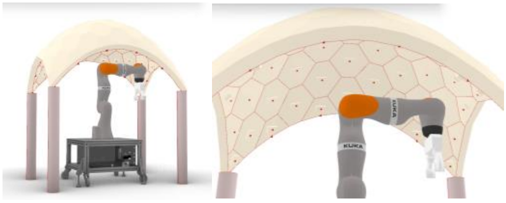

Fig. 5. An example of a parametric model of a segmented shell structure

In the construction stage, the panels rely on 3d-printed connection for stability. The segments can be affixed to each other using screws for stability. The connections were designed to act as temporary supports that minimize and possibly replace formwork.

The 3d-printed connections are standardized across the design, this provides excellent flexibility while exploring different solutions, given a practical limit of 25 degrees between any two adjacent panels is maintained. A single connection is shown in (Fig. 6a) joining 3 panels at their intersection (Fig. 6b).

Fig. 6. A single connection (a) and a connection joining three panels (b)

The design of the shell structure forces catenary curves for the edge arches on all sides, which simplifies the assembly procedure by providing a self-supporting perimeter for the structure in the construction phase. The side arches' panels, however, differ from other panels of the shell in that they require a different shape for the connection to form the arch (in the construction phase).

3.3 Assembly Sequence

Due to the large number of segments, it is not practical to have a dedicated pick-up space for each segment, hence the pick-up location for all segments is unified, and after a segment is assembled, a new segment is placed in the same position. All segments have a rectangular shaped cut-out for the end-effector of the robot to attach to.

The assembly sequence starts with the arm at home position, which refers to the position where all axes of the robot are at the zero position. The arm then moves to a pick-up approach position, a specified distance over the pick-up location. The assembly operation is similar to the pick-up operation; the arm moves to the approach position then follows a predefined path to correctly assemble the panel into position. The connection is attached to the panel manually before assembly. Shown in (Fig.7) are the steps to assemble a single panel.

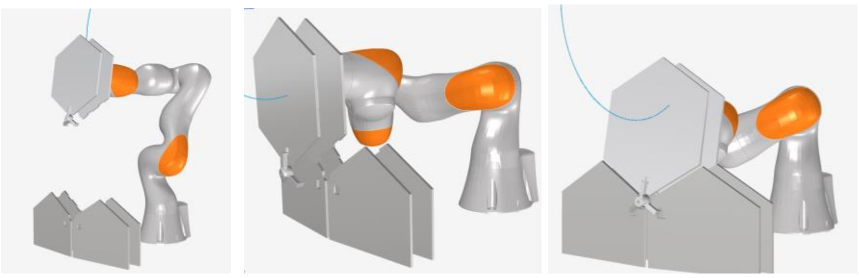

Fig. 7. Assembly of a single panel in position

The arm used is a 7-axis collaborative robotic arm. Due to the extra degree of freedom in the arm, it can reach an achievable goal in many different arrangements of joint positions. HAL robotics plugin for grasshopper handles motion planning, however, it only provides one solution for every run, which means that at every reachable target, only one solution is chosen. Some of the solutions provided are not optimal for an assembly operation, where a substantial manoeuvre is performed near targets. To get more favourable solutions, an intermediate axis-based goals are provided to force the arm to perform the needed manoeuvres away from the final target.

Each of the intermediate targets is shared between a number of panels. Panels are grouped into zones based on the intermediate target they share. Based on this approach, the assembly sequence of a single panel changes into the following: Home position, pick-up approach, pick-up target, back to pick-up approach, zone target, destination approach, and finally destination target. A detailed plan for N segments assembly procedure is found in (Fig. 8).

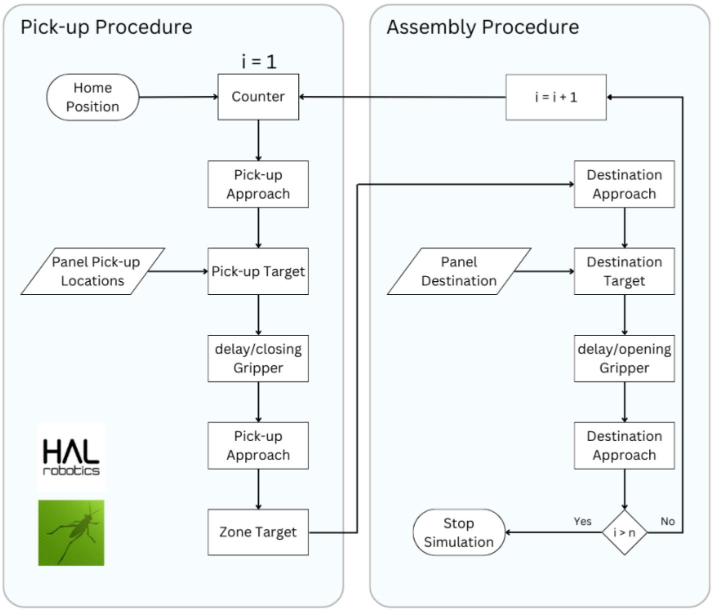

Fig. 8. A detailed plan for N-segment assembly procedure

4 Results

The parameters were adjusted to achieve a doubly symmetrical shell structure consisting of 61 hexagonal segments, 4 of which attach to the 4 supports (removed for clarity). The four edge arches are assembled in sequence as a first step, followed by the inner segments and finally the keystone (also known as the capstone). However, in this case, it was found that the keystone collides the structure due to the assembly from inside the shell. A possible solution was to use two segments as keystone (attached manually beforehand) which allows for twisting of the final segment to reach the approach location. The following (Fig. 9) and (Fig.10) show the initial and final stages of the simulation respectively.

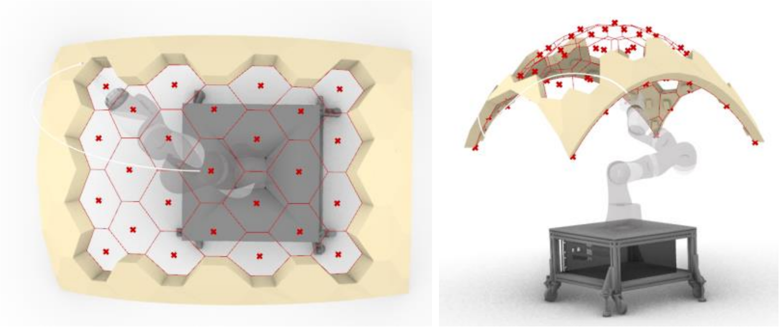

Fig. 9. Initial stages of the assembly procedure

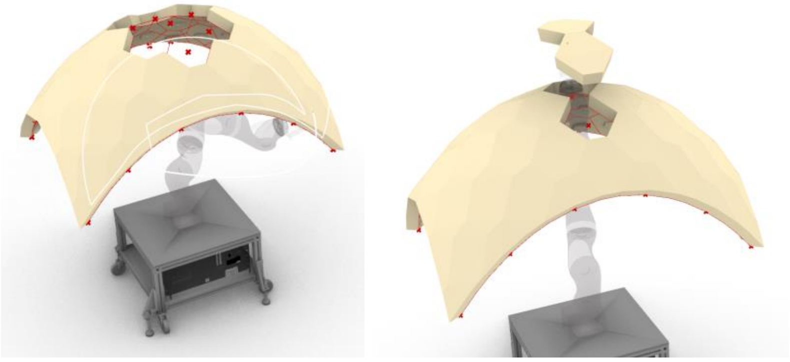

Fig. 10. Final stages of the assembly procedure

The overall simulation time is 1403 seconds (23 minutes 23 seconds) including the inserted delays for pick-up and place operations. The assembly can be examined visually or through a simulation dashboard and a timeline of joint movements, speeds, and accelerations. The visualised simulation is also available in all view ports. This gives an understanding of possible collisions or obstacles that can interfere with the assembly sequence.

Changing the parameters of the design changes the shell structure. A random set of parameters were chosen to present an example of a non-symmetrical shell (Fig. 11). The overall system worked as intended and a tool path was generated and simulated successfully.

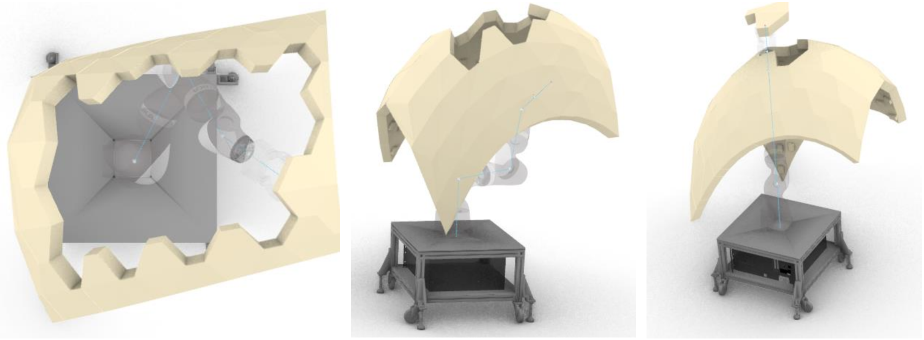

Fig. 11. An example of a non-symmetrical shell assembly

The 3d-printed connection was tested with 3 panels of a shell structure. The connection was able to maintain the correct angles between the panels and provide stability for the structure in place of formwork (Fig.12). Each panel was made out of two sheets of plywood, 5cm apart. A larger number of panels need to be tested to check the ability of the connection system to replace formwork entirely and to assess the viability of this solution in the robotic assembly of shell structures.

Fig. 12. 3d-printed connection replacing supports.

5 Conclusion

This research can serve as step towards the automation of a wide array of construction needs. The efficiency of shell structures in load transfer and the structural capacity per unit weight compared to traditional construction methods is poised to be a major contributor to the exploration efforts in the future where the cost of transporting traditional construction materials can be prohibitively expensive.

The methodology followed is independent of the shell structure form. However, an investigation of how different form-finding techniques can influence the results is of a great importance, as well as the possibility of adapting the system for different types of shell structures, such as grid shells. This research tries to assess the viability of a collaborative robotic system to work independently or in collaboration with individuals in the assembly of a light-weight shell structure, and the benefits and drawbacks of such a system from the parametric design stage to the automatic path planning and the generation of tool paths.

6 References

- Willmann, J. et al., 2016. Robotic timber construction — Expanding additive fabrication to new dimensions. *Automation in Construction,* Volume 61, pp. 16-23.
- Zlajpah, L., 2008. Simulation in robotics. *Mathematics and Computers in Simulation,* Volume 79, pp. 879-897.
- Bock, T., 2007. Construction robotics. *Auton Robot,* Volume 22, pp. 201-209.
- Bock, T., 2015. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction,* Volume 59, pp. 113-121.
- Parascho, S., Han, I.X., Walker, S., Beghini, A., Bruun, E.P.G. and Adriaenssens, S. 2020. Robotic vault: a cooperative robotic assembly method for brick vault construction. Construction Robotics. 4(3–4), pp.117–126.
- Vasey, L. et al., 2015. Behavioral Design And Adaptive Robotic Fabrication Of A Fiber Composite Compression Shell With Pneumatic Formwork. Acadia, Pp. 296-309.