Robotic Reticulations

A method for the integration of multi-axis fabrication processes with algorithmic form-finding techniques

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Abstract. This paper addresses the design and fabrication of non-uniform structural shell systems. Structural shells, particularly gridshells, have a long history but due to their complexity and the accompanying high cost of construction, their application has been limited. The research proposes a method for integrating the design and fabrication processes such that complex double curved reticulated frames can be constructed efficiently, from prefabricated components, requiring significantly less formwork than is typical. A significant aspect of the method has been the development of software tools that allow for both algorithmic form-finding and the direct control of robotic fabrication equipment from within the same modelling package. A recent case-study is examined where the methodology has been applied to construct a reticulated shell structure in the form of a partial vault. Components were prefabricated using 6-axis robotic fabrication equipment. Individual parts are designed such that the assembly of components guides the form of the vault, requiring no centring to create the desired shape. Algorithmically generated machine instructions controlled a sequence of three tool changes for each part, using a single modular fixture, greatly increasing accuracy. The complete integration of computational design techniques and fabrication methodologies now enables the economical deployment of non-uniform structurally optimised reticulated frames.
Keywords. Reticulated frame; robotic fabrication; dynamic relaxation; form-finding; computational design.

1. Introduction/background

Building design is becoming increasingly complex; structural, environmental, and programmatic requirements are necessarily intertwined with tectonic and formal design decisions. The ability to discretise multiple performance requirements has prompted the adoption of algorithmic approaches to design, allowing the precise and explicit negotiation of complex design parameters. Typically, algorithmic design strategies produce an output that is parametrically varied, and often generate components unique in size and shape. While at first the digital design and fabrication workflow may appear to create vast reductions in the labour of the design process, very often it simply shifts the labour from one aspect of design to another (Scheurer 2008). Significant work remains to be done to streamline the process from design conception to design realisation.

This research has been conducted as part of a larger body of work, which addresses the increasing complexity of the design and fabrication workflow (Pigram and McGee 2010). The research proposes that as opposed to a top down/serial approach, that the production process must be understood as a feedback between design and a multitude of constraints related to fabrication, materiality, and tectonic strategies. Of central importance to maintaining this feedback loop is the development of software that allows the designer to seamlessly migrate between design and fabrication, minimising one-way translations and the “reworking” that frequently occurs when fabrication constraints are not adequately understood during the conceptual design phase.

Specifically, this research has made use of fabrication scripts developed within a native CAD program. In this case, Rhinoceros 3d and RhinoScript have been used as a test bed for these custom software tools. The design and production of the prototype makes use of custom scripts which have been developed over a period of two years. Several groups of researchers have developed similar methodologies using Rhino and Grasshopper and other packages (Brell-Cokcan and Braumann 2010). What is important is not the particular program or scripting language, but the development of more numerous and more robust feedback channels between designing and making.

An advantage to this workflow rests on having algorithmically generated geometry. This allows fabrication output can be seamlessly integrated into the code framework, allowing a direct connection between the actual machine instructions and the underlying geometry of the design. Integrated simulation
and inverse kinematic verification (Figures 1 and 2) give the designer near instant feedback to fabrication issues such as reachability and collisions. The software tools were developed with open source distribution in mind. Currently it has been ported to multiple robot control languages, as well as to CNC G-code and Cartesian/hybrid kinematic systems.

As a specific application of this integrated workflow, the design and construction of a prototype structural shell system has been conducted. Several types of structural shell typologies exist, including grid shells and reticulated surface shells. Grid shells are structural systems that make use of a regular grid of structural members that are continuous and fixed only at ends (Figure 3). The members are assembled into a lattice that has a quadrilateral grid topology. This lattice is then deformed into the required curvature for the design, before being pinned at the intersections of the lattice. Shell structures are often characterised by large open spans, and double curvature in the overall form, which provides the shell with its structural performance, allowing the overall shell to be surprisingly thin.

Often grid shells are confused with reticulated surface shells, which typically use approximately equilateral triangles as the base grid. These shells cannot be “flattened” physically during construction. The system investigated here is
a type of reticulated surface shell, as the inability to be “flattened” is an important aspect of the approach.

The difficulties of this approach are immediately obvious from a fabrication standpoint. Irregular components require advanced fabrication methodologies. In the case of the grid shell, the system requires deformation or assembly onto precise scaffolding or centring systems, in order to achieve the final, designed form. In reality the optimal solution is often a hybrid of the two approaches.

2. Approach

This research has combined three aspects of enquiry into a coherent methodology: algorithmic form-finding; detailed tectonic and assembly development; and parametrically driven multi-axis robotic fabrication. In order to develop a structural system that maximises material efficiency, custom written dynamic relaxation software was used to “form-find” the resulting double curved shell geometry (Figure 4). While relaxation itself is far from novel, this implementation (written in Java) incorporated a series of valuable additions tailored to its specific use as a vault design tool. These additions were primarily interface related, designed to allow for, and to take advantage of, real-time adjustments to parameters during the form-finding process.

![Figure 4. Custom dynamic relaxation software, written in Java.](image)

Initial member geometry (of arbitrary topology) can be separated into a series of layers/groups, so that during the relaxation each group of members could have its own slack-length varied via a series of sliders. This functionality allowed for the development of a sophisticated intuition as to the emergent behaviour of the system. It also allowed for a nuanced control of the overall form while maintaining structural integrity. This affordance is not usually present in dynamic relaxation processes, which can tend to be overly initial-state dependent. In the reticulated surface described in this case study (Figure 5), differentiated slack-lengths were used to navigate a very tight situation while ensuring individual joint angles and member lengths remained within
fabrication limits (such as the requirement to overhang the edges of vacuum fixturing supports).

The design, development and testing of the specific joint tectonics of the system formed a significant segment of the enquiry. In order to produce a flexible structural system, which could react to the various potential inputs (many of which are not considered at this point), the relaxation software was developed to allow the user to specify the base grid topology. The initial prototype has been developed using a grid of hexagonal topology. This grid allows for a specific range of joint angles to be established at the nodes, which are always intersections of 3 members (Figure 6). This is significant because highly oblique angles generate cutting operations that engage large amounts of material and are therefore problematic.

![Figures 5, 6. Reticulated frame prototype; three member joint.](image)

A central benefit of this methodology is that the overall form of the grid shell is embedded into the form of the prefabricated components, which are self-aligning during assembly. The use of complex centring and or scaffolding (Figure 7) to create complex grid shell structures is well documented (Paoli 2007), however, the material and fabrication costs associated with such methods make them prohibitively expensive.

![Figure 7. Height adjustable scaffolding on Alvaro Siza's Serpentine Pavilion.](image)
Due to the potential for compounding errors, the proposed method requires very tight tolerances during component fabrication. With multi-axis machining, the tolerances of the machine can be difficult to quantify. In the specific case of 6+ axis robotic systems, the overall accuracy is inconsistent across the work envelope of the machine (this problem also exists for large CNC machines), and can at best be calibrated to within 0.5 – 1 mm spherical error. This must be considered at the design stage as it has considerable effect when considered in concert with the requirement for ‘self-alignment.’

The fabrication process relies on several features to realise a large number of unique parts efficiently. While all of the parts are geometrically unique, they are topologically similar (with the exception of boundary conditions), possessing 4 sides, a consistent number, sequence and arrangement of holes, connections and processes (routing, sawing and drilling). Members are pre-cut from flat stock using a 3 axis CNC router. They are initially approximated by a bounding box for nesting (Figure 8) to enable placement on the riser pods used in subsequent machining. More complex machine configurations exist that can accomplish this process in one setup.

![Figure 8. Nested cut sheet.](image)

An effort was made to minimise the visibility of hardware at the nodes, while maximising structural integrity of the joint. A bolt pattern that allowed the six bolts required at each node to “pass” each other was selected while acknowledging the inherent compromise of each pair’s location relative to the structural optimum. The combination of the compound miters and the placement of holes in each piece generates the desired curvature across all nodes.

As a result of the structures double curvature each node has a unique normal vector. To avoid this property translating into the requirement for twisting member forms all member centerlines are extruded towards a single point. This is crucial to allow the members to be cut from flat sheet stock while avoiding residual stresses within the overall structure. It is still necessary that the thin inner and outer surfaces of each member be ruled surfaces; this avoids any stepping at the top of the joints that would have resulted from the material
thickness if 3 axis cutting techniques were employed. Traversing from a node to its adjacent node along a single member, the surface ‘sweeps’ so that each end is perpendicular to its nodes normal.

The precise alignment of the hole system and the compound mitre that drives the overall curvature across nodes. In order to learn from a worst-case test of the fabrication strategy, the holes for the case study connections are designed with zero tolerance.

2.1. FABRICATION PROCESS

Each piece was placed on the riser pod, and then underwent three operations via a robotic milling workcell. Tool changes were performed automatically, and each part took around 2 minutes to fabricate. The first operation (Figure 9) made small slots to accept a square threaded fastener.

![Figure 9. Slotting operation.](image)

The second operation utilised a 300 mm saw blade fitted into a spindle (figure 10). The saw was chosen due to the high feed speeds achievable, with lower forces on the part as compared with a router. Low reaction forces are an important requirement, as the small surface area of parts makes vacuum-fixturing difficult. Surprisingly, it was possible to perform the variably swept edge cuts using the saw; intuition would suggest that a saw must be run straight in material. As described above only the longer edges twist, the end cuts are straight intersections.

The thickness of the part has a large effect, and the maximum rate of twist per unit length was determined experimentally. Exceeding this rate of twist resulted in friction and burning on the face of the blade or in lifting the piece of the vacuum pods.

The final operation utilised a drill in order to create the end and face alignment holes (Figure 11).
The accuracy of these holes became an area of intense study, as initial tests yielded parts that did not assemble correctly. Ultimately, due to the inaccuracies present in large robot kinematics, a solution was found that used tool calibrations that were local to each of the orthogonal work planes involved. The geometric similarity of the parts was important for this to be successful. In general, fabricating parts with these tolerances would be better suited to 5 axis routers, which have accuracies 10–50 times better than equivalently sized robots, and the high rigidity needed to cut harder materials.

The initial material fabrication studies have been performed using 18 mm Baltic birch plywood. Four sheets of material were used to produce the prototype. This material provides approximately isotropic properties parallel to the lamination plane, and the $4' \times 8'$ form factor allows for nesting to utilise material efficiently. Further testing utilising glue-laminated beams with the lamination plane perpendicular to the local surface normal of the node (currently the lamination plane is parallel) is planned for comparison.

3. Findings

The initial assembly of the grid shell prototype yielded several insights into the methodology. Overall accuracy of the prefabricated parts varied. Certain nodes were very accurately aligned (Figure 12), while others were off by approximately 2 mm between adjacent members along the normal vector of the node.

Over large spans, variation in the actual length of members would be significant, and would require allowance to be made at the boundaries of the grid shell. The variations in node alignment that were observed are most likely due to the aforementioned machine accuracy issues. Subsequent calibration of the robotic workcell via FARO Laser Tracker indicated the overall volumetric accuracy with a mean error of 0.5 mm and a max error of 0.8 mm. This is only valid for the checked positions in the calibration. Intuitively the drilling
operation represents a worst-case situation for the robot, where the drill axis traverses across 180 degrees of orientation, and the kinematic pose is significantly different between the two ends of each member.

Accuracy issues notwithstanding, the components were within the tolerance required for assembly, even with zero hole/fastener tolerance (Figures 13 and 14). Wood tends to be forgiving in this respect, as misalignment simply results in local material failure. The tectonic design ensures any of failures of this sort are concealed within the joint. Further research is needed to quantitatively test the joint tectonic employed. Predicted failure modes would be shear failure resulting in bolt pull through, and/or splitting failure between the plies of the lamination. This is significant as the bolt-holes act as stress risers for this mode of failure.

Figures 12, 13, 14. Node detail; Completed reticulated frame prototype.

Figure 15. Alignment of Alvaro Siza’s Serpentine Pavilion with Optical Metrology.

As an initial prototype, the structure behaved as expected, requiring no additional support during assembly. For larger spans the potential for component misalignment would compound and compounding errors could result in the load path deviating from the structurally relaxed form. As such a realistic method for the fabrication of large complex grid shells will require a hybrid
of prefabrication and onsite assembly control. While accuracy in the prefabrication of members is imperative, assembly tolerances will always exist. The research leads to new questions of how onsite construction practices, traditionally slow to change, can be augmented with technologies which allow compensations and corrections to be implemented to increase the overall efficiency of the system. One important area of study is the integration of onsite metrology methods in the assembly process, as current techniques are typically time consuming and labour intensive (Figure 15).

4. Conclusions

The complete integration of computational design techniques and fabrication planning methodologies opens up the possibility of economical deployment of non-uniform structurally optimised grid shells, while providing the opportunity for external design inputs, site-specificity and material efficiency to be incorporated algorithmically. Significantly the prototype and this research contribute to the larger ambition of tightly integrated feedback loops between design conception and design realisation achieved through computation.

References


