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Parametric skinning of complex-graphs: an airborne textile structure test-case

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Abstract: The research project presented in this paper aims to extend the repertoire of architectural design and construction. To achieve this purpose, research-through-design methods are used to match a commonly desired target geometry with a realistic and efficient materialisation strategy. The proposed approach has been tested through construction of practical prototypes that eventuated in a full-scale structure that performed well in a variety of outdoor conditions. The outcome of this work is a workflow for semi-automated skinning of complex graphs such as trusses or space frames. The project tests this workflow through an application to a topologically complex L-system. The L-system graph is parametrically skinned with a continuous, adjustable envelope. The outcomes of this skinning are materialised in fabric to produce a twelve-metre-long, wind-supported, airborne inflatable structure. This workflow is a novel extension of existing approaches to skinning and fabrication of structures based on complex graphs because it allows a hitherto unavailable, fabrication-ready geometric definition of joints between cylindrical and conical tubes of varying diameters. It is significant as a reusable approach to the geometric construction of such joints in a variety of materials and across multiple scales. Furthermore, it is interesting as an innovative prototype of possible wind-supported architectural structures.

Keywords: parametric modelling; space frames; textile structures.

1. INTRODUCTION

The aim of the research theme that encompasses the project discussed below is to extend the creative and technical repertoire of architectural design by supporting structures that can be influenced by their environment, during inception, refinement, construction or useful life. This capability is important for all forms of accountable, environmentally-sensitive design. As a particularly rich and challenging case, the project aims to investigate the feasibility and implications of architectural structures that can be supported by wind, without the need for artificially induced inflation (Figure 1, Figure 2). This research responds to the theme of higher habitation density by considering possible increases in the efficiencies of space-use through the deployment of non-destructive, on-demand and just-in-time architectural structures. In this pursuit, the textile structures have many important advantages. They can be cheap, lightweight, easy to install and relocate, available only when required, dynamic and aesthetically rewarding. Those inflated by wind, as it is innovatively proposed here, also encourage reconsideration of central architectural tenets such as that of permanence and continuous accessibility. With some reasonable sacrifices of predictable accessibility when the winds are unfavourable, they have a promise to be both efficient and sustainable. The complete discussion of these aspects is beyond the scope of this paper that, instead, focuses on one of the technical challenges of the 'wind-architecture' project: the need to manufacture continuous airtight skins for complex geometric configurations.

Figure 1: 12m-long self-inflating structure during a test flight. (source: Roudavski, 2017)

1.1 Gap

The geometry shown in the photographs (Figure 1, Figure 2) was produced algorithmically, by recursively iterating through L-system (Prusinkiewicz & Lindenmayer 2004) production rules (for an overview of dendriforms in architecture, see Md Rian & Sassone 2014).This approach is compatible with the overarching goals of the project because it allows automatic generation of geometry in response to constraints. However, automatic and fabrication-ready skinning of tree-like geometries produced by L-systems is not readily available.

Commercial modelling software that supports L-system generation including Maya or Houdini presumes that the geometry will be used for rendering rather than for fabrication. Therefore, they output roughly defined polygonal tubing with irregular stems and joints. The resulting geometry cannot be easily adopted or rationalised for fabrication. Fabrication is also not targeted by the research software implementing various L-systems in other fields, such as biology or computer science.

The Rabbit plugin in Grasshopper can create skeletons for L-systems and supports custom tube profiles. Its tubing can be linearly scaled between the start and the end of the L-system but does not support generation-driven or other custom scaling or properties. Furthermore, it also uses polygonal geometry for tubing, compromising precision and introducing artefacts that make unwrapping difficult. No graph-informed selection or manipulation of geometry is supported and the graph system itself is only a limited implementation of L-systems.

To sample the space of possible geometries, the 'wind-architecture' project produced multiple prototypes driven by a variety of L-system-based and other methods that included boid-like guidance for growth (e.g., Neubert et al. 2007),vector fields for the manipulation of the branching (e.g., Ling & David 2015),space-colonisation approaches to branch distribution (e.g., Runions et al. 2007, Palubicki et al. 2009) and A* path finding. This variety of experimental structures emphasised the need for an automated and controllable skinning routine.

Figure 2: The airborne structure seen from above, with people for scale. (source: Roudavski, 2017)

The challenge presented in prototype above (Figure 1) is further exacerbated by the fact that this structure is not purely dendritic but includes closed loops. Skins for strictly dendritic structures, such as those produced by classic L-systems can be represented as distorted spheres. If one disk is cut out, such a surface can be turned inside out through the resulting boundary; an important consequence for the assembly of textile structures through stitching or other methods.

The classification theorem of closed surfaces states that any such surface is homoeomorphic to one of three families: 1) the sphere, 2) the connected sum of g (genus) tori, for $g \geq 1$; and 3) (not relevant here) the connected sum of real projective planes (e.g., Zeeman 1966).The orientable surfaces in the families 1 and 2 can be grouped and the sphere can be considered the sum of 0 tori (or genus 0). Topologically closed surfaces of $g \geq 1$, of the wind-supported structure shown above are one example, cannot be turned inside out without self-intersection.

Complex surfaces that incorporate multiple tori (or multiple holes) are common in architecture. Living trees can also fuse and this process of inosculation is common in some species such as figs. Other natural structures, such as sponges, are characterised by the presence of very many holes. A typical approach to constructing such geometries in man-made structures is through assembly from parts. The sequence of assembly can matter but the process is forgiving because individual rigid parts are often designed in a way that supports disassembly.

Soft structures, such as those made with heat or chemical bonding cannot be easily disconnected. Stitched parts are also difficult or impossible to disconnect, depending on fabrics, types of seams and locations of the seams. Assembly procedures for rigid structures are constrained because such structures cannot undergo topological manipulations such as folding, inversion or stretching. In soft structures, as it is clearly demonstrated by the techniques of tailoring, surface manipulations are an essential method of construction. In general, soft structures can be turned inside out completely, if they are spheres with a disk removed. Or partially, if they are of genus n+1.

Manual workflows for assembly of soft structures do exist in fashion design and, in a limited way, in the design of architectural inflatables, sails, parachutes and kites. Some software for fashion patterning does exist (e.g., Clo or Tuka) but due to its many limitations the predominant techniques in garment design involve hand-fitting material on a human body or a mannequin. Such manual fitting is even more common with scales and configurations beyond the human body. These procedures can be fast and very sophisticated. They cope well with well-studied shapes of the human or, with more time and effort, with finely controlled but topologically simple shapes of sails and parachutes. When more complex shapes are attempted, as is commonly done in large inflatable kites that frequently aim to represent known entities such as animals, the control is sacrificed, the forms become crude and the surfaces wrinkled.

1.2 Hypothesis

Given this gap, the research described in this paper hypothesises that it is possible to produce a design-and-construct workflow that will extend the existing state-of-the-art by skinning and patterning topologically complex forms, as defined above, automatically.

2. EXPERIMENT

2.1 Methods

To develop an example of such an approach, the project relies on the practice-driven method of research-through-design. The application of this method involved the development and outdoor field-testing of a completed design, at full scale. The construction of such an object necessarily involves multiple versions and partial prototypes that explore the space of possible designs seeking a workflow that can accommodate the following requirements:

- accept a topologically complex graph;
- produce a continuous, adjustable skin;
- accept varying tube diameters;
- accept conical tube sections;
- use developable geometry;
- produce rational, fabrication-ready patterning;
- produce instructions for fabrication and assembly; and
- assemble in fabric without creases.

2.2 Workflow

The process begins with the production of a line graph that can serve as an input. The current implementation can accept an arbitrary graph but the test structure was defined as an L-system. A four-branch version of this L-system (Figure 3) can be defined as follows.

Premise: FA; (1)

Rules: A="[-FB][+FC][^FD][&FE]; B=+F[A]; C=-F[A]; D=&F[A]; E=^F[A];

where F is move forward, + is turn right; - is turn left, & is pitch up,
^ is pitch down and " is length multiplier

This definition supports interactive parametric control of the number of generations, step size, step angle and can be easily customised and automated further.

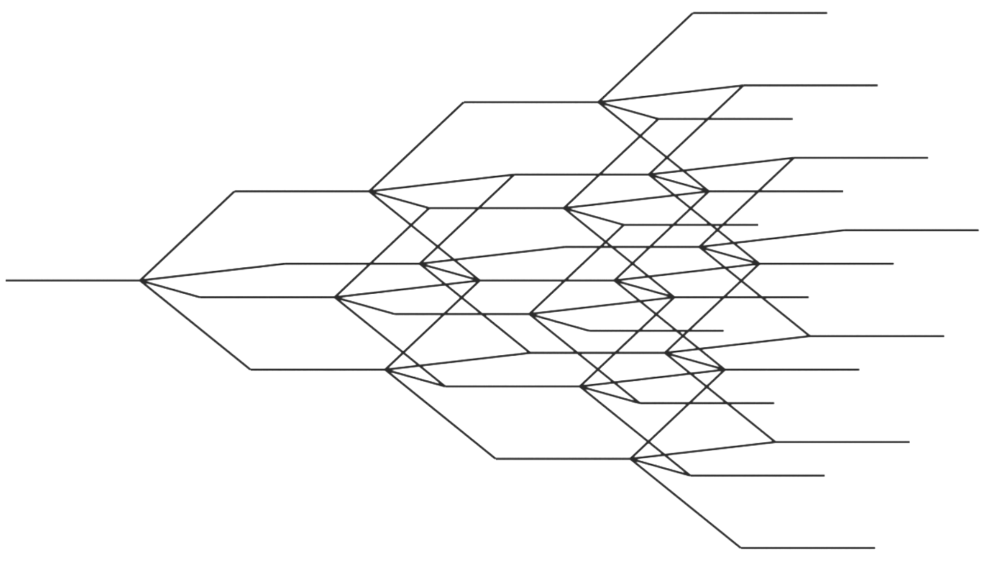

Figure 3: Four-branch L-system at the 6th generation. (source: Roudavski, 2017)

After the configuration of the graph is established (e.g. in Houdini or elsewhere), the graph can be parametrically repeated in Grasshopper 3D, with limited control.

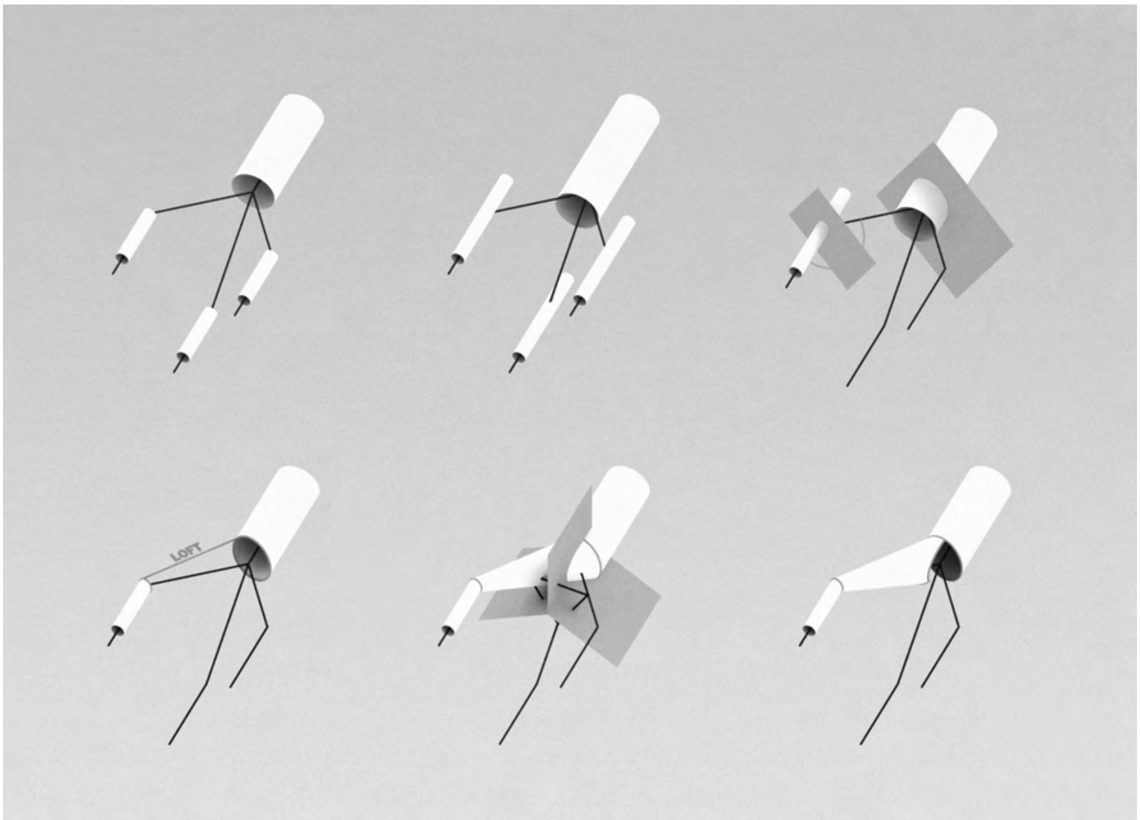

Figure 4: Steps of the skinning algorithm applied to a typical element. (source: Elias, 2017)

From here, the skinning workflow is as follows (Figure 4): top left) pipe all straight sections of the L-system linework; pipes may vary in radius in accordance with user-specified parameters; in the fabricated prototype (Figure 1), the pipe radius is directly proportional to the length of each base segment; top-middle) extend the pipes beyond the joints; top right) position a bisector plane at the elbow joint and copy a parallel plane to the tripod joint then split the pipes; bottom left) loft between the resulting edges to create diagonal tubes; bottom middle) draw three bisecting planes to resolve the intersection between diagonal tubes; bottom right) repeat for the other branches.

This approach relies on NURBS geometry rather than on polygons and can produce clean and precise intersections. Resulting parts can be easily unrolled, adorned with offsets for stitching, labelled, nested into the dimension of the desired rolls of fabric and output for fabrication and assembly.

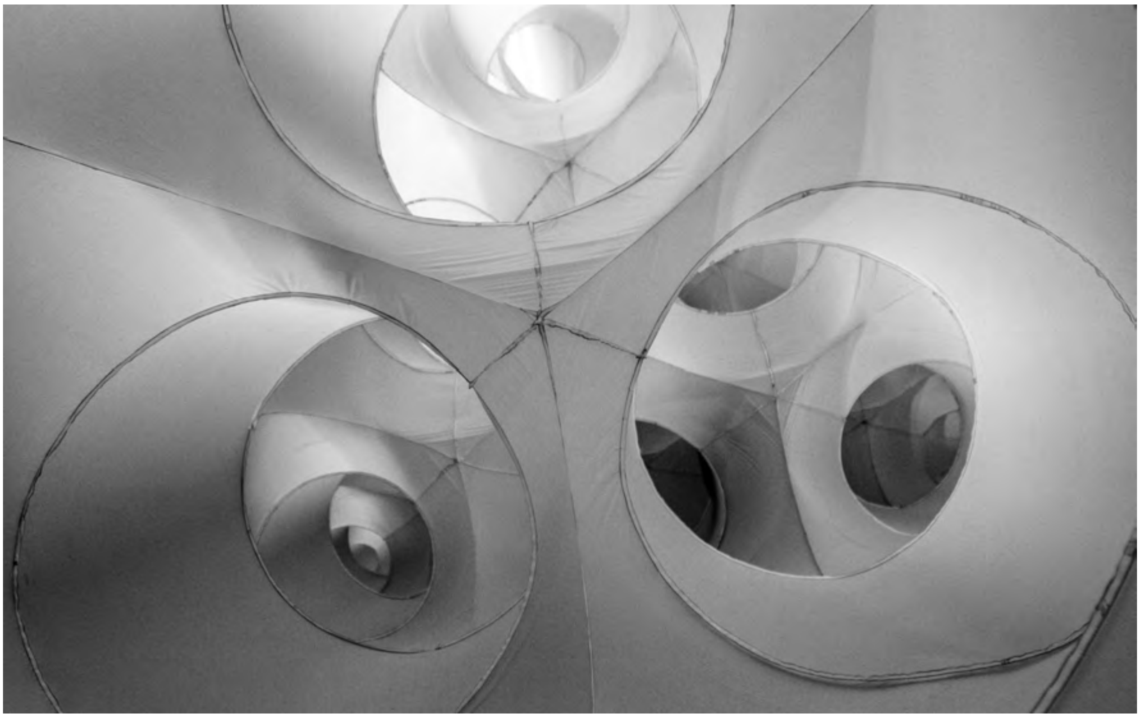

Figure 5: The interior showing seams and relative scales. (source: Roudavski, 2017)

2.3 Outcomes

The principal outcomes of the project in reference to the hypothesis stated above included, in reverse order: 1) a use-case airborne structure that performed well in a variety of conditions; 2) a workflow for the fabrication and assembly of such structures; 3) a workflow for semi-automated skinning that can be applied to a variety of complex graphs; and 4) a use-case workflow for the automatic generation of such graphs.

2.4 Discussion

The practice-based method of investigation proved useful because it has brought into consideration a range of issues specific to the construction of complex non-rigid geometries. Existence of these geometry, material- and performance-specific challenges was not obvious to the team before the engagement with the practical work. They, and the solutions proposed here, are also novel in the context of architectural construction and even in the more sophisticated fields of parachute-, sail- or kite-making.

To give an example, an airborne structure's balance requires symmetry not only at the level of geometry but also at the level of material where weft/warp orientation can introduce uneven distortion and unstable aerodynamics. Consequently, symmetrical parts of the structure had to be mirrored on the material and assembled accordingly. This assembly was complicated by a range of characteristics.

Firstly, the large scale of the structure, especially in the latter stages of assembly, made it difficult to correctly orient or attach new modules. Common piece labelling and case-specific edge-labelling techniques were used but proved only partially helpful because the labels could not be easily accessed in hard-to-understand distorted segments. The process was easier in a large assembly space. There, partial unfolding of the already-sewn portions of the structure into volumes similar to the shape of the final inflated form made understanding much easier. Errors were further minimized by the pinning of seams prior to sewing. When errors occurred, pinned modules could be re-arranged and re-attached correctly with relative ease. Once the assembly was completed, the structure could be inflated with a fan on the ground, allowing for the substantially easier detection of twisted or damaged parts. Remaining errors had to be identified during the first flight and corrected after that.

Figure 6: The deflated structure arranged on the flat for inspection. (source: Roudavski, 2017)

The construction was also difficult because the structure must be deflated for assembly (Figure 6). Deflation introduces severe distortions, including complex folding and self-wrapping, making it harder to recognize the geometry and introducing errors. The process is further complicated by the form and operation of industrial sewing machines that are produced within a narrow range of dimensions and presume that material will be folded and moved during stitching. Such manipulations were challenging, especially towards the end of construction when the structure was large and unwieldy. However, strategic order of assembly and the ability to isolate parts of the structure for stitching helped to overcome this difficulty.

The need to isolate parts and access the internal surface of the structure that cannot be completely turned inside out highlight another typical challenge. In response, the project developed a sewing workflow that relied on a customized sequence of assembly that only required topologically adequate portions of the overall structure to be turned inside out. The tripod modules were assembled first. Then these tripods were connected into generations, as inherited from the original L-system. Finally, the generations were connected to each other, starting from the last as its branches had most narrow tubes and continuing in the reverse order (Figure 5). These portions could be threaded through other parts of the structure in a way that made them accessible to the sewing machines. This assembly workflow cannot be correctly simulated in currently available software that struggles with large structures, folding, friction, distortions and folding.

3. CONCLUSION

Seeking to fill a specific gap in current research and practice, this paper discussed a successful workflow for automated production of skinning for topologically complex forms. While this work is integrated into a larger research theme, this paper focused on a very specific aspect. Therefore, the role of this conclusion is to briefly highlight the achievements of this project in relationship to its field by emphasising its innovativeness and significance.

3.1 Innovation

The project provides a novel extension to the existing approaches to skinning and fabrication of structures based on complex graphs because it allows a hitherto unavailable, automated and fabrication-ready geometric resolution of surfaces that can include cylindrical and conical tubes of varying diameters. The workflow uses fabrication-friendly NURBS surfaces and has been tested in a full-scale structure. This award-winning structure itself is an innovative outcome that has not been previously achieved in architecture or in the fields that design and build airborne structures, as has been confirmed via extensive peer review during Artevento | Festival internazionale dell'Aquilone in Cervia, IT in 2017, the world-leading gathering of kite designers.

3.2 Significance

The proposed workflow is significant because it can be used to produce skinning for a variety of structures that can have different functions, scales and be intended in a broad assortment of materials. The project outcomes indicate that an innovative idea of wind-supported architectural structures might be feasible. Thus, the project serves as a demonstrator that succeeds in integrating several capabilities – such as complexity, dynamism or adaptation – that are necessary for the production of environmentally-sensitive evidence- and performance-driven structures.

3.3 Future work

Future work will aim to extend this experiment with other types of structures and seek to apply the abstracted principles of environmentally-sensitive structures attempted in this stage to functionally useful or habitable structures. This work has begun.

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