Spatial Graded Patterns

A case study for large-scale differentiated space frame structures utilising high-speed 3D-printed joints

Iacovina Kontiza1, Theodora Spathi2, Patrick Bedarf3
1,2 MAS dfab, ETH Zürich 3 Digital Building Technologies, ETH Zürich
1,2 {i.kodiza|spathitheodora}@gmail.com 3 bedarf@arch.ethz.ch

Geometric differentiation is no longer a production setback for industrial grade architectural components. This paper introduces a design and fabrication workflow for non-repetitive large-scale space frame structures composed of custom-manufactured nodes, which exploits the advantages of latest advancements in 3D-printing technology. By integrating design, fabrication and material constraints into a computational methodology, the presented approach addresses additive manufacturing of functional industry-grade parts in short time, high speed and low cost. The resulting case study of a 4.5 x 4.5 x 2.5 m lightweight kite structure comprises 1380 versatile fully-customised connectors and outlines the manifold potential of additive manufacturing for architecture much bigger than the machine built space. First, after briefly introducing space frames in architecture, this paper discusses the computational framework of generating irregular space frames and parametric joint design. Second, it examines the advantages of MJF printing in conjunction with integrating smart sequencing details for the following assembly process. Finally, a conclusive outlook is given on improvements and further developments for bespoke 3D-printed space frame structures.

Keywords: 3D-printing, Multi-Jet Fusion, Space Frame, Graded Subdivision

Background: Space Frames & Architecture

The research presented here extends Alexander Graham Bell’s early 20th century concepts of multilayered space frame kites, which enabled aerodynamic lift through maximizing volume. From 25 cm long spruce rods, Bell constructed a 3939-cell regular structure, weighting only 91 kg. Furthermore, by those pioneering experiments, the principles of tetrahedral construction were formalized, which employ rigid space frames of light materials with scalable volume to weight ratios (Bell, 1903). Therefore, Bell lays the ground for uniform space frame structures developed by mid-20th century architects such as Buckminster Fuller and Konrad Wachsmann (Chilton, 1999). Fuller’s octet truss (Chilton, 1999) structures employed aluminium profiles without extra nodes, targeting machinability and industrial mass-manufacturing of its members. The growing
demand for efficient long-span structures nurtured the novel development of a modular and systemic aesthetic quality (Figure 1).

[Images of Bell's kite, Fuller's space frame, and Wachsmann's joint]

Wachsmann’s grid system already incorporated a universal flexible connector, allowing up to twenty members to be connected with ease. Hence, this demonstrates the changing manufacturing requirements of space frame architecture capable to adapt to any morphology (Tripeny, 1999). Throughout the course of late-20th century architecture sculptural experimentation, non-uniformity of space frames enters the design disciplines in form of smaller artistic installations and large-scale building projects. To name a few, Melbourne’s Federation Square by Lab Architecture Studio, the Beijing National Aquatics Center by Herzog and De Meuron as well as the BMW World by Coop Himmelb(l)au exemplify some of the most ambitious structures. Consequently, differentiation in irregular frames shifted the manufacturing demands from standardization to mass-customization which affects workflows in planning, logistics and assembly (Fischer, 2005).

Building on previous work on the example of a lightweight kite structure, this research investigates new design possibilities, which exploit the advances in digital fabrication technology. Here, recent advances are enabling a shift from a geometry-centric to a material-centric design practice (Mogas-Soldevila, Duro-Royo and Oxman, 2015). As part of a 3 month long thesis project of the MAS ETH DFAB program, the authors demonstrated novel design and fabrication strategies for differentiated functionally-graded space frame structures beyond the repetitive modular grid (Figure 2).

**Material Design: Functionally Graded Structures**

Physical materiality and fabrication constraints can inform the computational design workflow instead of post-rationalization routines after construction. Based on this perspective, the desired functionality in this project is achieved by exploiting material properties through a computationally generated subdivision process resulting in a multi-hierarchical functionally differentiated material system. Firstly, a morphological design space is populated with space-filling cells. Secondly, this space is differentiated in distinct stiffness zones in response to the aerodynamic drag and support forces. Physically, the stiffness is alternated by varying the length of the linear members and is estimated empirically by using a simple heuristic method of testing their bending behaviour (Figure 3). After testing different materials in multiple lengths, beech wood rods are used because of the desired bending behaviour and low cost.

After testing the mechanical behavior, different stiffness zones could be articulated:

- Central stiff zone where aerodynamic forces are applied. Bridle laces are placed (spine) | rod average length = 20 cm
- Bilateral semi-flexible zone that produces the lift. Steering laces are attached to control the manoeuvring (wings) | rod average length l = 40 cm
- In-between flexible zone transmitting the forces | rod average length l = 50 cm

Hereby, the gradient from rigid to flexible areas is achieved through subdivision density grading. The resulting space frame acts as a structurally graded material system.
Compliant mechanism composed of bending rods and stiff joints (Figure 4).

Figure 3
Physical prototypes testing rod bending behaviour (photograph by T. Spathi)

Figure 4
Rod length distribution throughout the functional zones of the structure

Computational Design: Spatial Subdivision
Subdivision processes have traditionally been used in computer graphics to generate smooth surfaces from a coarser polygonal mesh. Given the appropriate process parameters, they can produce forms of astounding complexity from even the most undifferentiated input (Hansmeyer M., 2010). Hansmeyer and Dillenburger explore how these subdivision processes can be reconfigured and applied to produce ornament. This paper investigates subdivision applied to space frames as a computational recursive process that adds spatial complexity. It explores varying densities for visual and structural purposes within tetrahedral boundary geometries. Hereby, regular tetrahedra perform the highest structural efficiency in space frames due to the inherent rigidity of triangles (Chilton, 1999).

The presented approach here is self-subdividing all space-filling tetrahedral boundaries, based on two methods: subdivision by tetrahedra centroid (SC) and by edge midpoint (SM). While the first adds geometric complexity on the nodes by bisecting the node angles and maintaining the initial edges, the latter adds more nodes on the structure by splitting the initial edges while maintaining the initial nodes. This process is applied on the resulting new tetrahedra recursively and was studied extensively in catalogues of different combinatorics. The resulting effects of recursive subdivision on geometric and performative differentiation such as stiffness, face proportions, edge lengths and angles were controlled using a number of procedural techniques in Grasshopper and Rhino Python Script.

Furthermore, combinations of SM & SC methods were applied based on their impact on the structure’s uniformity, intricacy and density. The designer had to balance the structural and manufacturing requirements as well as aesthetic qualities, such as emphasizing contrasts and transitions between dense and sparse areas, in each iteration by using modulo operations, graphs or mathematical equations. The subdivision process results in a population of tetrahedra in each generation given by the relation: P(tn) = 4n. In general: P(tn) = {x0,…,x4^(n)-1}, where tn: generation, n: number of generations, xi: individual, P(tn): population of individuals in n-generation.

In each generation the subdivision methods are governed by a set of exclusion routines following structural and aesthetical rules. Selected tetrahedra of the population are prevented from further subdivision and maintain their current form in the following generations. Structural Exclusion routine is applied in order to secure that the generated space frame is structurally efficient - the angles of the tetrahedra are between 30-60 degrees - and assemblable - the length of edges have a global minimum of 10 cm. Aesthetical Exclusion routine aims to control extreme densities and irregularities throughout the structure and controls transitions between to foster an overall appearance of controlled irregularity rather than chaos. To implement this, gravitational points in selected areas are used to define a graded transition between the differentiated patterns (Figure 5).
In iterative subdivision processes the algorithm is enabled to affect increasingly smaller detail; first iterations can control the overall form, while successive iterations create the microstructure (Hansmeyer and Dillenburger, 2013). In the proposed approach, the first iteration is followed by a Subtractive routine removing completely selected tetrahedra from the initial population and strategically creating holes in the initial global form. Based on Bell’s kites, a large central empty space preserves best the equilibrium of the kite (Bell, 1903). The resulting global shape is a free form structure deformed further by modifying its bounding control surfaces. Once the final network is generated (Figure 7), rod thickness is attributed to the linear elements corresponding to their resulting lengths, following the lightweight principle of reducing mass for shorter distances of transmitting forces (Krame, 1998).

Bell’s winged superstructures had a much greater power than one would assume at first sight. He provided wing-like sails adapted all in the same direction being able to lift the kite and maintain the balance while flying. We introduce the propellor type - a trilateral wing - attached to the tetrahedra generated by the SC method. Each design iteration is evaluated in terms of fabrication data giving feedback to the designer and influencing the decision-making process in terms of fabrication constraints.
Figure 7
Generative functional differentiation controlled through three zones and generated in five generations. Each generation yields fabrication data.

and cost. The Feedback routines calculate the total numbers and weights of components giving to “Weight Structure to Surface Area” ratio, an indicator for kite validity derived from Bell’s experiments (Figure 6).

Summarising, the developed computational design tools of the presented approach are:

- Iterative tetrahedral subdivision based on boundary condition of target geometry
- Exclusion routine of tetrahedra not complying with structural criteria
- Structural refinement routine modifying the length and thickness of members
- Sail surface generator creating two types of sails with different aerodynamic behaviour
- Ratio calculator checking the validity of kite structure
- Fabrication data feedback routines

Joint Design: Parametric Design Nodes
The kite structure is conceived as a network data structure consisting of nodes, edges and surfaces. The followed approach grounds on algorithms developed as Python Grasshopper components, which generate fully-parametrized generic joints based on the data structure of members’ angles, lengths and widths. Consequently, the joint is designed as a rule-based spatial geometry bringing together all elements in an interdependent system.

Owing to the level of network complexity, node attributes are measured at the level of the edges. Firstly, an initial geometry features various extended branches that are calculated by edge lengths and the assigned widths of 2, 3 or 4mm. Then, through multiple iterations of intersection-checking between node-branches and subsequent adjustments in their extension, the established workflow allows the generation of 1380 joints with implemented structural, fabrication and assembly sequencing logics (Figure 9a).
Thus, in quest of material reduction, the joints were parametrically designed with minimum wall thickness of 0.9 mm and their collets further hollowed out with framed facets. Those improvements could only be achieved due to the material properties of MJF-printed parts, which will be described in the following section. Lastly, all joints were computationally sorted in 3D-printed snap-off grids and referenced by assembly sequence in 4 segments containing all 22 tetra families for easy transport (Figure 8).

**Fabrication: Multi-Jet Fusion 3D-Printing**

Since 2016 a new 3D printing technology promises to revolutionize the market of additive manufacturing for on-demand components in large scale production applications. Multi-Jet Fusion (MJF) works on the crossroads of binder jetting and sintering: a fusing and a detailing binder are jetted uniformly on a powder bed and heated on every single material layer resulting in isotropic parts even in between horizontal layers. Based on their distinct absorption the binder types react to thermal energy differently and either fill the interiors of parts and walls solid or define the outer surface detail. Consequently, through this parallelization of a sinter process, MJF produces ten times faster and at half the cost compared to other 3D printing solutions. Due to the use of fine-grained polyamide nylon powder and the voxel-level fusion of multi-agents, the parts feature high resolution, durability and accuracy requiring minimal post-production finishing.

Consequently, this research exploits the rapid production of 1380 industry-grade parts that were densely-packed into one 400x300x400 mm print box, by covering only 250 mm layer height, enabling a structure of 4500x4500x2500 mm much larger than the built space. The 3D printed objects weighted 28% of the total kite structure compared to wood rods taken up 52%. Adding on MJF printing values, the printed parts hence were attached upon a 1mm thick high-density component lattice with no additional material-consuming id tags (Figure 9b). In comparison, Selective Laser Sintered (SLS) printed parts demonstrate greater design constraints with wall thickness of 2 mm, lower durability and higher porosity (Figure 10). Furthermore, unlike other 3D-printing techniques, such as Stereo Lithography (SLA) and Fused Deposition Modeling (FDM),
MJF does not require support structures for convoluted geometries and allows to reuse untreated powder entirely.

Assembly
Production of the large-scale structure focused on smart assembly sequence of custom manufactured joints of excessive quantity and off-the-shelf linear members. Moreover, the kite is composed of 1380 3D-printed nylon connectors, over 1000 m wooden rods varying in widths and 30 sqm Ripstop Nylon fabric. All 3D-printed joints were cleaned manually which took about 3-4 hours. The 863 sails were computationally unrolled and nested in sheets for cnc-cutting within 4 hours, while the rods were cut manually in 2 days. It took for two people 10 hours a day for 20 days to assemble separately the 22 tetra-modules into 4 larger segments and combine them into the final structure covering 215 sq.ft (Figure 11).

Conclusion and Outlook
This research presents an approach to fully exploit the novel benefits of industry-grade 3D-printed parts for a complex space frame structure which incorporates smart assembly as design driver to enable building an object multiple times larger than the printer built space. Several computational design instruments and refinement mechanisms were embedded and extend the architectural vocabulary of precedent research.

The results are convincing in three aspects: a. the computational workflow produced 3D-printed connectors of any geometric complexity for mass-customized manufacturing, b. the successful assembly process was fully-informed by fabrication data, c. the significant rigidity of whole structure weighing app. 10 kg. Beyond the scope of this research towards more sustainable applications, assembly sequencing or module stitching require further integration into the design strategy and give way to alternative processes of disassembly and reusability. This can result in weight savings, better logistics handling and cost reduction for highly complex building assemblies. Applications enabled by this work could include emergency spaces, where transportability and adaptation are prerequisites, light and large-span cover for temporary use in dense urban environments but also extremely remote areas.

The impact on architecture and large scale construction is promising: Differentiation in industrial grade manufacturing is no longer a production setback. While modularity of conventional space frames symbolize strength and stiffness of 20th century engineering culture, conceptualizing irregular space frames as compliant mechanisms combine strength with elasticity for highly adaptive and integrated architecture. Consequently, resourcefulness doesn't
need to compromise architectural design but opens opportunities for innovative building solutions.

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