Redefining Polyhedral Space Through 3D Printing

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Abstract

Space frames (SF) are perhaps the most used lightweight spatial structures in the construction sector. They are identified as a highly prefabricated and standardised construction system. However, as computational design brings forward more complex forms and freeform shapes, standardized modular systems are presenting difficulty to retro-fit complex forms.

Advances in Additive Manufacturing (AM) present opportunities to fabricate customized structural parts. More specifically, the fabrication of bespoke connections with AM bares great potential to overcome geometrical limitations in SF construction. Geometrical differentiations can be combined with functional integration at no extra cost. 3D printing offers the missing link to effectively establish a digital chain, from design to fabrication for non-standard SF.

This paper examines generative computational methods for creating case-specific, bespoke connections designed for AM. In combination with studies in density, topology, and materiality of the connections possibilities of new geometric space articulation, new aesthetics, and finally, multi-functional structural frames arise.

A series of case studies of bespoke SF design at different scales are reviewed and address a variety of functional nodes ranging from stiff axial connections to fully flexible spring ones. Finally, the paper critically discusses the geometrical benefits and limitations of the presented methods for digital bespoke space frames.

Keywords: 3D printing, space frames, bespoke prefabrication.

1 Introduction

Lightweight structures, and more specifically space frames, formed by a spatial arrangement of polyhedral cells, are a versatile construction system, while they have a small carbon footprint. This is because material strengths are optimally used and hence, no resources are wasted (Schlaich and Schlaich 2012). Space frames favor a more sustainable model of construction, as structures can be easily disassembled and elements can be reused, or recycled. Furthermore, single members can be easily replaced, if faulty.

However, complex architectural forms pose several challenges for space frame fabrication as great resources are needed to fabricate bespoke connectors for non-standard spatial structures. It is expected that joints of a space frame should be easy to fabricate without recourse to more advanced technology (Lan 1999). This is because the connections represent a large amount of the cost associated with space frames, more so if special node components are required. However, recent technological developments in digital fabrication have allowed customization of building components at no extra cost that go beyond the flexibility and aesthetics of the standardized systems like the Mero-ball Node or similar (Chilton 2000). Additive Manufacturing (AM) offers great flexibility in design, as it can produce almost any geometry in a variety of materials with high resolution. Especially metal AM provides today a method to fabricate bespoke structural elements.

These technological advances present new opportunities for spatial structures, because the complex construction scheme of the latter can be resolved within the jointing elements. The research presented in this paper seeks to find out if advances in AM can be extended to architectural applications, and if, in combination with digital design tools, they can lead to the design and fabrication of high-performance and adaptive structures, promoting lightweight, filigree construction.

2 Background

In the past years there has been an increasing interest in the production of bespoke architectural connections with AM. Advances in the technology have laid the groundwork for the shift from rapid prototyping to rapid manufacturing. Today we can directly print building components out of high strength, regulated materials like steel or aluminium and so design questions arise relating to material savings and functional integration in structural connections.

2.1 Topology optimization and material savings

The first application of additively manufactured connectors in the construction sector was brought forward in 2014 by the engineering company ARUP for a series of tensegrity structures in the Hague, Netherlands (Galjaard et al. 2015). The joints were topologically optimized for their specific position and loading case. In the same trajectory, research from RMIT Australia is investigating optimized nodes for applications in construction. In the quest to combine highly designed parts with standardized elements, nodes of a free-form shell structure are formed through a similar process of topology optimization and refinement of each individual node (Crolla and Williams 2014).

2.2 The ‘seamless’ connection

These investigations led other research groups and practitioners to investigate seamless connections of bespoke structures that use additive manufacturing (**fig. 1**). Their goal is to avoid arduous and expensive processes like milling, manually welding steel plate connections, or creating patterns for casting and post processing the metal cast. The table series *Multithread* from Weisshaar and Kram (2012), similar to the *Airtable* (Raspall et al. 2019) and *vMesh Pavilion* from the Airlab (Raspall and Banon 2016) are illustrative examples.

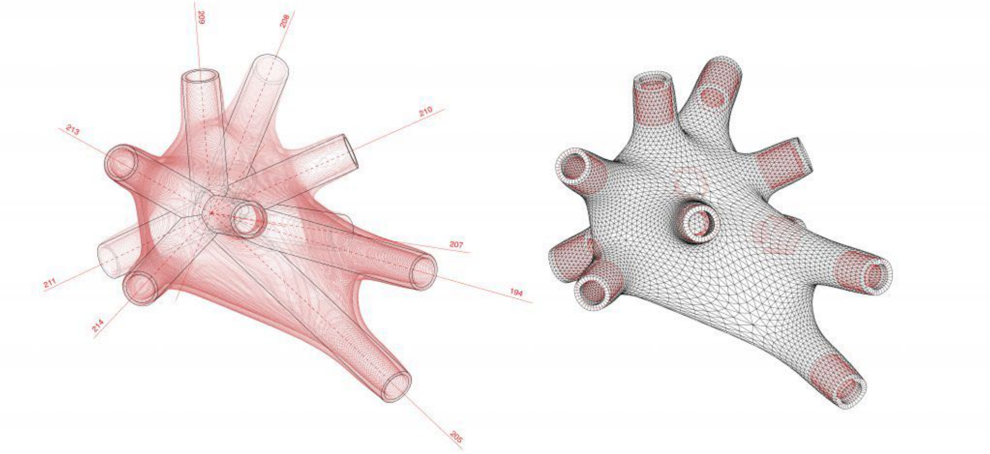

Figure 1: Seamless connection developed for metal 3D printing by the Airlab at the Singapore University of Technology and Design. Image credits: Airlab, SUTD.

2.3 Findings and opportunities

However, there is a lot of unexplored territory on the bi-directional relationship of spatial structures. The formation of the connection derives from the design of the overall form, but the latter is also informed and refined by the former. The opportunities that are presented with the ability to create bespoke, informed, even ornamented structural connections have not yet raised the question *what kind of structures can we design*. New constellations of elements with novel qualities can be explored only by changing the topology and geometry of the connection: malleable joints that assemble soft structures, kinetic joints that form deployable ones, spring joints that allow deformation, but also stiffening or structurally informed ones. The design space is not limited to a CAD ready optimised model or a volume-filling transition from element to element. On the contrary, the design space is expanded when we create design processes for additive manufacturing for the functional qualities we seek in a prefabricated system. The investigations presented in this paper are an initial mapping of this design space in order to start a dialogue on how the future prefabricated modular system will be.

3 Expanding the design space of AM connections

A series of studies on computational design processes are examined in this chapter to demonstrate the possibilities of design from a seamless, stiff connection to a dissolved space-filling network structure. Some of the presented design studies were developed by the authors and others in collaboration with postgraduate students in teaching modules of the Master of Advanced Studies in Architecture and Digital Fabrication (MAS dfab).

The authors reflect and cross compare the projects and their digital design approaches and further discuss and conclude their impact for SF construction.

3.1 Volumetric modelling for seamless connections

Basic minimal nodes for 3D printing are most commonly designed with Boolean operations of primitive shapes (Boundary representations or Meshes) that follow seamlessly the linear elements of a spatial truss. Alternatively mesh relaxation and/or geometric smoothing of a convex hull at the moment of connection is used (**fig. 1**). These methods often involve a lot of post processing in a robust software to execute the Boolean operations required to achieve precise detailing.

Volumetric modelling (VM), in contrast, presents an opportunity to achieve all of the above in a seamless process (Bernhard et al. 2018). VM is a method that describes geometry using function representation (FRep) instead of boundary representation (Brep). All points (x,y,z) in the discretized model space are assigned a value according to a signed distance function that represents the point's distance to the described shape. A negative or positive value indicates that the point lies inside or outside the geometry respectively while the surface of the shape passes through all points for which **eq. (1)** is true (**fig. 2**).

$$F(x, y, z) = 0 \tag{1}$$

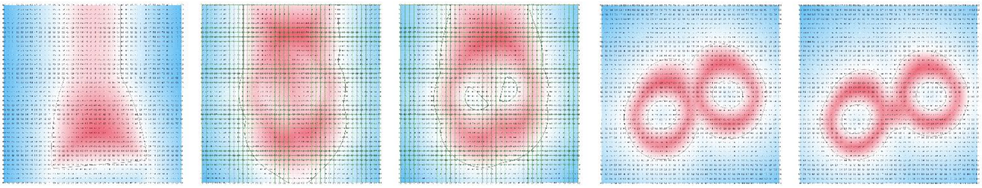

Figure 2: Sections of one connection developed with volumetric modelling using the Axolotl plugin in Grasshopper. In these images the iso-curve shown in black passes through all points for which the function evaluates to 0 and thus represents the section of the iso-surface at a certain plane.

Geometric operations and shape transformations in this method are reduced to the calculation of arithmetic values for the set of points in the discretized voxel space. This allows for a smooth process where blending of shapes, connection details, assembly data and tags can be embedded in one single distance object (Mitropoulou et al. 2019).

The following models demonstrate a process in which bespoke minimal connections are designed for a bamboo structure. An initial network of curves is connecting all the elements which meet at the node. Along this network we compute the distance function for the circular sections, blend them and incrementally add or subtract the additional details for assembly (**fig. 3**). Those can be additional parts that facilitate the assembly of triangulated modules like the slit-part connection that allows the insertion of members from the side or mechanical details, such as a thread in which a steel rope can be fastened to.

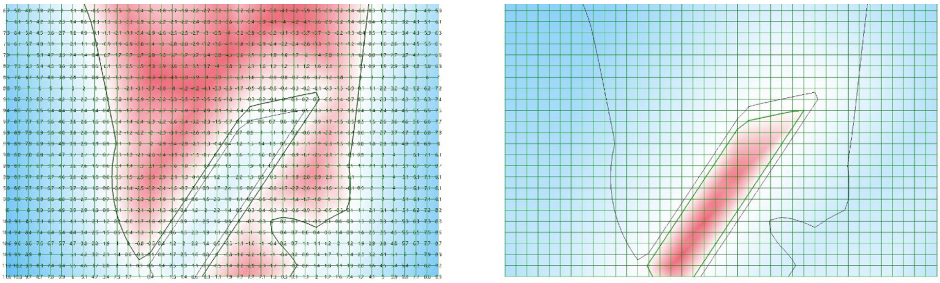

Figure 3: Section of one connection with male-female parts. The male part is “carved out” numerically and then a new geometry is described with a certain offset for assembly tolerances for the female part.

No matter how complex the node, how many members are coming to that point with different profiles and connection details, a “watertight” high resolution geometry ready for printing is calculated within seconds and visualized with a mesh-generation algorithm (Lorensen and Cline 1987) within a few minutes.

The connection in **fig. 4** is developed with the *Axolotl* plugin for volumetric modelling (Bernhard 2018). It is 3D printed in high strength Nylon and extremely lightweight. This drove the choice of the smallest possible interface between elements.

Figure 4: Minimal connection with all embedded details for fabrication designed for a bamboo structure with volumetric modelling.

3.2 Soft connections

This section describes two methods to generate soft and spring-like connections for transformable structures. Such types of connections usually depend on the materials used to fabricate them in order to act as malleable and deformable parts or a highly engineered sequence of connected parts that allow translational or rotational freedom. However, what follows is an investigation on how one can achieve the same result with the characterization of geometry.

The knot

VM is not limited to the creation of primitive shapes, on the contrary it is diverse, as mathematical equations can be used to describe non-standard connections. As a result, complex shapes can be easily described and meshed, and thus, qualities of spring-like geometries can be expressed through knot theory (**fig. 5**). The definition of shape is provided by the following systems of equations describing 3-dimensional knots (**fig. 6**):

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 10(cos(\phi) + cos(3\phi) + cos(2\phi) + cos(4\phi)) \\ 6sin(\phi) + 10sin(3\phi) \\ 4sin(3\phi) * sin(\frac{5}{2}\phi) + 4sin(4\phi) - 2cos(6\phi) \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 4cos(\phi + \pi) + \frac{cos(3\phi)}{3+2cos(3\phi)} \\ \frac{4}{3}sin(\phi) + 2sin(3\phi) \\ sin(4 * \phi) + \frac{1}{2}sin(2\phi) \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 4cos(\phi + \pi) + \frac{cos(3\phi)}{3+2cos(3\phi)} \\ \frac{4}{3}sin(\phi) + 2sin(3\phi) \\ sin(4 * \phi) + \frac{1}{2}sin(2\phi) \end{pmatrix} \tag{4}$$

for a constant β we define:
$\rho = 6.4 + 12.8 \sin(6\beta)$
$\theta = 2\ \beta$
$\kappa = 0.6\pi * \sin(12\beta)$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \rho * cos(\kappa) * cos(\theta) \\ \rho * cos(\kappa) * sin(\theta) \\ \rho * sin(\kappa) \end{pmatrix} \tag{5}$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} -22 * cos(\phi) - 44cos(3\phi) - 78sin(3\phi)) \\ -10cos(2\phi) - 27sin(2\phi) + 38cos(4\phi) + 46sin(4\phi) \\ 70cos(3\phi) - 40sin(3\phi) \end{pmatrix} \tag{6}$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} cos(\beta) * (2 - cos(\frac{2\beta}{\gamma+1}) \\ sin(\beta) * (2 - cos(\frac{2\beta}{\gamma+1}) \\ -sin(\frac{2\beta}{\gamma+1}) \end{pmatrix} \tag{7}$$

The next step in voxel space is to combine geometries by adding or modifying the values of each voxel in order to make variations of stiffer connections, or ones that receive more members (**fig. 7**). This step allows the overlay of several geometries. The angle in which members meet can be controlled as well as the thickness of the connection, if it is a hollow shell, if there is an infill structure and finally if it is perforated.

This modelling approach requires a better understanding of algebraic equations as there is little visual feedback while modelling compared to most CAD modelling software.

Figure 5: Spring-like connections defined by a mathematical knot. Photo credits: Julius Hatt.

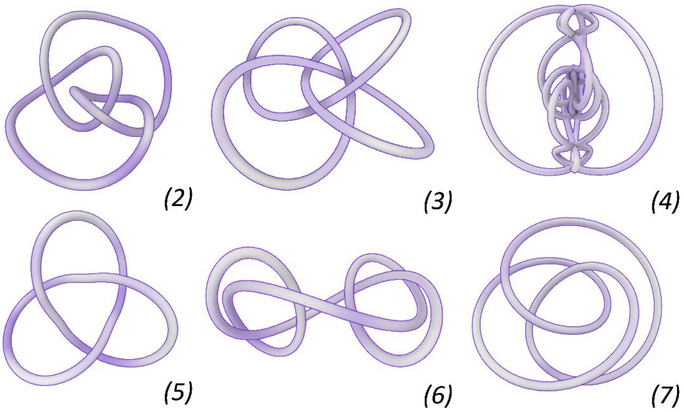

Figure 6: Series of topological knot studies for the creation of a spring-like connection corresponding to the equations above. Image Credits: Wenqian Yang and Eleni Skevaki.

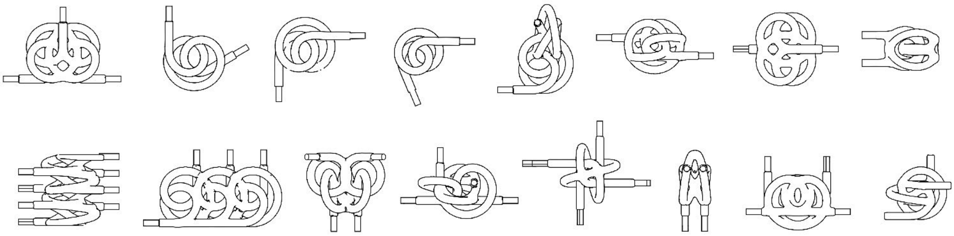

Figure 7: Modified knots in voxel space to accommodate several members or combine multiple knots in one stiffer connection. The combination of multiple knot topologies was created using Axolotl (Bernhard 2018). Image credits: Wenqian Yang and Eleni Skevaki.

Prototypes at different scales were investigated in order to examine the behaviour of the structure as a sequence of spring connections. The topological information of the node informs the initial line-network of the structure in order to create stiff or flexible areas (**fig. 8**).

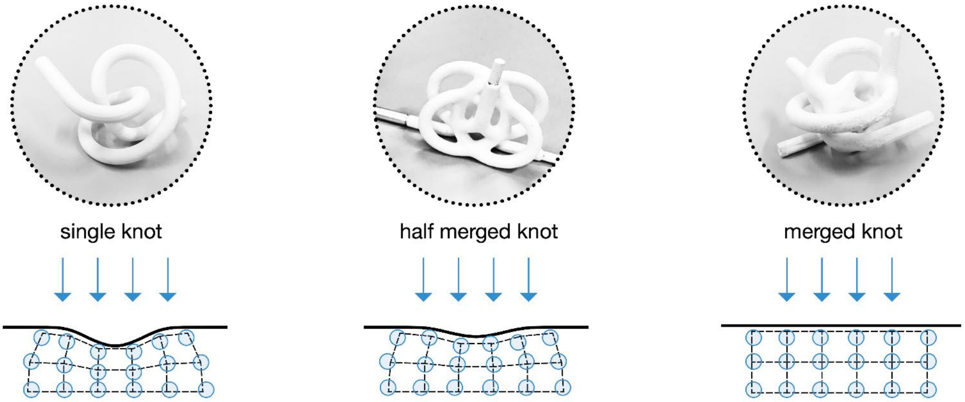

Figure 8: Studies on the aggregation of single and merged knots that affect the flexibility of the space frame. Merged knots become stiffer as they are topologically more complex. Image credits: Wenqian Yang and Eleni Skevaki.

Soft bodies

The next case study is borrowing elements from another discipline to revisit the concept of a connection. So far, the nodes connected one end of a member with another, but what if linear members were positioned in space unobstructed and the node would need to be squeezed and formed between them? An atypical connection between multiple members is investigated. The nodes shown in (**fig. 9**) are generated through a series of soft body collision simulations, leading to geometries that are unpredictable, fit perfectly to the constellation of members while being unique and could not be created in any other way.

The process starts with primitive shapes, which follow motion paths and attractors. As they collide with other objects they exhibit plastic deformation according to the compressive, bending, shearing, and stretching behaviour.

Two distinct cases of deformation are studied in depth. The first one consists of n primitive shapes that are initially outside the constellation of bundled elements (**fig. 10**). Attraction forces pull those primitives towards the bundling point deforming those shapes onto the bundled elements. The result is a n-part connection, where all the deformed pieces “click” together to assemble it (**fig. 11**).

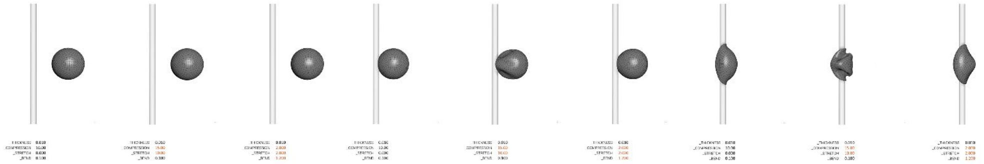

Figure 9: Studies on plastic deformation of a sphere colliding on a round timber beam. The parameters of material are shell thickness, compressive strength, bending capacity, and shear strength. Image credits: Rahul Girish and Antonio Barney.

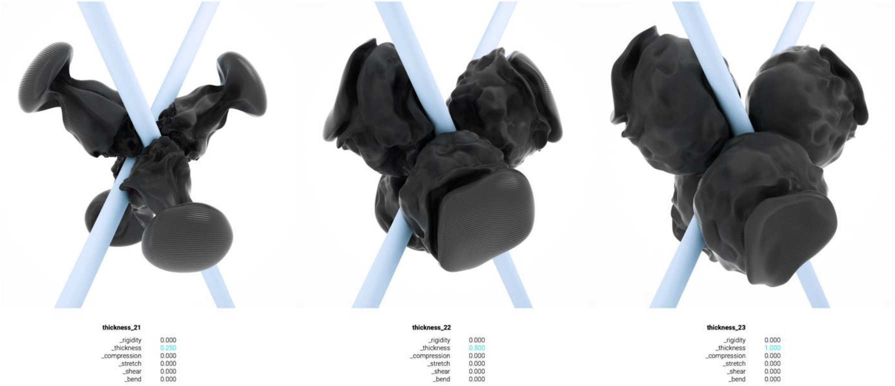

Figure 10: Deformation of four primitives colliding on the meeting point of three timber beams. Their shape is informed not only by the linear elements but by the other members, forming a locking mechanism. Image credits: Rahul Girish and Antonio Barney.

Figure 11: Fabricated models of studies with primitive geometries outside the bundling (**a**),(**b**) and in between the members (**c**). Photo credits: Julius Hatt.

The second case, contrary to the first, consists of one sphere situated in between the elements. As the latter move closer together, the sphere deforms and encapsulates them, providing both the interface between the elements and a locking mechanism (**fig. 12**). Finally, a multi-material 3D print creates a differentiation in materiality by printing a solid core with a soft snapping connection (**fig. 13**). The connections are 3D printed with a thermoplastic material and a series of tables was assembled to validate the method (**fig. 14**).

Figure 12: Deformation of a sphere as the three elements are approaching the connection point. Image credits: Rahul Girish and Antonio Barney.

Figure 13: Strategies to adjust the flexibility of the connections by: (a) creating two parts out of a stiff core and soft grips, (b) interlocking detail of the two part connection, (c) differentiated perforation on the surface (d) adjusting the infill structure and (e) creating a hollow core. Photo credits: Julius Hatt.

Figure 14: Series of fabricated tables with the different connections studied. Image credits: Rahul Girish and Antonio Barney.

3.3 Mesh grammar

Researching more controlled topologies of connections, an investigation of a mesh grammar allows the formation of geometrically complex nodes in consecutive iterations. Three case studies show how to achieve an ornamented structural node from a low-poly mesh.

Custom mesh subdivision

The first exploration aims to create a stiff but porous connection. Material is not discarded through a topology optimisation process, but by creating rule-based porosities and stiffening ribs through a generative process. The topology of the node is designed initially in a simple manner: trigonometric rules define the minimum bounding volume of the node according to the collision of profiles that come together to the node point ***N***. The linear elements are scaled back to a new set of endpoints p_i (**fig. 15a**) for which a convex hull is defined. The edges of the convex hull are used to further define the main ribs of the node by creating the faces between ***N*** and each set of three adjacent edges that form a closed boundary (**fig. 15b**). The faces are offsetted according to the profile width of the linear elements (**fig. 15c**), they are split (**fig. 15d**) and perforated (**fig. 15e**) according to subdivision rules to provide microstructure and lightness.

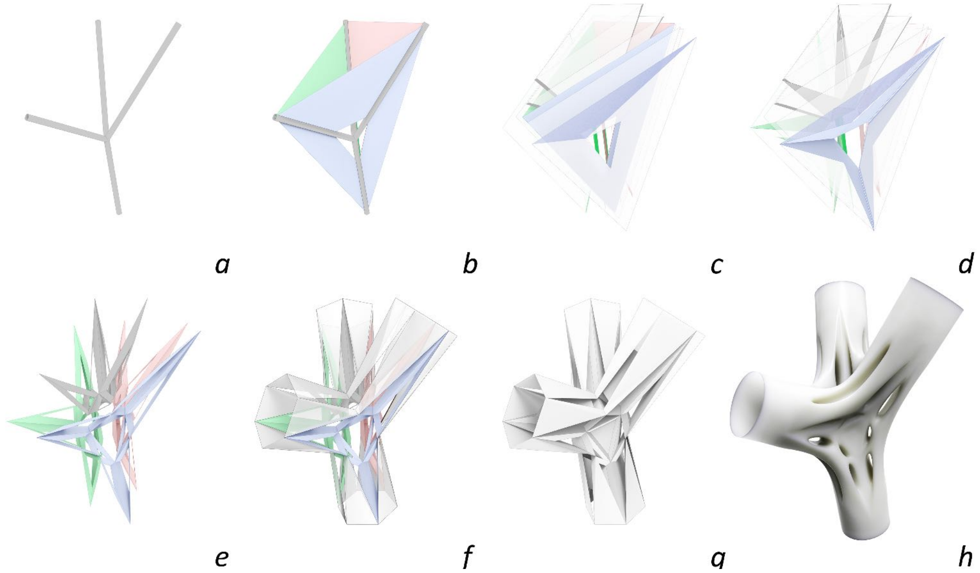

Figure 15: Process of creating a custom mesh based on the skeleton lines of a connection and subdivision steps to form the perforated ribs and finally smoother the geometry.

In a second step, quad faces are generated to connect the ribs and form a hexagonal profile at every p_i that will later describe the circular section of the linear elements (**fig. 15f**). A last step generates the necessary faces to form a closed object (**fig. 15g**).

The final step is a smoothing subdivision to form the organic final shape, for which we used the catmull-clark subdivision rule (**fig. 15h**). This specific sequence was used to ensure that perforation and reduction of material are in plane with the axial force flow, and thus the rib orientation is able to fully support the connection. The resulting object showcases a unique topology where structural qualities, such as stiffening ribs, are embedded in the generative process (**fig. 16**). This node typology allows the formation of a more spatial and stiffer connection.

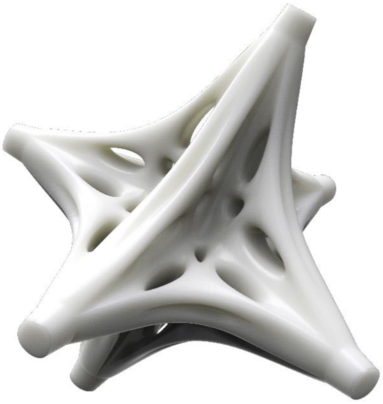

Figure 16: Stiff connection with complex topology created with MOLA (Dillenburger et al. 2019) open-source pure python mesh library and subdivided with customized rules".

Subdivision and ornament

Further explorations on the same methodology showcase the potential of such a mesh grammar to create not only unique forms but develop them into self-contained ornaments. We want to highlight the opportunities within this process to form an amalgam of a structural part and an ornament.

Since industrialization mechanical and structural components are puristic, thus fitting the mass production line. However, with AM visual and ornamental qualities that were lost with industrialization can be again embedded in those elements. Freed from its manufacturing constraints a connection can express a strong visual language, designed for a specific setting. Following the process of creating a "base mesh" of the node in **fig. 16**, the next steps of mesh subdivision create the *ornament* (**fig. 17**).

Figure 17: Different rules of mesh subdivision, illustrated in top view. Image credits: Noor Khader, Aya Shaker.

Analyzing attributes for each mesh face, like the curvature, distance from ***N***, perimeter and area we assign values to each mesh face that indicate the magnitude of further subdivision steps (**fig. 18**) which develop a textured surface (**fig. 19**). Such a type of connection was fabricated with FDM 3D printing for an ornamented split-level table design (**fig. 20**). The table, designed through a mesh relaxation process, featured more than 20 bespoke ornamented connections.

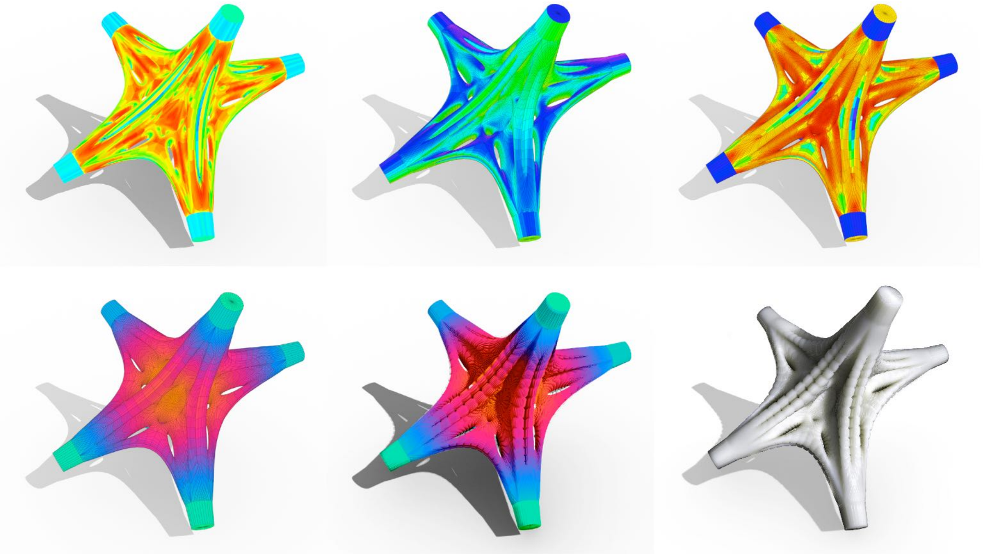

Figure 18: Stiff connection with complex topology. Created using a pure python mesh structure and subdivided with customized rules.

Figure 19: Close preview of an ornamented joint with two levels of subdivision to articulate the surface.

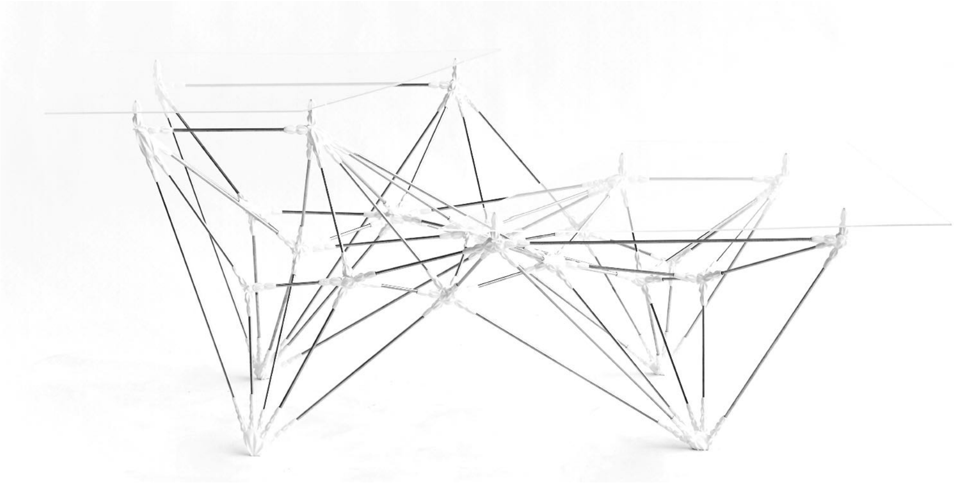

Figure 20: Table made from 25 bespoke ornamented nodes and off-shelf aluminum round profiles. Photo credits: Julius Hatt.

Structurally informed timber connections

A similar process was used to create load bearing axial connections for a $6x2.6x3$ metres large timber canopy. The highlight of the structure is a 4-meter long cantilever held by FDM 3D printed connections. In this case study the node was optimized for hierarchy of members, profile and tension-compression forces (**fig. 21**).

Figure 21: FDM 3D printed joint, made from PLA thermoplastic material. The node connects three members of 1st, two of 2nd, and four of 3rd hierarchy.

Standing in between the last two examples this mesh grammar creates reinforcement branching and a subtle ornament in a streamlined design process. The process begins with a network of lines that carries information defining which members are of primary structural importance, secondary members, but also which of those are stressed under pure tension or compression. A collision dependent scaling of the initial line-network, based on hierarchy and the size of the members, returns the metric data of each element and the reach of each connection (**fig. 22**).

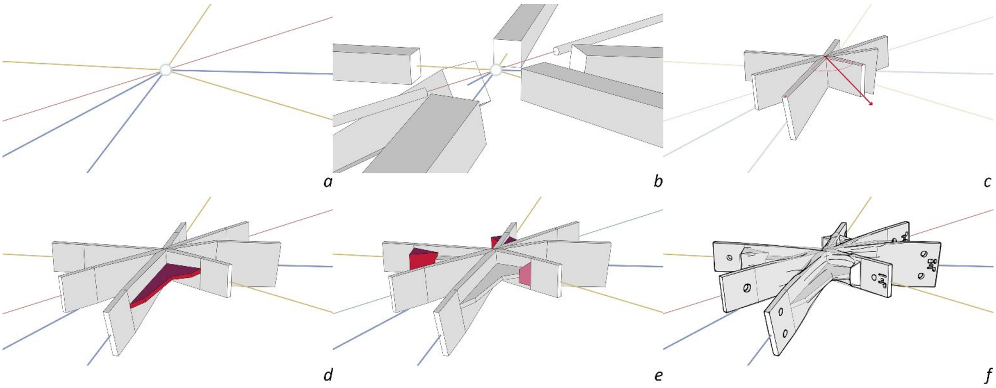

Figure 22: Node generation steps. (**a**) line network, hierarchical sorting. (**b**) collision dependent scaling of members. (**c**), bivector calculation and base mesh generation. (**d**), profile dependant connection plate and hierarchical reinforcement displacement. (**e**), introduction of compression plates or cable connections. (**f**), labeling and connection holes, geometrical articulation. Image credits: Alexander Enz.

According to those, a simple UV mesh topology is created bridging the nodal point and the linear member. Wide angles between linear members are filtered and a connecting rib is created between those to reinforce the connection. The hierarchical order leads to adaptable thickening of reinforcement details as well as the addition of compression plates or a cable binder for members under tension.

Furthermore, a force-flow informed surface detailing is added using mesh subdivision. The surface articulation is created only at the core of the node while both connection and compression plates stay untouched for accurate dimensioning. As a final step connection holes are introduced, as well as labelling with custom symbols signed with intrusion of selected mesh faces.

The benefit of this algorithmic approach is that it generates all fabrication data in a single process, including all necessary matrices for a smooth preparation of linear members and assembly data.

The canopy created as a demonstrator for this connection consisted of 157 individual timber beams and 47 unique connections (**fig. 23**). It demonstrates not only the diversity of the method presented but also exhibits how a weak material printed out of thin plastic can be used for construction if the connections are designed and articulated intelligently.

Figure 23: The canopy in numbers: 47 bespoke 3D printed nodes, 157 members, 600 screws. Max. height 3 m , width 2.7 m, and cantilever 4 m. Photo credits: Alexander Enz.

3.4 Dissolved Connection

The last and most abstract joint definition was developed in a collaborative project at the MAS dfab at ETH Zurich (Meibodi et al. 2019). A spatial structure driven from the ease of assembly is transformed with a custom algorithm by dynamically pushing the linear elements away from each other until they don't collide. As a result, the elements no longer meet at a single point $\boldsymbol{O}$, while they are distributed non-uniformly in space (**fig. 24**).

Harvesting the advantages of large scale 3D printing we define an algorithmic process where each connection is dissolved into a micro-network of elements within the overall structure. First we identify all the elements that are "close" given a certain tolerance t to the node center $\boldsymbol{O}$ prior to the shift of members. As the proximity members are identified, a new point n_i for each member is defined along its axis. In a next step, a network is generated between this set of points $N = \{(x_i, y_i, z_i) \mid (x, y, z) \in \mathbb{R}\}$, following stiffening and stability criteria. Each point n_i has at least three neighbours in the network, but no more than five. Around the point itself a cylindrical geometry is designed to host the linear member. The edges of the network e_i as well as the nodes n_i are used to generate the distance field values from which a triangulated mesh is generated using the Marching Cubes algorithm. The result is an interwoven connection around the area point $\boldsymbol{O}$.

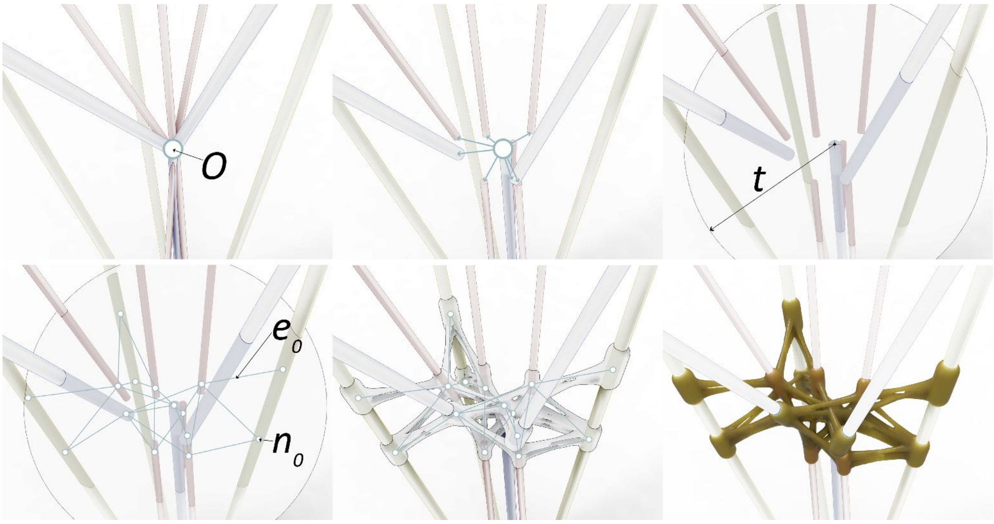

Figure 24: The generative process of this spatial connection: members are spread out to facilitate assembly and new points along their axes are created. A network of lines is developed between them according to fabrication and structural related rules. A mesh geometry is formed with the marching cubes algorithm.

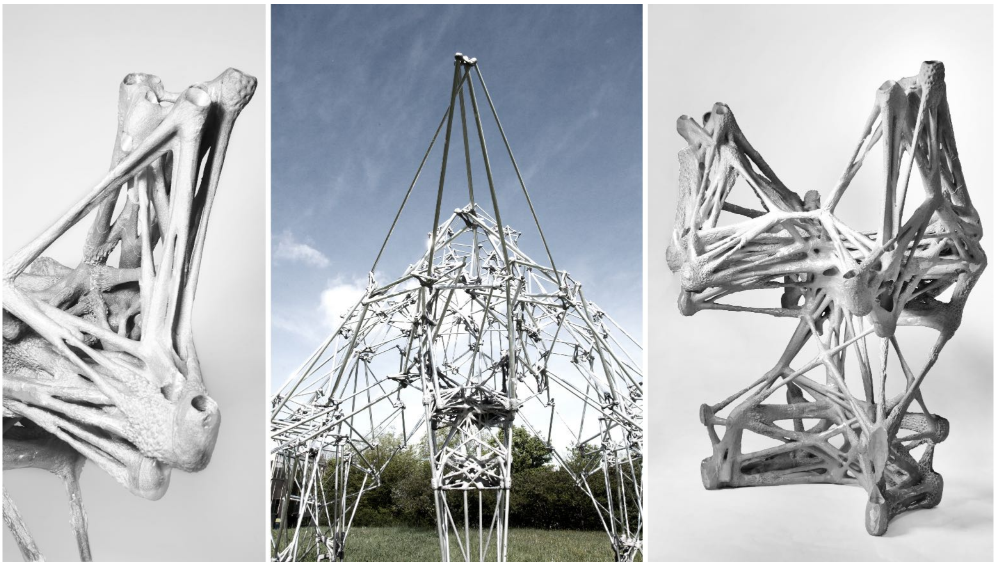

Figure 25: One of the connections produced for the Liquid Metal Pavilion, showcasing how versatile this process is. This connection was situated at the capital of the column where the space frame roof connected. Photo credits: Ma Xjie.

The complexity of such an emergent object attests to its sculptural and visual quality (**fig. 25**). Without digital fabrication such an object would demand extreme resources to be produced. However, its mold is now automated through a computational process and metal is cast in it. The visual language of a shifted space frame with these purpose-made connections is unique and born within the computational process that embeds assembly and fabrication of non standard structures.

4 Results and Discussion

The design strategies shown in this paper can be understood as a canvas for design explorations for future prefabricated spatial structures. However, this list is not and can never be complete as new approaches will be investigated, old ones are reinterpreted and advancements in computational design will continue to develop at a fast pace. The different node typologies presented are designed with a specific AM method and material in mind, as all of them are too complex to be manufactured using traditional fabrication techniques.

It is not within the scope of this paper to discuss the variety of fabrication constraints of AM processes, as those are as individual as the 3DP printing techniques themselves. Nevertheless, it is important to highlight that certain fabrication constraints can be embedded early in the computational workflow of such diverse and malleable processes. This is to be understood as the principal difference between the state of the art of AM connections and the new approaches described: the difference between a CAD ready solution and the richness of a customized, even paradoxical, computational process. Fabrication constraints related to the presented connections were embedded in the computational process, but are not discussed in the methods. However, we found the most critical to be:

- wall thickness
- ratio and diameter of ribs or elongated members
- stiffening infill patterns in case the geometry is hollow
- transition and angles between members in the case of FDM prints

We assume that not all elements of this new universe will prove to be suitable for construction sites. Material properties need to improve for non-metal 3D printing, while printing costs have to drop. The last years show exactly this trend (Wohlers et al. 2018), and so the authors are convinced that 3DP will have a disruptive influence on architecture in the coming decade, especially on lightweight bespoke space frame structures.

The geometrical freedom to create unique connections will ultimately lead to a more versatile approach for space frame design. Nonetheless, being able to create “nearly anything”, computationally and physically, raises a question on how we must design for these new fabrication methods. Spatial structures do not need to be assembled by a singular system anymore, but by differentiated adapted systems:

each connection generated for its specific use within the structure, respecting assembly tolerances, materiality of the members connected to it, or assembly sequence.

Furthermore, we believe that the coming of age of augmented and virtual reality (AR/VR) will have a big impact on bringing customized elements and systems to the construction site. Assembly of architectures with bespoke elements can be performed by laypeople using assistive equipment of AR/VR.

Finally, all methods were tailored to a small project that gave content to the design and drove decisions on geometrical articulation. Moreover, every method shows advantages on different aspects:

- VM offers an unmatched advantage on preparation of files for 3D printing, as all meshes calculated are watertight and do not display common problems like non-manifold edges, noise shells or holes.
- The integration of physical simulations provides a tool to create unexpected forms but also a new approach where all elements in a structure organically interlock with each other by programming material creasing and plastic behavior. A contradictory approach to highly engineered connection systems that can lead to more organic arrangements of structural elements.
- Mesh grammars offer a unique opportunity to create a rule-based process informed by structural performance and fabrication limitations, while maintaining a compositional order that cannot be achieved with topology optimization software packages.
- Finally, in disjoined structures new rule-based approaches can provide new and filigree connections driven by ease of assembly.

5 Conclusion

The design domain of spatial structures and their formal expression was bounded by industrial design for almost a century. Today, Additive Manufacturing provides the right interface to expand this design domain achieving a grand diversity of constellations and qualities of spatial structures: bespoke, ornamented, deformable, fractal-like to name a few. The presented catalog of generative methods contributes to the research of geometrical processes and operations for purpose made connections and sets an example for architects and designers to refine polyhedral space through 3D printing. In the broad field of computational design, there is no single/right solution, generative methods hold the potential for creating new types of structures by inventing new types of connections.

We find ourselves in an interesting crossroad; computational design has matured and is embedded early in design education, while on the other hand AM technologies have emerged from prototyping to the manufacturing world. Therefore, we have acquired the interface to fabricate complex and unprecedented architectures. Research on topology and geometry of space frame construction can be revived from the computational and digital fabrication lens.

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