Abstract. In architecture, the use of Additive Manufacturing (AM) technologies has been typically undermined by the long production time, elevated cost to manufacture parts and the low mechanical properties of 3D printed components. As AM becomes faster cheaper and stronger, opportunities for architectures that make creative use of AM to produce functional architectural pieces are emerging. In this paper, we propose and discuss the application of metal AM in complex space frames and the theoretical and practical implications. A functional lightweight metal table by the authors support our hypothesis that AM has a clear application in architecture and furniture design, and that space frames constitutes a promising structural typology. Specifically, we investigate how AM using metal as a material can be used in the application of fabrication of complex space frame structure components and connection details. The paper presents background research and our contribution to the digital design tools, the manufacturing and assembly processes, and the analysis of the performances of a parametrically designed and digitally fabricated large meeting table. Insights from this paper are deployed in an architectural scale project, AIRMesh, a metal 3D-printed pavilion set in the greenery of Gardens by the Bay, Singapore.

Keywords. Metal Additive Manufacturing; Space Frame; 3D Printing; Furniture Design.
the applications are complex, small parts, that can resolve high complexity with minimal material consumption.

In previous research, polymer printing was investigated in a light installation, (ultra) Light Network (Raspall & Banon, 2018) as well as a bamboo structure (Amtsberg & Raspall, 2018). Using insights gained from these projects while building upon learned knowledge from another metal 3D-printing project, vMesh (Raspall & Banon, 2016), our research aims to investigate metal 3D-printing and its applicability in the fabrication of complex space frame structures in the form of a functional lightweight metal table.

Figure 1. (ultra) Light Network -left-, Bamboo Structure -middle-, vMesh -right-.

2. Background

Applications of AM in the construction of architecture are limited to a handful of cases with diverging goals. Most approaches aim to enlarge the build volume while reducing operation costs. An initial example is concrete contour crafting, which utilizes a large-scale gantry system to control the extrusion and contouring of concrete (Khoshnevis, 2004). A second approach involves the use of AM to produce small, complex-geometry architectural components. The application in space frames or similar types becomes apparent, since this type of structures combine larger standard components -bars- and small specialized connectors -nodes-, which concentrates the complexity in a small volume. The 3D-printed steel node by Arup (Ren & Galjaard, 2015) showcases the possibility of the application of this approach.

This line of research remains a seldom explored area with potential for architectural innovation. Materiality, connection detail, time, cost and structural performance are just some of the many parameters investigated with specific regards to the space frame structure designed in this paper.

3. Methods

Our research investigates the feasibility of AM to produce functional architecture and, more specifically, centered in space frame assemblies. It advances custom digital design tools, understanding on manufacturability of complex geometry part and assembly of complex structures. Our previous project vMesh, completed in 2016 sets the basic instruments that are needed to design, manufacture and assemble a complex 3D structure. This project was a temporary structure to hold
an exhibition in the SUTD main hall (Raspall & Banon, 2016) and the predecessor to the main matter of this paper. vMesh was a pavilion not subjected to large static or dynamic loads. The research project at hand, AIRTTable, focuses on refining the joint details to create stronger connections to withstand larger and more dynamic loading conditions in the form of functional furniture. Its main innovation lies in being able to create a rigid complex geometrical structure using very thin elements. The main objective was to test how AM can enable the design and fabrication of complex parts and intricate connection details which are then used to assemble structural systems of complex geometry through mechanical connections.

The methodology covers all stages in the design and manufacturing process, using a single demonstrative project to advance associative modeling, connection detailing design, part manufacturing, assembly and load testing.

3.1. ASSOCIATIVE MODELING

The AIRTable is a chamfered equilateral triangle of 3m along its sides, supported by a system 306 round, thin hollow stainless-steel bars of 6mm diameter connected by 84 metal 3D-printed nodes, forming an intricate system of tetrahedrons. The table is topped with a white translucent Corian table top.

A robust parametric script was developed to accurately manage the geometric complexity of the nodes. The modeling and programming platform used was McNeel’s Rhinoceros and Grasshopper. The script defines the rough geometry of each node which was then refined using T-Splines, a plug-in for Rhinoceros. Structural analysis of the structural frame was conducted in the same modeling
and programming platform, which validated the structural stability of the project before moving into the next stages of design development.

The first step involved the creation of the basic topology of the node, where the length of the branch in each node is determined by the angle with its closest neighbor branch. Branches that are very close together will be longer, to avoid self-intersections. The script then generates the rough solid geometry of the nodes. These solids are then smoothened out and further refined using T-Splines to create a smooth and seamless transition between the nodes and the bars. The solid is then offset inwards to create a shell of approximately 2-3mm to reduce material usage while still giving structural strength to the node.

At this point it is important to note that in the AM technology used for this project, to create a shell object, it is necessary to create small holes in the object to allow fabricators to remove the support material within the object after it has printed to reduce material wastage and cost. Hence, the next step was to create the holes necessary for this in the nodes.

![Figure 3. Node Sections.](image)

3.2. CONNECTION DETAIL

For a strong and rigid connection, a mechanical connection is ideal. After various experimentations, the use of threaded joints was deemed most suitable for its application. It allowed for the least removal of material in creating the connection which is especially crucial for such a thin profile as was used in this project. Each bar was threaded with a clockwise and an anti-clockwise thread on each end to allow the joining of the two adjacent nodes to the bar through the rotation of the bar. As the bar rotates, the adjacent nodes get pulled towards each other. With this detail, it was imperative to ensure that the length of the thread left on both nodes adjacent to the bar were equal. This is required as the bar will rotate through the threads on both ends at the same rate. Having uneven spacing on either side of the bar would result in imprecision.
The ends of the node which had clockwise threads were made to be 10mm long while the ends with anti-clockwise threads were 5mm long. Having one end being longer than the other aided in the assembly process in a few ways. Firstly, it allowed the rough placement of the bars onto the nodes, having them in position ready for the proper fixing. This allows for one person to assemble the table legs without aid needed. Secondly, it allowed for precise assembly of the table legs. The assembler would be able to measure the length of threads on both nodes adjacent to the bar and adjust accordingly without having the bar fall off the nodes, making the assembly process easier and more precise. At the base of the connection detail on the nodes, a neck was designed to better distribute the load through its section to reduce the risk of the connection breaking off.

3.3. FABRICATION

Metal was an obvious choice of material to be used in the elements of the table legs to give strength and rigidity to them. The 84 nodes were 3D-printed with 420 Stainless Steel using binder jetting technology followed by curing, sintering, and bronze infiltration. The nodes were modeled and printed without threads. The printing process did not present any major problems, but the lead time was around one month. The 306 round, thin and hollow stainless-steel bars of 6mm diameter were standard sections used in the industry cut to length as specified based on the 3D model. Once the nodes and bars have been fabricated, they were then threaded with clockwise and anti-clockwise threads on their respective ends.

The table top is made of white Corian which was chamfered and the bottom hollowed out using a 6-axis CNC Router. It was then filled with a lighter material, plywood, to reduce the weight of the table. The weight of the table top was estimated to be approximately 90kg. Its white translucent appearance confers the desired illusion of lightness despite its stiffness, which aided in the stability of the table.
3.4. ASSEMBLY

After the fabrication process, upon receiving the nodes and the bars, the first step was to label them to expedite the assembly process. The strategy for the assembly of the table legs was to grow the structure. As the table leg was symmetrical in three axes branching out from the center, the core of the table leg was first assembled then extended outwards. The extension from the core of the table leg was done with the addition of one node at a time, giving priority to the next node with the least number of connections and the connections all pointing in the same general direction. Doing so allows the assembler to better rationalize and react empirically to the nuanced changes in the structure during assembly in spite of the complex geometry of the structure.

Before each bar is connected, the length of threads on each end of the nodes adjacent to the bar being attached were measured to millimeter precision and made equal. After a few threads were caught by the bar, the threads were measured again to millimeter precision to double check before fully connecting the bar to the adjacent nodes. The table legs took a single person one month to assemble.
After the table leg was assembled, it was then leveled. Spacers were digitally modeled and 3D-printed in PLA (Polylactic Acid) to level the table. Both the spacers and table leg were then spray painted in matte black before being mechanically fixed to the Corian table top using machine screws. Due to the size and weight of the tabletop, the table leg was assembled and fixed to the Corian tabletop upside-down and the whole table was then flipped after the assembly is completed.

The results demonstrate that AM can be successfully used to produce complex and detailed elements in architecture, and open new paths for designers to deal with complex geometries where lightness, continuity and sleekness play an important role. The resulting hyper-redundant structure is not only structurally functional, but also reinforces a narrative of lightness, both conceptually and literally. The complexity of the project was successfully managed through an associative model that automatically validates the structural performance, produces each node
The fabrication process was straightforward, as the associative model produced the print files and cut length sheets automatically, although additional post 3D-printing machining was required to create the precise threads needed for the connection detail. The precision of nodes and bars and well-designed node-bar connection made for a very sturdy structure. The assembly process was rather smooth for a structure of such complexity. However, we did experience some difficulty in rotating the bars, which required the use of an unconventional method of using the friction of rubber gloves to rotate the bars into place; which will benefit from better detail engineering. We also experienced some challenge in predicting the behavior and reaction of the complex geometric structure during assembly which required us to empirically react to its behavior at every point of the assembly.

3.5. LOAD TESTING

A load test was conducted on the table. Loads were distributed evenly over the surface of the table. Weights were then added in increments of 9kg and the deflection of the table measured between each increment. Deflection of the table was determined by taking the difference between the height measurement of the underside of the table to the floor before and after each increment of weight added. Measurements were taken at 9 different positions under the table. The test was terminated when a deflection of 9mm was measured. The deflection did not increase despite leaving the load on the table overnight.
4. Results and Reflection

The behavior of the holistic structure was extremely sturdy and stable due to its tetrahedral composition and redundancy. A load test was conducted on the table which showed that the table legs, upon application of 2kN of static load uniformly distributed over the top of table legs, had an average deflection of 6.4mm, minimum deflection of 5mm, and maximum deflection of 9mm. No visible signs of buckling were observed in the individual elements. The table legs weigh an estimated of 18kg. At a three-meter span with no fixed ends, the table leg is able to hold 2kN with an average deflection of 6.4mm. Based on the high structural performance of the structure and its material behavior, the system opens new directions to fabricate stable and complex functional geometries that can span large distances with high material efficiency. Using AM, complex three-dimensional structures can be designed and manufactured to highest precision, making the assembly process simple.

5. Conclusion

This project validates that AM technologies has a promising future in architecture beyond model making. The proposed space frame system takes advantage of the geometric freedom of AM and translates it into architectural and structural efficiency and expression. As each part can be uniquely designed and produced, the formal possibilities are maximised. Moreover, the high resolution of AM enables the design and fabrication of intricate detailed connections in the space frame system, which is highly customizable to fit the various needs and requirements of projects. In our project, a common detail (threads) was used for the connections, but we envision other types of mechanical connections can be employed to resolve some of the issues faced in this project.

One such project to further this research into metal AM is AIRMesh, a metal
3D-printed space frame structure designed as a pavilion to be situated in Gardens by the Bay in Singapore. The project further improves upon the connection details from this project to enable an even easier method to connect the bars and nodes. The project also investigates the application of the space frame structure using metal 3D-printing on an architectural scale, allowing people to walk through the pavilion. Lastly, the project looks at the integration of multiple architectural systems such as cladding, structure, foundation, decking, as well as lighting with the space frame structure, to investigate how the different systems can come together in a seamless, aesthetic and functional way. In carrying out the AIRMesh project, we hope to further the research into this method of creating space frame systems, bringing it closer to a fully realised architectural project.

![Figure 11. AIRMesh Prototype.](image)

References