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FloaTree: a system for making artificial habitat structures informed by AI-generated visual abstractions of large old trees

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Abstract

Birds and many other living organisms rely on large old trees for their survival. However, these trees are rapidly disappearing from many landscapes. The regrowth of such trees takes hundreds of years, and in many disturbed landscapes, wildlife populations cannot persist without temporary human-made replacement structures. In 2022, Mirra et al. [1] conducted a study on the AI-based generation of 3D models, or visual abstractions, of large old trees. An AI agent analysed a dataset of these trees to identify features that appeal to animals and generated forms that approximated these features. The researchers also evaluated the usefulness of the AI-generated forms as artificial replacements for trees using morphological and cost criteria.

Building on this research, we developed our pavilion entry for the IASS 2024 design competition. Our focus was on creating (1) a design strategy to translate the AI-generated visual abstractions into buildable tensegrities, and (2) a fabrication method that facilitates the transport, assembly, and disassembly of these structures using repurposed and biodegradable materials. We named this prototype “FloaTree”. We have constructed prototype tests in Melbourne, Australia, and will build the full-scale pavilion during the annual IASS symposium in Zurich, Switzerland, in August 2024.

Keywords: AI visual abstraction, tensegrity, artificial tree-like habitat, design for disassembly, fabrication methods.

1. Introduction

This paper illustrates the design and fabrication of an artificial tree-like habitat structure that we shall build for the IASS 2024 symposium activities in Zurich, Switzerland.

Since many bird species and other living organisms live in large old trees and the number of such trees is diminishing, research on the design and construction of effective human-made replacements is a significant international priority [1, 2, 3, 4]. In 2022, Mirra et al. [1] developed an Artificial Intelligence (AI) agent trained to produce line sketches of large old trees to capture and reproduce their characteristic features in a simplified form. This AI agent produces visual abstractions of tree geometries used to train it, and such abstractions retain features that animals look for when choosing nests or perch locations.

Our pavilion entry for the IASS 2024 design competition expands this study by translating the published AI-generated abstractions into structural configurations using a tensegrity system. Additionally, we have developed a fabrication method utilising modular components made of biodegradable materials that are easy to transport, assemble, and disassemble at scale. We named our prototypical design “FloaTree”.

The paper is structured as follows:

- Section 2 illustrates how we designed a structural configuration based on X-shaped kite tensegrity modules to materialise the AI-generated visual abstractions of old trees published by Mirra et al. [1]. It describes our parametric workflow to transform a 3D polyline sketch into a tensegrity configuration and the procedure we used to calculate and optimise the structure.
- Section 3 details our fabrication method, which simplifies the transport, assembly, and disassembly of components, offering a scalable approach to building artificial tree-like habitats. This section includes drawings of the strut-and-cable design and photographs of our prototyping.
- Section 4 highlights the innovative aspects of our work, including the polyline-to-tensegrity design strategy and key elements of the fabrication process. It explains why the pavilion entry is a suitable prototypical structure that can produce versions for field testing and monitoring.

2. Pavilion design

We made several assumptions to define and test a prototypical structural system for an artificial habitat structure. We chose the tensegrity system because of its unique morphological features, which result from combining a continuous series of tension elements with non-touching axially compressed struts. [5]. This system minimises the mass of the structure and simplifies the shapes of structural components while preserving key features of trees, such as spatial complexity and large size [6, 7, 8]. Tensegrity structures can also emulate the functionality of long branches [2].

We observed that most tensegrity systems are built using linear struts and can replicate the simplicity of the AI-generated visual abstractions we used as our starting point. This geometric simplicity of the strut elements makes construction easier while preserving spatial complexity of the overall configuration – a characteristic that birds find appealing. Additionally, the tensegrity system used in our pavilion can grow by incorporating additional modules. This ability to transform an artificial habitat structure over time can be useful for repairing damaged elements [3] or responding to animal use.

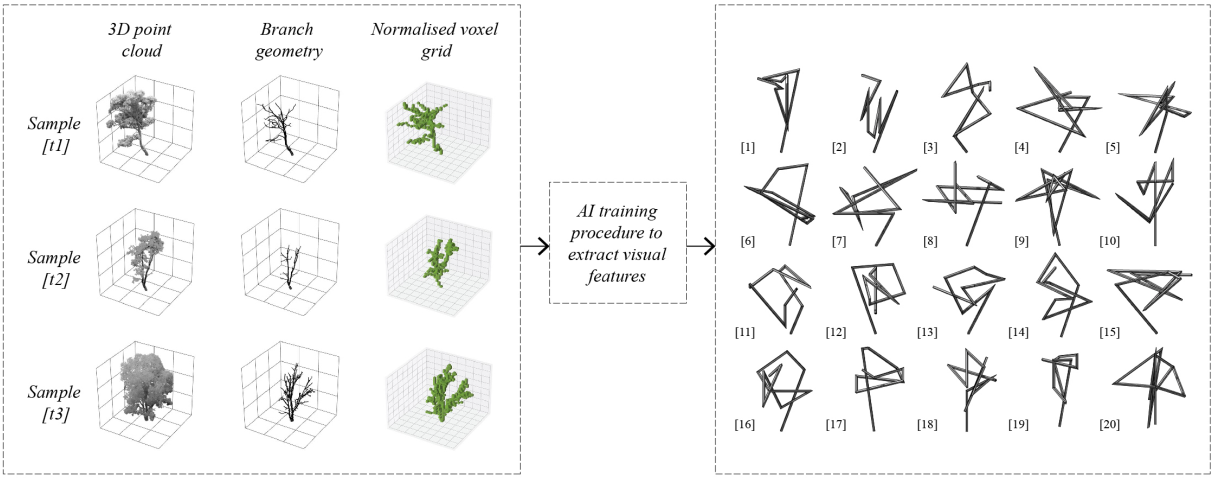
Although several researchers studied tensegrity systems as foldable structures [7, 9, 10], our design does not consider this possibility. It favours a low-tech strategy to discretise struts into smaller components for ease of transportation and disassembly needed to manufacture the pavilion in Melbourne and assemble it in Zurich. This strategy can also be useful for future installations in remote locations.

2.1. AI-generated visual abstractions

Figure 1 illustrates the workflow used by Mirra et al. [1] to generate visual abstractions of tree forms. This method involves preparing a 3D dataset of natural trees, training an AI agent to extract geometric features from such models and producing simplified representations that preserve the visual features of the original geometries. The AI model generates these visual abstractions by tracing line segments.

The training dataset comprised high-resolution 3D point clouds [2], from which the researchers first isolated the most relevant features – the points representing the branch geometry – and then clustered and converted them into line segments. This data format was translated into a 32x32 voxel representation to suit AI training requirements: the goal was to minimise the computational cost of geometry processing while preserving essential information about the structural complexity and mass distribution of the original trees (Figure 1, on the left). At each iteration of reinforcement learning, the AI agent observed samples from the dataset of voxelised tree forms and attempted to reproduce their geometries by drawing lines within a 3D canvas. The AI agent was constrained to use a maximum of 10 lines for each attempt, forcing it to generate simplified representations – or visual abstractions – of natural trees. Figure 1, on the right, shows 20 visual abstractions generated by the AI agent during the last training iterations.

The researchers analysed the performance of these 3D polylines using two metrics – the Perch Index and the Complexity Index – and discovered that their AI-generated forms were more similar to natural canopy structures than the reference human-designed trees used for the comparison. Moreover, many of the generated solutions contained diverse canopy shapes and branch distributions.



Construction of voxelised training dataset

Polyline representations of tree forms produced by AI agent

Figure 1: From 3D scans of natural trees to 20 AI-generated visual abstractions [1]
[Additional modelling: G. Mirra, M. Mack; Additional editing: M. Mack]

We used these AI-generated forms as conceptual sketches to design the *FloaTree* pavilion for the IASS 2024 design competition, hence translating these 3D polyline sketches into tensegrity configurations.

2.2. From visual abstractions to tensegrity configurations

We developed a parametric procedure that automatically generates a tensegrity configuration from a 3D polyline to transform the AI-generated sketches of tree forms into buildable artificial habitats. This parametrisation allowed us to rapidly produce multiple configurations and select versions that best complied with the constructability and other requirements of the IASS 2024 design competition.

Automated design strategies for tensegrity structures based on modules with three or more compressed elements are usually designed from a starting reference surface or polyhedric geometry [10, 11]. Instead of using a three-strut module, common for tensegrity towers, we implemented a simpler quasi-tensegrity structural system inspired by Kenneth Snelson's *X-piece* sculpture of 1948. Acknowledged as the first built tensegrity, this structure consists of two X-shaped compressed elements and 14 cables in tension. One X module is called a kite. Snelson later described this and other tensegrity systems in his 1965 US3169611A patent [12].

This tensegrity configuration facilitated the exploration of stacking modules that deviate from the vertical direction of growth. Joining simple kite modules at different angles preserves the legibility of the overall structural system as a sequence of vertical and horizontal planes – the tree trunk and branches – defined by the vertices of the module struts.

This strategy also avoided using too many structural elements, which is an important consideration when designing an artificial replacement habitat with the ambition to build it at scale. Like other tensegrity systems described by Snelson [13], this configuration can be expanded indefinitely by stacking one kite module on the other. Our parametric definition can generate Snelson's kite configuration in any number of modules along any polyline.

We used Grasshopper for Rhinoceros 3D as the visual scripting interface to implement this parametric procedure. Figure 2 illustrates how we generated Snelson's kite tensegrity topology from an input polyline in four steps. For clarity, the polyline consists of two perpendicular segments, although the construction procedure does not have such a restriction. To be able to apply our parametric definition to any input polyline, we defined the template topology as an L-shaped structure made from four kite modules (a, b, c and d).

Step A consists of constructing pairs of planes to orient the kite modules. The initial polyline segments are extended by a fixed distance *c*, corresponding to half the height of the modules located at the corner (module b) and the end of the polyline (module d). This step also involves calculating the number of additional plane pairs that can be placed along each segment. The variable *h* determines the spacing between the planes, whereas depth *d* adjusts the relative positioning of consecutive plane pairs. For the 2-segment L-shaped polyline shown in Figure 2, this process results in constructing one additional plane pair per segment, corresponding to modules a and c.

Step B involves constructing the axes of the struts that define the kite modules. We rotate every second pair of planes by 90 degrees about their Z-axis to orient the kites correctly. For each module, we then construct the start and end points of the struts along the X-axis of the reference planes. We created the variable *w* to control the distance between these points and define the width of kite modules.

Step C generates a network of lines that represent cables. We construct three types of tension lines, following Snelson's kite design: (1) *edge* lines, defining the sides of each kite module; (2) *draw* lines, connecting two consecutive modules and pulling them towards each other; (3) *sling* lines, also connecting and suspending consecutive modules.

Step D adds two additional tension lines to stabilise the structure and anchor it to the ground. Variable *s* controls the distance between the anchoring points.

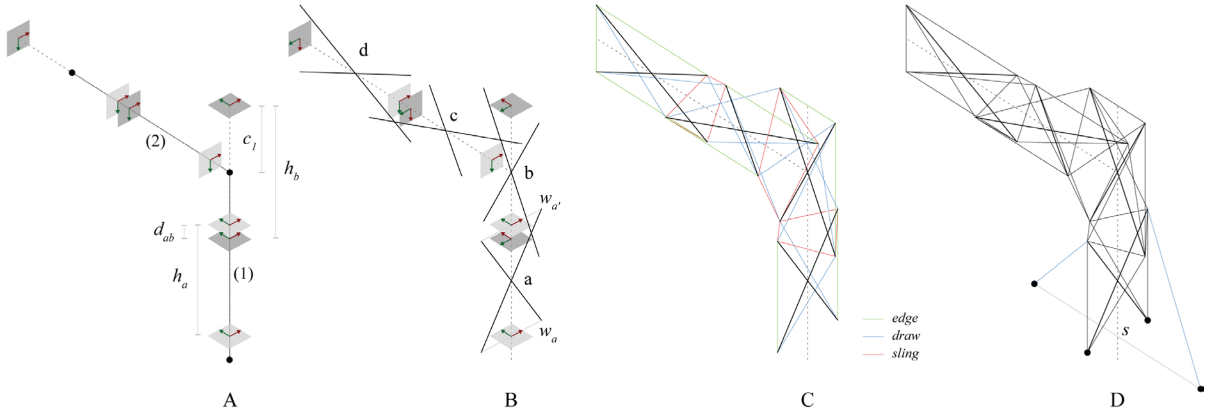


Figure 2. Parametric design steps to transform a polyline into an N-module kite tensegrity
[Modelling: G. Mirra, A. Pugnale, M. Mack; Editing: G. Mirra]

This procedure allowed us to rapidly create 3D models of tensegrity systems from the 20 AI-generated visual abstractions defined in Mirra et al. [1]. We selected visual abstractions prioritising single trunk and branch-like structures as main features. We also selected AI-generated polylines with long horizontal lines, as these configurations are more suitable for perching.

Using these criteria, we shortlisted solutions 6, 7, 8, 15 and 17, as shown in Figure 3. We selected solution 8 for the pavilion design because it consists of several near-horizontal kite elements.

While our pavilion design is a prototype of an artificial habitat structure, it should also be seen as a creative output. Other tensegrity topologies or structural systems could work equally well. However, the proposed design is a significant advancement over existing structures, such as utility poles. The approach to generating this prototypical design and the fabrication using packable components are the two key aspects of our submission for the IASS 2024 competition.

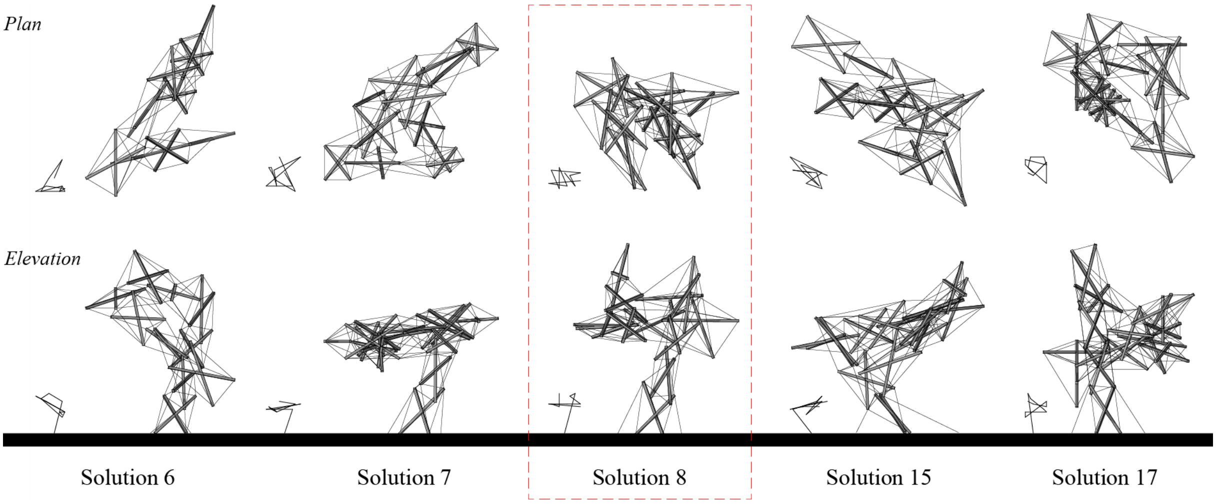


Figure 3: Tensegrity configurations developed from the AI visual abstractions 6, 7, 8, 15 and 17
[Modelling: G. Mirra; Editing: M. Mack]

2.3. Structural analysis and optimisation

The abovementioned procedure produces topologies for tensegrity systems that require verification through subsequent structural analysis and optimisation. Therefore, we implemented a workflow that determines the deviation of the proposed design from the structural behaviour of tensegrity and adjusts the configuration to conform to the structural logic.

We used the FEM solver Karamba 3D within Grasshopper/Rhinoceros 3D to calculate the structure, which consists of 12 kite modules (or 24 struts) held together by a network of 114 cables. We assigned four fixed support points at the base of the structure and only considered self-weight as gravity loads. We applied an initial strain of 0.02% (2mm/m) to simulate the cable pre-tensioning.

We modelled all struts as truss elements in generic wood with a 40mm x 40mm X-shaped cross-section and all cables in steel with a 3.2mm diameter. We performed a quasi-static structural analysis using the “AnalyzeThII” Karamba component to include geometrical non-linear effects.

The analysis of the geometric configuration revealed that although all the struts were compressed, 14.8% of the cables were not in tension, preventing the system from performing as a tensegrity. We also registered a maximum displacement of 54cm, which made the structure deviate considerably from the input polyline.

We ran an optimisation process to overcome these issues using the Multi-Objective Genetic Algorithm implemented in Octopus for Grasshopper. We aimed to minimise three objectives simultaneously: the percentage of compressed cables, the percentage of tensioned struts, and the maximum displacement of the whole structure.

This problem formulation allowed us to search for the best combination of local adjustments in the structural nodes. For each of the 46 nodes, we defined three variables that controlled the translation in the x, y and z directions by a maximum of 20cm. The total number of variables was 138. To help the optimisation process converge and integrate fabrication requirements, we also implemented a Dynamic Relaxation algorithm that relaxed the adjusted tensegrity configuration.

Figure 4 illustrates the structural analysis results after optimisation, which returned a design solution with all cables in tension and all struts in compression. The optimisation also minimised the maximum displacement, bringing it down to 3.64cm.

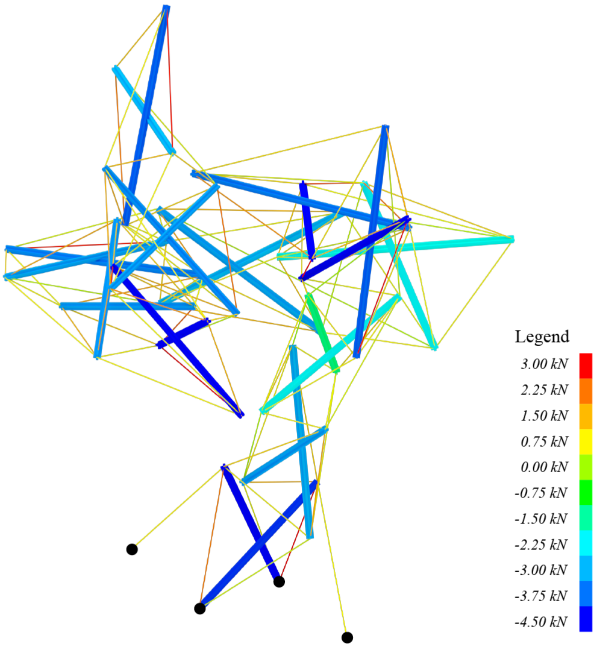


Figure 4: Structural analysis of the *FloaTree* pavilion
[Modelling: G. Mirra, A. Pugnale, M. Mack; Editing: M. Mack]

3. Fabrication and prototyping

The IASS 2024 design competition provides an opportunity to test the design, fabrication, and assembly of a geometrically complex tensegrity system that uses sustainable materials and accessible, low-tech tools. This paper focuses on the design of compression members made of subcomponents to optimise packability and transportation. This approach supports our strategic objective of allowing for future modification of component details to better suit bird use. In this section, we show prototype tests and a half-scale model we assembled to validate the structural analysis and test the workflow for prefabrication and assembly.

3.1 Materials

Our prototypes and simulations also compared conventional and biodegradable materials. For example, one prototype used 25mm rolls of jute webbing for tension members. This material is biodegradable and has a 1-2 year outdoor lifespan, providing a point for comparison with conventional steel cables.

For the full-scale prototype tests (Figure 5), we fabricated the struts from modular CNC-cut components of 6mm birch plywood. This modularity offered three advantages: (1) the subcomponents are adaptable, allowing for variable lengths of struts and multiple design variations; (2) the identical pieces are easy to assemble with standard joiners; and (3) the structure packs flat, minimising the volume for transportation. This packability is an essential feature of the project, which will be manufactured in Melbourne and installed in Zurich. Cross-sections of the struts add stiffness to the plywood and recall the X-shape of the kite modules, adding redundant structural strength to the design and visual continuity across scales.

3.2 Two-module prototype

We built a two-module tensegrity prototype, inspired by Snelson's 1948 kite design, to study material behaviour, connection details, and assembly sequences. This test allowed us to resolve the design of modular struts and tensioners. This practical build also allowed us to estimate the time needed for construction. Prototyping also fed back to the conceptual design stage.

Each strut subcomponent had a length of 200mm and an irregular profile designed to provide a visually appealing feature for birds (Figure 5a). We notched the components to produce an overlap in both the parallel and perpendicular planes, providing greater resistance to buckling (Figure 5b).

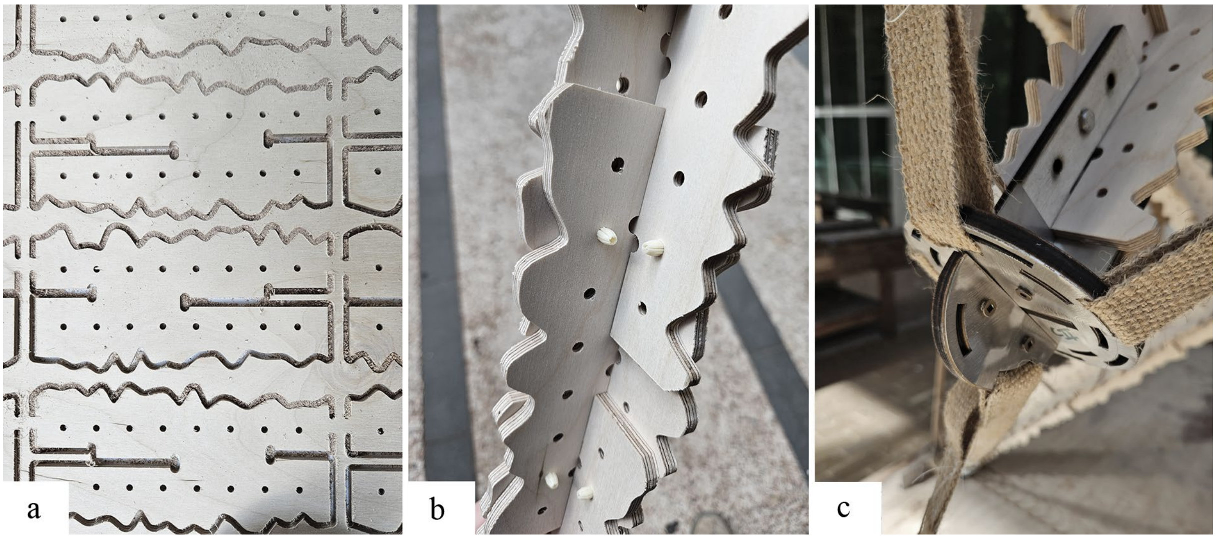


Figure 5: Strut design and construction: (a) Fabrication of subcomponents; (b) Assembly and overlapping of subcomponents; (c) Joint design [Photographs: J. Halls]

Geometrically flexible tensegrity systems allow for many degrees of freedom and require pre-tensioning [14]. We tested jute webbing and stainless-steel cam buckles as tensioners (Figure 5c). Key design considerations were vector alignment to ensure the tension vectors align with the load path, slippage and friction between the tensioner and the strut, and minimisation of rope wrapping around the strut.

We designed the end detail for all struts using a steel plate with slots designed to suit the flat section of the jute webbing and using the orientation of the struts to track the vector alignment. We made these end details from the same plywood as the struts and 1mm stainless steel face plates to enhance the rigidity of the tensioner connection points (Figure 6). With these end details, we assembled the prototype within a short time frame and with minimal deviation from the digital model (Figures 7a and 7b).

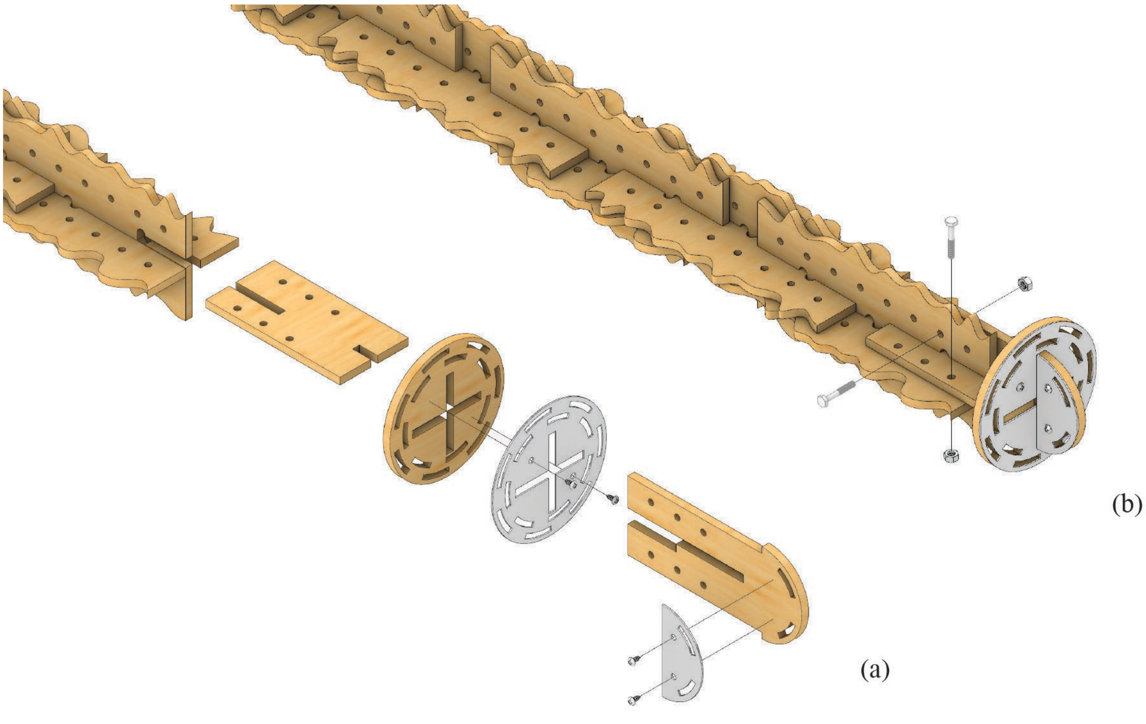


Figure 6: Isometric views of the strut end detail [Modelling: M. Mack, J. Halls; Editing: J. Halls]

3.3 Half-scale prototype

We then made a 1:2 scale model consisting of four modules out of the twelve originally designed, made of steel cables, turnbuckles, steel round tubes and 3D-printed strut ends (Figure 7c). This test was essential to optimise ground assembly through labelling and diagrams depicting the exact position and connection of each element. The scale model was positioned and stabilised in about 5 hours. The validation of the structural design and optimisation of component preparation that followed this assembly test has proved the feasibility of the final pavilion. It also demonstrated the reliability of the *FloaTree* as an integral, flexible and adaptable system, where struts and cables can be designed in different ways to adapt to wildlife response, costs, materials availability and longevity.

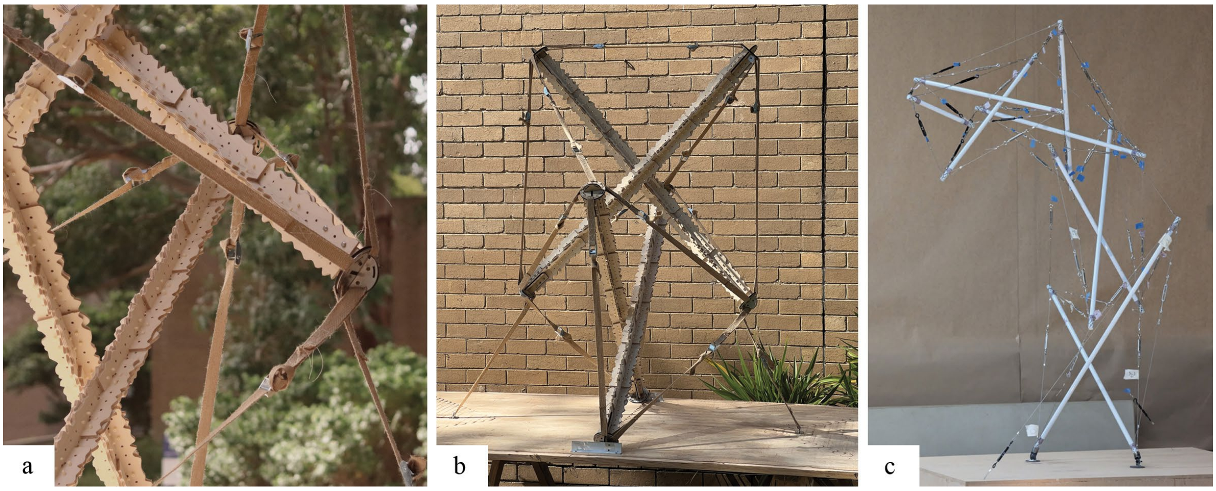


Figure 7: Prototype photos: (a) Detailed view of the full-scale prototype; (b) The full-scale prototype [Photographs: A. Pugnale]; (c) The 1:2 scale model with four kite modules [Photograph: M. Mack]

As remarked by René Motro [5], working with physical and digital models simultaneously when designing a tensegrity can help refine the final configuration and understand its complexity with all implied parameters. In our case, the refinement process of the prototype fabrication supported the decision-making explored in section 2 – Pavilion design – relative to form-finding problems, self-stress feasibility, compatibility between self-stress and component stiffness, identification and stabilisation of mechanism, sizing of components and sensitivity to imperfection. The full-scale prototype and scale model tests are promising in demonstrating that tensegrity systems are robust enough to incorporate non-skilled labour and a degree of imperfection that includes biodegradable and repurposed materials.

4. Conclusions

The *FloaTree* project presents a pioneering approach to designing and constructing lightweight artificial habitat structures for avian species, with broader implications for biodiversity conservation. The innovative use of AI-generated visual abstractions as a reference to generate structural systems that mimic the formal complexity and functionality of large old trees represents a significant advancement in ecological design and engineering. Our research successfully translated these AI-generated visual abstractions into tensegrity structures through a parametric design process prioritising modularity, adaptability, ease of assembly, transportability, and sustainable materials (Figure 8).

The implications of this project extend beyond its immediate application to arboreal habitats. *FloaTree* serves as a prototype for how AI and structural design can integrate to address critical ecological challenges, and the ability to translate simple polyline models into structural systems that emulate the evolved forms and functions of tree habitats highlights a novel opportunity for architectural and engineering practices to contribute more actively to environmental sustainability and multispecies cohabitation.

Our work shows the feasibility of constructing such structures at scale, benefitting from the adaptability of the tensegrity system and the efficient use of cost-effective biodegradable materials. This scalability is critical for the practical use of artificial habitat structures because large-scale interventions are necessary to mitigate habitat losses that threaten many species worldwide.

As we move towards the IASS 2024 symposium, where the *FloaTree* will be exhibited as part of the annual pavilion competition, we anticipate that this project will stimulate further research and innovation in the field of generative design for biodiversity. The principles and techniques developed through the *FloaTree* project can be useful in other initiatives, where the synergy between technological advancement and ecological awareness can lead to more sustainable practices. The collaborative effort of our interdisciplinary team underscores the importance of combining expertise in AI, architecture, biology, and engineering to tackle complex environmental issues. This project not only contributes to academic discourse but also sets a precedent for future ecological intervention strategies that are both innovative and practical.

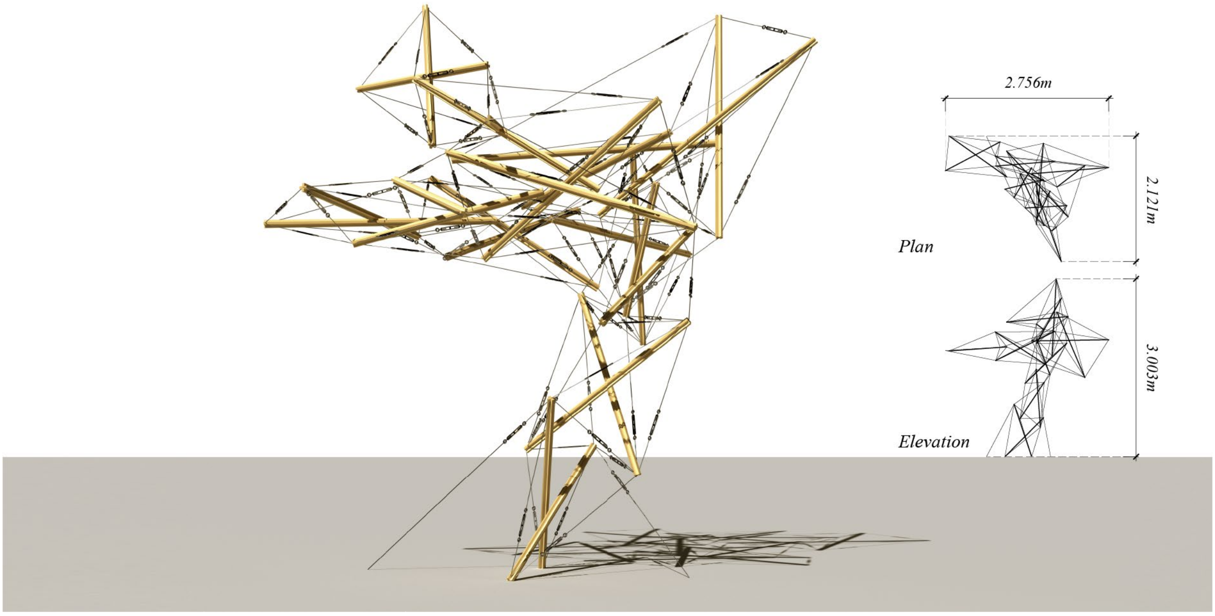


Figure 8: Visualisation of the *FloaTree* pavilion [Modelling and editing: M. Mack]

Acknowledgements

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Author contribution

All authors contributed to the study conception and design. Alberto Pugnale oversaw the development of the paper and the figures, contributing to the design and prototyping of the pavilion, as well as the writing of all sections as the first author. Gabriele Mirra and Michael Mack contributed to the pavilion design and the writing of section 2. Gabriele Mirra further contributed to this section by calculating and optimising the structure. Sofia Colabella, Jack Halls, Michael Mack, and Michael Minghi Park contributed to prototyping the structure and writing of section 3. Sofia Colabella also contributed to writing the conclusions. Stanislav Roudavski contributed to the writing of the introduction and the conclusions and provided feedback on the design and fabrication of the structure throughout the process. All authors contributed to the final editing and approved the published version of the manuscript.

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