

A Deployable Mast for Adaptable Textile Architecture

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Abstract

Proposed here is a concept for a deployable mast with angulated scissor units, for use in adaptable temporary architectural constructions. The adaptable structure serves as a tower or truss-like mast for a temporary tensile surface structure and doubles up as an active element during the erection process. The mast consists of scissor-like elements (SLE's) which are an effective way of introducing a single D.O.F.(degree of freedom) mechanism into a structure, providing it with the necessary kinematic properties for transforming from a compact state to a larger, expanded state. The scissor units used here are not comprised of straight bars, but rather consist of angulated elements, i.e. bars having a kink angle. Although primarily intended for radially deployable closed loop structures, it is shown in this paper that angulated elements can also prove valuable for use in a linear three-dimensional scissor geometry.

Keywords: Deployable structures, transformable structures, adaptable architecture, angulated scissor elements, kinetic architecture

1. Introduction

An innovative concept for a deployable hyperboloid mast with angulated scissor elements is presented. The scissor structure is a central vertical linear element, used to hold up several anticlastic membrane canopies at their high points. The question was raised whether it would be possible to design such a deployable mast for a temporary tensile structure and to use it as an active element during the erection process. In addition, the pantographic mast allows visitors to access several platforms to enjoy the views, under or above the different membrane elements. The proposed concept is a transformable version of a static concept, designed by The Nomad Concept, a Belgian architectural office for tensile surface structures. The original (undeployable) mast (or tower) consists of several modules which are assembled and dismantled on-site by stacking them vertically, for which a lifting device

is needed. After assembly the membrane would have to be attached to the top, after which the pre-tension in the membrane can be introduced. By making the mast deployable, all connections can be made on ground level, while the mechanism is in its undeployed, compact state, therefore eliminating the need for additional lifting equipment. After connections between the membrane elements and the mast have been made, the mechanism is deployed until the required height is reached and the membrane elements become tensioned. The mast could be deployed to such an extent that a sufficient amount of pre-tension is introduced in the membrane, ensuring the ability to withstand external loads. Since the mast is basically a mechanism, additional bracing is needed after full deployment to turn it into a load-bearing structure. To illustrate the concept, the simplest incarnation of the concept is used throughout the paper: a mast of triangular shape. But it must be noted that the concept is valid for any n-sided polygon. Extensive formulas for obtaining the geometry based on architectural design parameters have been derived by [De Temmerman].

2. Geometry

2.1. Dimensions

The deployable mast is horizontally divided in several modules, which are closed-loop configurations of identical hoberman's units or otherwise called angulated SLE's. Figure 1 shows an example of a mast with - in this case - triangular modules, of which three are stacked vertically. The mast is 8.5 m high and 2.7 m wide, while the tensile surfaces are identical and measure 10 m along their longest diagonal. The top of the second module, at which the membrane elements are attached, is located at 5.2 metres above ground level. The other high point of the membranes is held 4 m above ground by additional masts.

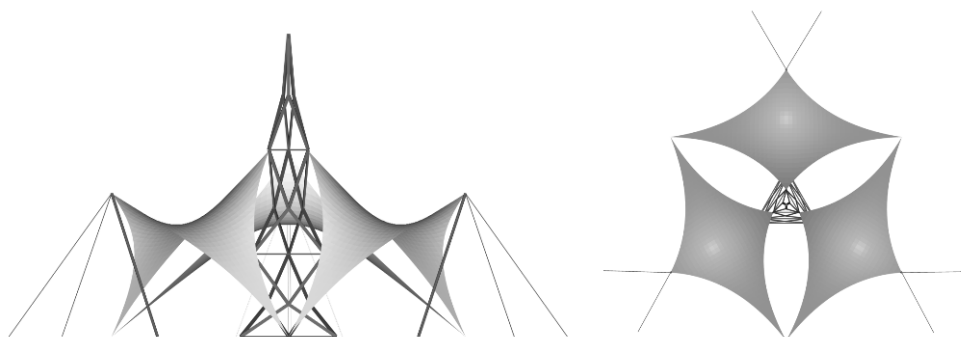


Figure 1: Side elevation and top view of the structure showing the three tensile surfaces arranged radially around the central mast

2.2. Angulated elements vs. polar elements

It could be argued that a mast with a broad base and a narrow top can equally be built with polar units with decreasing size as they are located nearer to the top. In Figure 2 two linkages – one with angulated elements, another with polar units - are shown, with identical height and width, but with varying number of units U and different bar lengths. Using the angulated elements offers an advantage: while the linkage with angulated elements is built from only 3 SLE's with 11 hinges and nodes, the equivalent polar mechanism needs 8 units with 26 connections to reach a similar deployed geometry. The effect that the angulated elements have on the modules is that, during deployment, the top of a module becomes narrower than its base. The radius of the top of a certain module becomes equal to the radius of the base of the next, higher located module. This means that the narrowing effect is enhanced and passed on through the mechanism, from module to module, from bottom to top. The dimensions of the individual bars of the scissor units are such, that the horizontal projection of b is equal to a , as shown in Figure 3. The most important parameters are the kink angle β of the angulated element and the deployment angle θ , as depicted in Figure 4. The relationship between a and b , as shown in Figure 3, leads to a hyperbolic shape for the mast. By satisfying alternative relationships between a and b , a simpler, prismoid shape for the mast can be obtained, with a simpler kinematic behaviour, as later will be explained. For a full and exhaustive description of all relevant design parameters and a comprehensive geometric design method, drawn up from the designer's point of view, the reader is referred to [De Temmerman].

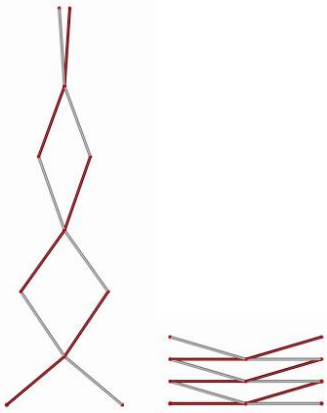
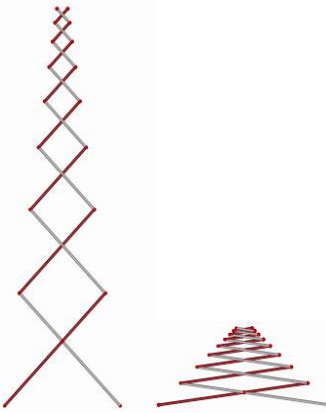
Linkage with angulated SLE's:	Equivalent linkage with polar SLE's:
	
Number of SLE's: $n=3$ Number of hinges and end nodes: 11	Number of SLE's: $n=8$ Number of hinges and end nodes: 26

Figure 2: Comparison between a linkage with angulated SLE's and its conventional polar equivalent

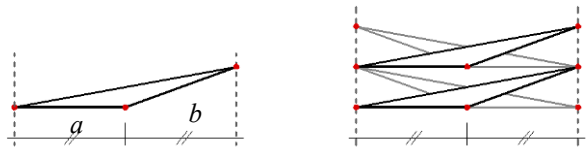


Figure 3: Imposed condition on the length of the semi-bars a and b ($a < b$), in order to make the linkage foldable along the vertical axis

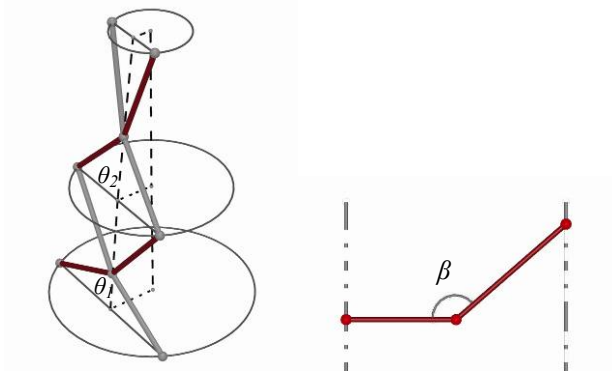


Figure 4: Most important parameters used for describing the geometry and the deployment

3. Transformation

3.1. Compacting for transport

The imaginary vertical axes connecting the end nodes of the bars can act as fold lines, used to further flatten the linkage. Therefore, the modules are ‘cut open’ along one fold line, after which the whole can be flatly folded for easier transport. Such a fold sequence is shown in Figure 5, which depicts the simplest possible structure: the one with a triangular base. This way of further compacting is presented as an option and could be ignored, on the condition that the dimensions in the undeployed state are kept reasonable.

Step 1 (Compacted for transport)	Step 2	Step 3	Step 4 (ready to deploy)

Figure 5: Initial unfolding of the compacted linkage (transport) to its polygonal form (ready to deploy)

3.2. Deployment

The deployment sequence of the tower is presented in Figure 6, showing a top view and a side elevation for each stage. Stage 5 is the most compacted state, while stage 10 illustrates the fully deployed state. The maximum deployment is reached when the upper end nodes of the top module meet in one point.

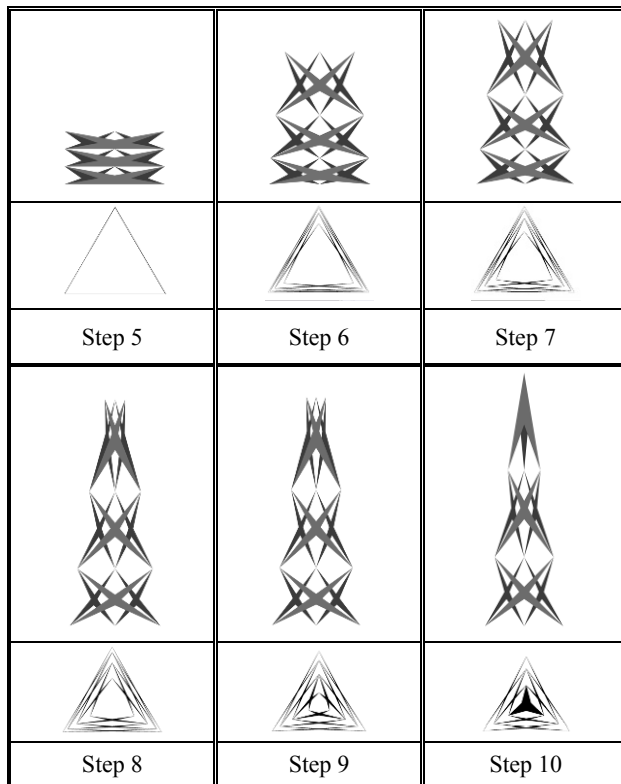


Figure 6: Six stages in the deployment of a triangular mast: elevation and top view

A short description is given of how the erection process could be executed, as shown in Figure 7:

- A: the tower is in its undeployed form. The membrane elements are attached to the nodes of the mechanism and fixed by their low points to the ground
- B: As the tower gradually deploys, the membranes are raised. When sufficient height is achieved, the additional masts are inserted and gradually put in their right location. Then, the cables fixing the secondary masts to the ground are brought under tension.

- C: Finally, the tower is slightly deployed further to add pre-tension in the membrane. Then, the tower is fixed to the ground by pinned supports and additional horizontal ties (cables or struts) can be inserted at the appropriate level.

After deployment horizontal ties are added to enhance structural stiffness. Several solutions are possible: cable ties could be used, which are already present before deployment and are shortened as the structure deploys and becomes narrower. Struts could be added afterwards to brace the structure. An active cable can run over appropriately chosen nodes along a path and can be shortened to aid in the deployment.

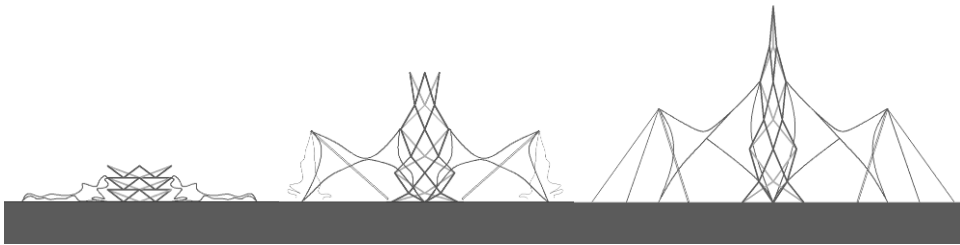


Figure 7: Deployment sequence (A, B and C) for the tower with the membrane elements attached

3.3. Influence of parameters

Minimal changes in the design values can have a profound effect on the overall geometry. The parameters with the strongest impact on the geometry are the kink angle β (as shown in Figure 4) and, logically, the number of stacked modules n in the linkage. Figure 8 shows the undeployed and fully deployed position for three different configurations with specific values for β of 135° , 150° and 165° . All configurations have the same edge length. As β increases, the overall height of the deployed configuration also increases, while the radius of the footprint decreases. The biggest impact however is noticeable in the undeployed configuration. By increasing β from 135° to 165° , the height in the stacked position is reduced to a third. So blunter kink angles lead to linkages which are more compact – easier transportable - in their undeployed state.

The top module in the linkage is the determining factor for the deployment range. Units with sharp kink angles tend to quickly reach their maximal deployment, therefore halting the deployment of the remaining modules. So if a substantial expansion in height is desired, it would be a better option to choose a blunt kink angle in combination with a higher number of modules: the blunt kink angle makes the undeployed configuration more compact in height and increases the deployment interval (0 to θ_{max}). A choice will have to be made concerning the optimal number of modules that will suit the design, taking all relevant parameters into consideration.

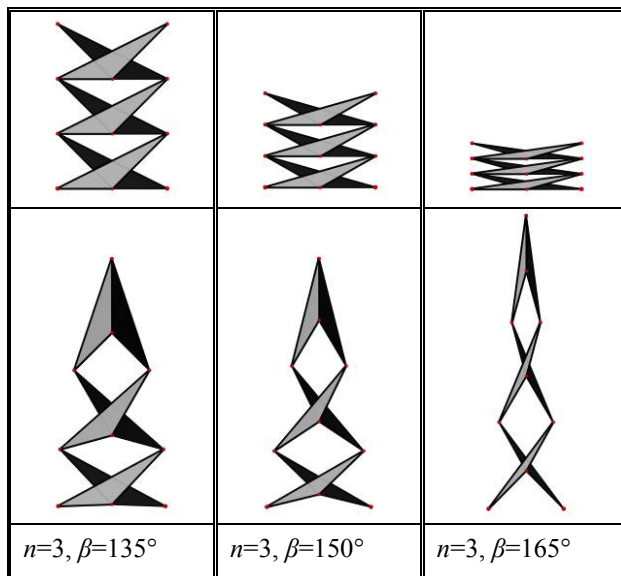


Figure 8: Illustration of the influence of the apex angle β on the geometry of a linkage with angulated SLE's with three modules ($n=3$) in the undeployed (top) and fully deployed configuration (below)

4. Kinematic behaviour

Figure 9 (left) shows a schematic representation of an undeployed and an intermediate deployment position of the same linkage. As the deployment progresses, the angulated SLE's of each module tilt inward at the top. The dotted lines are imaginary fold lines around which mobility has to be allowed in order to complete the deployment. Through connection of the end nodes, each scissor unit can be represented by a trapezoid, of which the contour changes constantly during deployment. Between quadrilaterals ABDC and CDFE and between CDFE and EFHG there is a relative rotation which causes them not to remain coplanar. The joints connecting the end nodes of the units will have to take into account all aspects of this mobility. In Figure 10 a proposal for such a joint is pictured, showing the seven rotational degrees of freedom needed for the deployment, as well as for the linkage to be compactly folded

In order for the mechanism to be usable as a structure, the mobility will have to be constrained. To analyse the mobility of the system, an equivalent hinged plate model is presented in Figure 9 (right), which represents the linkage with the rotational degree of freedom of the scissor linkage removed. After removal of this D.O.F. the remaining mobility determines to what extent constraints have to be added. Due to triangulation of the modules, there is no additional mobility which means it is basically a single D.O.F.-mechanism. Therefore, it is sufficient to constrain the movement of the rotational degree of

freedom of the scissor units. As usual, fixing two appropriately chosen nodes is enough to remove the rotational D.O.F from the scissor linkage. But for using the tower as a load bearing structure, all three lower nodes have to be fixed to the ground by pinned supports. Additionally, it has been found through preliminary structural analyses, that horizontal ties - cables or struts - between the nodes greatly improve structural performance and lead to much smaller sections for the individual bars, thus enhancing the weight/height ratio [De Temmerman].

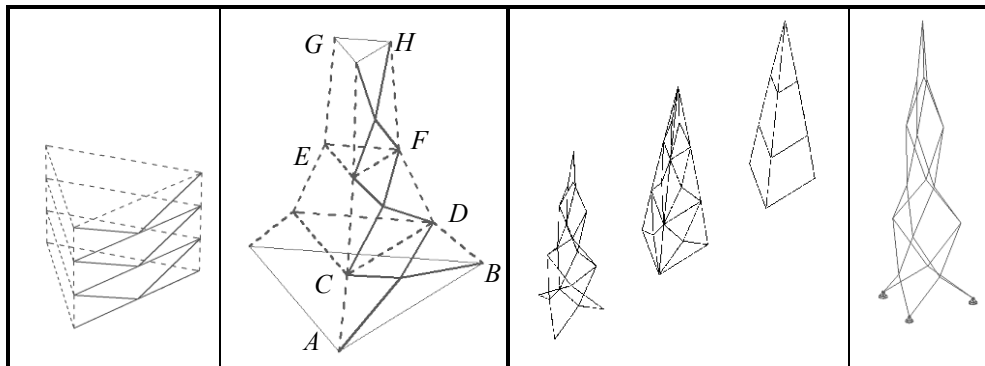


Figure 9: A schematic representation of the relative rotations of the quadrilaterals around imaginary fold axes during deployment (left) and the scissor linkage in its deployed state, its equivalent hinged plate structure for mobility analysis and the necessary pinned supports (right)

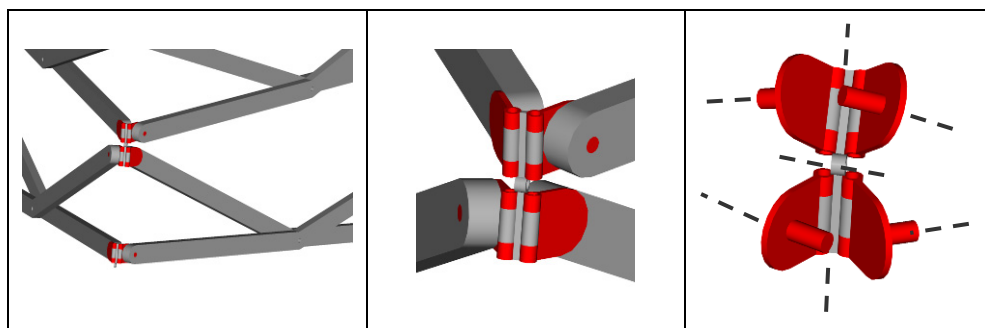


Figure 10: Kinematic joint connecting the angulated elements at their end nodes and the axes of revolution for the seven rotational degrees of freedom

5. Simplified geometry

The scissor linkage in the previously described geometry has in its undeployed state a prismatic shape and all angulated elements per vertical row (or lateral face of the prism) are coplanar. During deployment, however, the shape gradually changes into a hyperboloid,

which means that the angulated elements per vertical row are no longer coplanar, i.e. they experience relative rotation, as can be seen in the triangular example of Figure 11 (left). As a consequence, the articulated hinges (Figure 10) will have to allow an extra rotational D.O.F around the horizontal axes between modules to cope with this movement, which adds to the complexity of the joint design.

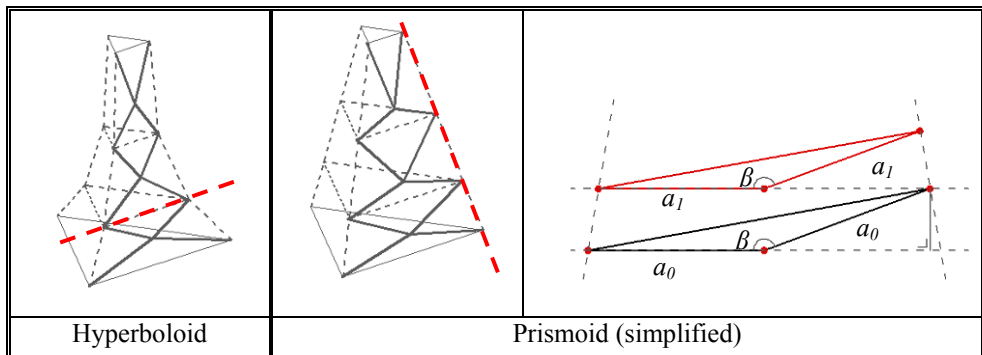


Figure 11: Difference in geometry between the hyperboloid and the prismoid version (left and middle) - Symmetrical and non-identical angulated elements result in a fully compactable configuration: *prismoid solution* (right)

The described deployment behaviour is caused by the particular geometry of the angulated elements, which consist of two differently sized semi-bars a and b , turning the angulated elements non-symmetrical. The overall geometry of this solution shall be referred to as *hyperboloid*. Now, an alternative concept is proposed, which is similar in setup to the hyperboloid version, but has simplified joints for interconnecting the modules. If the angulated elements within a vertical row can be kept coplanar, then the hinges between modules would not have to allow an extra rotational D.O.F. around the horizontal axes between modules, effectively decreasing the mechanical complexity. Also, the end nodes of the angulated elements remain collinear, as shown in the triangular example of Figure 11 (right). The effect on the overall shape is that it resembles a prism before, during and after deployment. More precisely, such a shape is known in geometry as a *prismoid*. This particular prismoid geometry can only be achieved if symmetrical angulated elements are used, i.e. elements with identical semi-lengths.

Furthermore, an extra condition is imposed on the scissor geometry, as Figure 11 (right) shows. The angulated elements become smaller near the top and their geometry is such that their lower end nodes and intermediate hinge are collinear in the undeployed position. This configuration ensures the highest degree of compactness.

The relationship between the lengths of semi-bars of consecutive angulated elements can be derived. The length of the semi-bar a_1 can be expressed in terms of a_0 as follows:

$$a_1 = a_0 \cos(\pi - \beta) \quad (1)$$

With the kink angle β and the length of the semi-bar of the bottom most angled element a_0 chosen as design parameters, the length semi-bar of the n^{th} element can be written as:

$$a_n = a_0 (\cos(\pi - \beta))^n \quad (2)$$

To illustrate what happens during deployment, Figure 12 shows the corresponding closed loop structure which uses the same vertical linkage, but arranged radially in a common plane. The planar linkage is depicted in three consecutive stages - undeployed, partially deployed and fully deployed. During deployment, a constant angle (marked by the red intersecting lines), is subtended by each vertical linkage. This characteristic is precisely what makes the design of radially deployable closed loop structures possible [Hoberman].

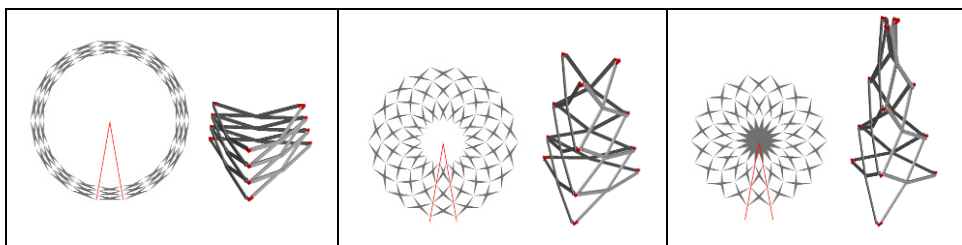


Figure 12: Three consecutive stages of the corresponding planar closed-loop structure

The simplified solution for the articulated hinge - which connects four bars at once - is shown in Figure 13. In Figure 9 (right), an equivalent hinged-plate structure for the hyperboloid geometry was introduced, which has shown that the only D.O.F. in the system is the rotational D.O.F. of the scissors. When the same method is applied to the prismoid solution, it can be seen that this holds no longer true. It can be concluded that the prismoid solution is – apart from the triangular geometry – a multiple D.O.F.-mechanism [De Temmerman]. To turn the mechanism into a structure, and therefore removing all D.O.F.'s, all lower nodes are fixed to the ground by pinned supports.

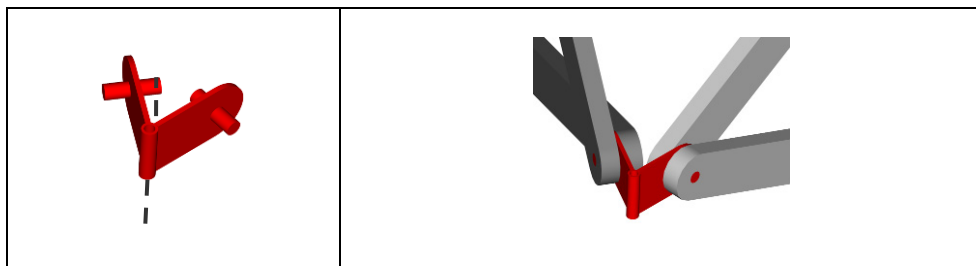


Figure 13: Detailed view of the simplified hinge connecting four scissor bars in the prismoid solution

6. From model to realisation

In order to evaluate whether the obtained kinematic behaviour of the hyperboloid mechanism is indeed the desired one, a detailed working model has been constructed, as shown in Figure 14 (left). This 1/20 scale model with triangular section allows the same D.O.F.'s as the full scale original and demonstrates, as expected, a single kinematic D.O.F. The kinematic behaviour of the simplified prismoid solution has been verified by means of a 1/2 scale model, resulting in a 4 m high mast, as shown in Figure 14 (right). Laminated wood was used for the angulated elements and steel for the connections. A cable-pulley system driven by an electric winch is used for the deployment.



Figure 14: Deployment of the 1/20 (left) and the 1/2 proof-of-concept scale model (right)

7. Summary

In this paper, a novel idea has been put forward for a deployable hyperboloid mast or tower, used for the deployment of a membrane canopy, without the need for additional lifting equipment. Angulated elements are of great use in the design of all kinds of radially retractable roof structures [Jensen]. This concept has shown that these elements can be used in a slightly different way, i.e. in a linear mechanism. The two-fold purpose of the mast, namely holding up the membrane elements in the deployed position and serving as an active element during the erection process, has been demonstrated.

It has been found that the proposed linear structure offers an advantage over existing solutions: using angulated elements instead of polar units for the same deployed geometry, has led to a significant reduction of the number of scissor members and connections. Further, an alternative shape, called a prismoid geometry, has been proposed. This has proven to be a simpler solution compared to the hyperboloid geometry in terms of kinematic behaviour, therefore allowing the use of greatly simplified joints.

Through the use of an equivalent hinged-plate model, the mobility of both the hyperboloid and prismoid geometry has been assessed. It was found that the hyperboloid configuration is always, regardless of the polygonal shape, a one-degree-of-freedom mechanism. The prismoid solution, on the other hand, is always, apart from the triangular geometry, a multiple-D.O.F.- mechanism.

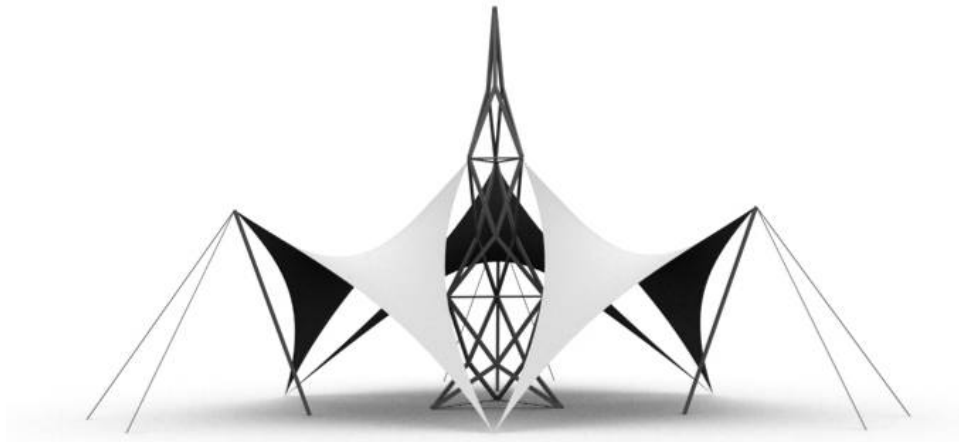


Figure 15: Rendered image of the concept

The proposed concept has made innovative use of angulated scissor elements in an original application (Figure 15). Although the concept has been proven to work, more detailed analysis, including structural design of the joints, is needed.

8. References

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