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Deployment analysis of a pentagonal tensegrity-ring module

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Abstract —Ring modules are tensegrity systems that include a single strut circuit and recently, they have been shown to be viable systems for pedestrian bridges. Furthermore, their shape can be controlled using cable actuation. This paper focuses on the deployment of a pentagonal tensegrity-ring module. A geometric study is conducted to identify the deployment-solution space without strut contact. Deployment paths and actuation requirements are explored. The structural response of the module during deployment is analyzed using a modified dynamic relaxation method.

Keywords — Tensegrity structures, deployable structures, dynamic relaxation

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1 Introduction

Tensegrity structures are spatial reticulated structures that are composed of cables and struts. Therefore, they contain only axially loaded elements. The stability of tensegrity structures is based on the equilibrium among cables and struts. Since the introduction of the tensegrity concept in the 1950s, there have been many definitions for tensegrity systems [1]. A widely accepted definition was proposed by Motro [1] in 2003: *"A tensegrity is a system in stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components"*. This definition includes systems with interconnected compressed elements into the broader class of tensegrity structures. Moreover, a class characterization was proposed to distinguished tensegrity systems that contain interconnected compressed elements: "*class I*" tensegrity systems have no connection among struts, while "*class II*" systems include strut-to-strut connections [2].

Throughout the four last decades, scientists and engineers have shown interest in the tensegrity concept [3-5]. Although tensegrity systems can be combined to create lightweight modular structures with high strength to mass ratios, few examples of tensegrity structures have been used for civil engineering applications. The Rostock tower in Germany is an assembly of six "simplex" modules designed by Schlaich [6]. The structural system of the roof of the World Cycling Center Arena in Aigle (Switzerland) is composed of a tensegrity structure [7]. Furthermore, a tensegrity grid was proposed for the Swiss National Exhibition in 2002 [8]. Research on double layer tensegrity grids resulted in the construction of an 81 m^2 double layer tensegrity grid [9].

Tensegrity modules are attractive systems not only for conventional structures but also for active/adaptive structures and deployable structures. Active structures can interact with complex environments with the use of embedded actuated elements. In tensegrity systems, actuated elements and structural elements can be combined. Consequently, both actuated cables and telescopic struts can be used for active control. Furthermore, tensegrity systems require small amounts of energy for actuation and control [10]. A modular full-scale active tensegrity structure with telescopic struts was designed and constructed by Fest [11]. Active control was enhanced with advanced informatics such as stochastic search and case-based reasoning in order to improve service performance and perform self-diagnosis as well as self-repair [12-13]. Moreover, vibration control was also studied and verified experimentally [14].

Deployable structures change shape from a compact configuration to an expanded one. Actuation can thus have a dual action: control the shape of the structure and enhance service performance after deployment. Furuya [15] studied the deployment of a tensegrity mast. Tibert and Pellegrino [16] compared deployable tensegrity masts to conventional ones. Lack of stiffness during deployment and low bending stiffness were identified as obstacles to practical applications for deployable tensegrity masts. Sultan and Skelton [17] studied the deployment of tensegrity systems and showed that cable control has the advantage of keeping the system close to an equilibrium manifold throughout deployment. The system can thus maintain stiffness during deployment. Bouderbala and Motro [18] studied folding of “expanded octahedron” assemblies with cable and strut actuation. Smaili and Motro [19] investigated folding of tensegrity systems using finite mechanisms. Similarly, Sultan [20] studied shape control of tensegrity structures through infinitesimal mechanisms. Moreover, Schenk et al. [21] studied the application of statically balanced mechanisms in tensegrity systems. Although cable actuation has been used for deployment, no study explored the use of continuous cables. Furthermore, most of the studies do not focus on civil engineering applications.

This paper focuses on the deployment of a pentagonal tensegrity-ring module using actuated cables. The deployment-solution space is identified through a geometrical study. Deployment paths are compared based on the number of actuators required. Furthermore, continuous cables and spring elements are used to decrease the number of actuators. The structural behavior of the modules during deployment is investigated using a deployment-analysis algorithm.

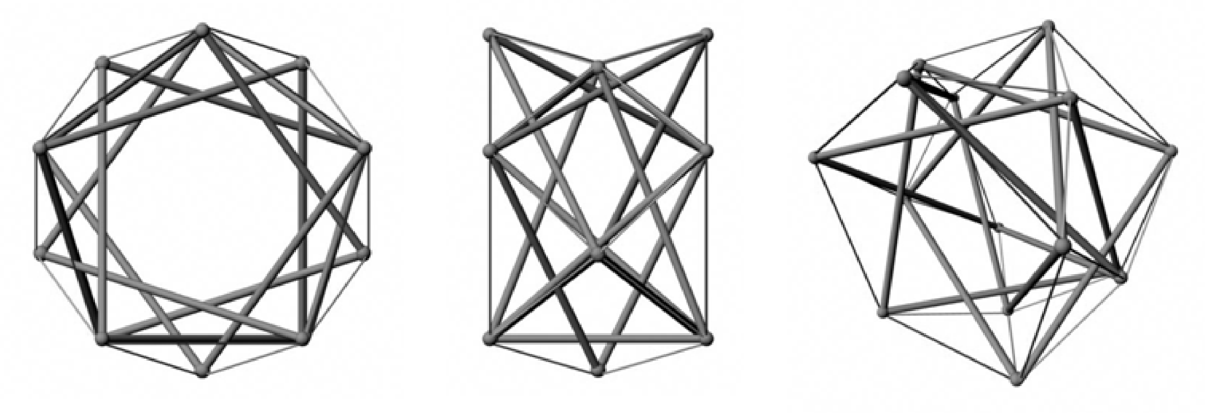

FIG. 1 – Illustration of a pentagonal tensegrity-ring module including struts, layer cables and x-cables

2 Pentagonal tensegrity-ring module topology

Tensegrity-ring modules were presented in 2006 by Motro [22]. They are named after their topology that includes interconnected struts in a single circuit in the form of a ring (Figure 1). Motro studied their topology and their deployability [22]. Ring-module topology is based on straight prism geometry. Moreover, straight prism geometry can be used to further characterize the geometry of the module. The authors showed that pentagonal ring modules are viable systems for a pedestrian bridge [23-24]. A single pentagonal ring-module is shown in Figure 1. The module includes 15 struts and 30 cables. There are two sets of cables: *layer cables* and *x-cables*. Layer cables form a pentagon on the front and back side of the module, while x-cables form an “x” on each lateral side of the module.

Ring-module topology guarantees deployability with cable actuation [22]. If cables can change rest length, then modules can change shape (deploy) from a folded to an unfolded configuration. Dung studied the structural response of the deployed configuration of a pentagonal ring-module and its folding [25]. Cable stiffness was found to be more important for the overall stiffness compared with strut stiffness. Folding was simulated using FEM where the structure is compacted under nodal external forces leading to some cables to go slack. Therefore, this method is not suitable for studying deployment under cable actuation.

3 Geometrical study of deployment and cable actuation

The motion of ring modules during deployment is composed of a translation, a rotation and a dilation of their pentagonal faces. The translation between front and back pentagonal faces defines the deployment length L. The transverse rotation θ of the two faces and their dilation given by the external radius R describe the repositioning of the strut circuit under the new deployment length. Both R and θ increase with folding and decrease with unfolding. Consequently, during deployment ring-module topology can be described based on the module length L, the external radius R and the transverse rotation θ between front and back pentagonal face of the module (Figure 2). However, there is no explicit relationship among the parameters since various configurations have the same length. If module topology is respected, R can be expressed in terms of L and θ. Consequently, the deployment space is reduced into a 2D-space described by L and θ. Figure 2 shows the deployment-solution space for the pentagonal module with a total length of 75 cm with an external radius of approximately 57 cm. Struts have a length of 100 cm. Cable length is set at approximately 68 cm and 51 cm for layer cables and x-cables respectively. The space in white describes the space where deployment is conducted without strut contact. Isometric curves in Figure 2 represent the closest distance between struts from 1 (inner curve) to 9 cm (outer curve).

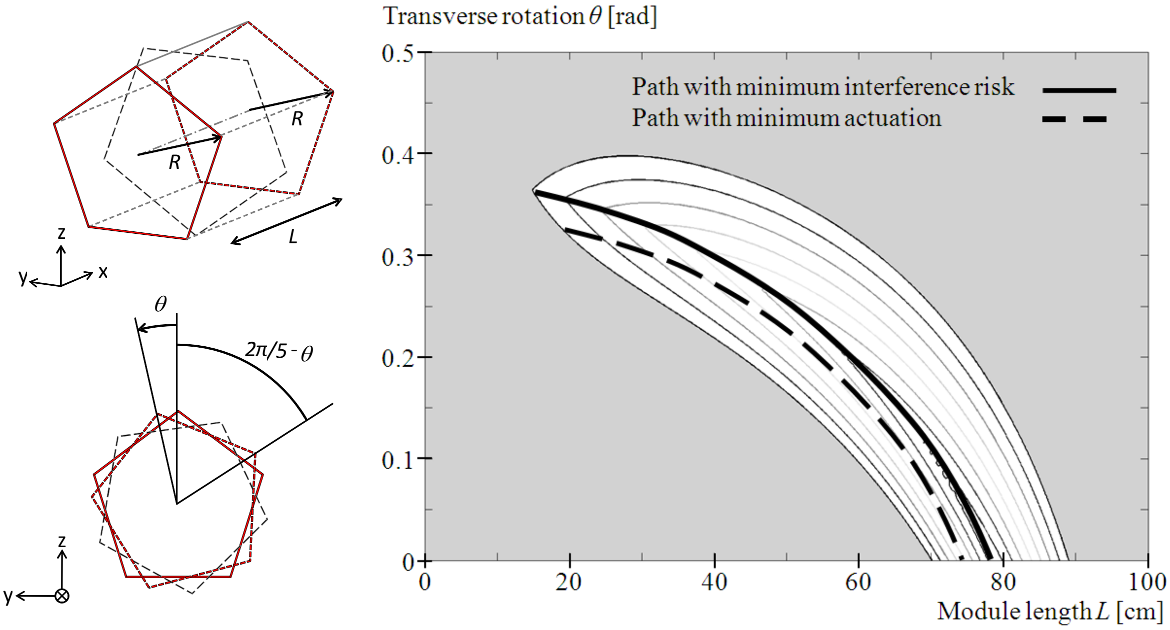

FIG. 2 – Deployment-solution space and studied deployment paths

A deployment path is defined based on the tip of isometric curves along which the risk of strut contact is minimized (maximum strut-to-strut distance). The same path is followed for both unfolding and folding (Figure 2). This path requires the actuation of all cables in the pentagonal ring module (10 layer cables and 20 x-cables). Layer cable length is decreased for unfolding while x-cable length is increased. Inversed actions take place for folding. Consequently, layer cable action controls unfolding while x-cable action controls folding. However, actions in both types of cables are required to obtain new stable configurations.

A deployment path that reduces the number of actuated cables form 30 to 20 was found. Along this path, x-cables that are coplanar with struts do not require actuation as their length remains constant. Layer cables remain actuated to control unfolding. This path is similar to the path with minimum risk of strut contact (Figure 2). A lower transverse rotation and a slightly larger folded length are the main differences.

In order to further reduce the number of actuators, continuous cables and spring elements are used in the module. Continuous cables affect the mechanics of tensegrity systems by changing the number of independent states of self-stress and the number of infinitesimal mechanisms in the module [26]. The use of continuous cables in all actuated cables (layer cables and x-cables) results in an unstable configuration. Therefore, continuous cables are used only in actuated x-cables found on each lateral side of the module. The total number of actuators decreases thus to 15: 10 actuators in layer cables and 5 actuators in x-cables. Furthermore, spring elements can be used to replace actuated layer cables. Spring elements allow length changes without requiring actuation. Both deployment phases are thus controlled by x-cables. The configuration including continuous cables in actuated x-cables and spring elements for layer cables requires only 5 actuators for deployment.

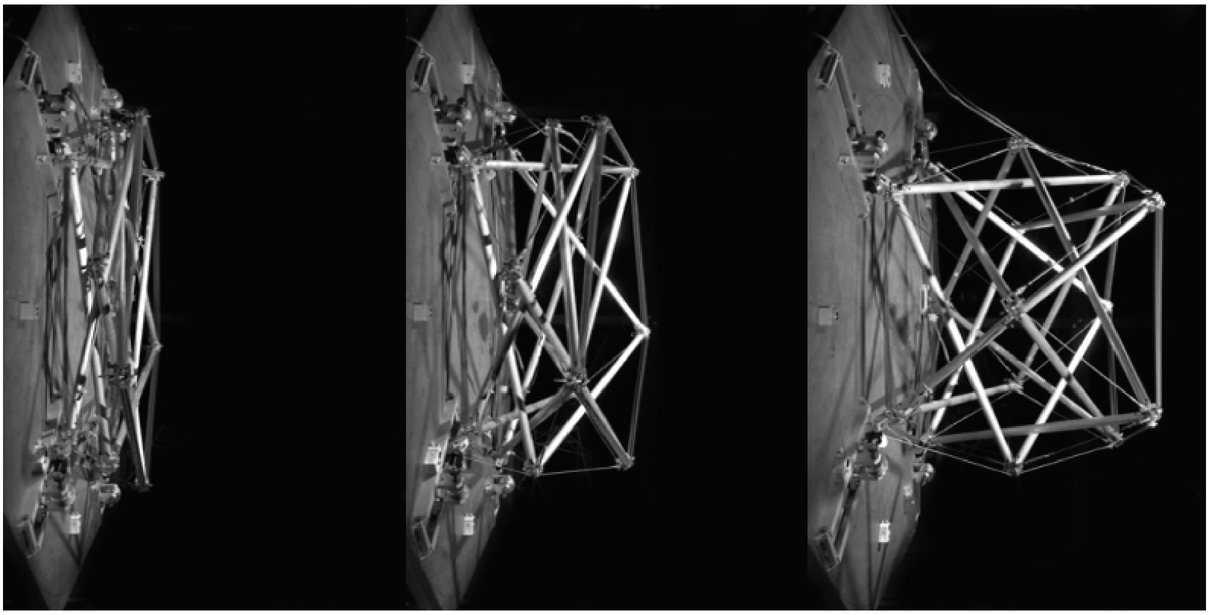

FIG. 3 – Snapshots of the deployment of small scale physical model of the pentagonal ring-module

A small scale physical model of the pentagonal ring module was constructed for experimental validation of the deployment path (Figure 3). Therefore, the module was designed according to the ring-module topology used in the geometrical study. The module is composed of aluminum struts and steel cables. Joints allow the required movement for deployment. The minimum actuation configuration is used for the control of the model. Continuous cables are thus used in actuated x-cables and spring elements are used to replace layer cables. Cable actuation is conducted manually using cranks placed on the support of the model. Both unfolding and folding were conducted successfully without strut contact. However, a systematic error in the transverse rotation is observed due to joint design.

4 Structural analysis of the deployment

A deployment-analysis algorithm was conceived for the structural analysis of tensegrity modules during deployment. The algorithm is based on a modified version of the dynamic relaxation method. Dynamic relaxation is a method suitable for the analysis of highly non-linear structures such as tensegrity systems. The modified version of the dynamic relaxation accommodates continuous cables [27]. Furthermore, the method was adapted to take into account spring elements. Structural analysis during unfolding and folding is conducted with self-weight as unique loading. Friction and dynamic effects are not part of this study. Moreover, boundary nodes should allow deployment while blocking rigid body movements.

The deployment-analysis algorithm integrates the ring-module actuation scheme. The algorithm starts from a known folded or unfolded topology. Cable actuation is used to create a finite mechanism that will allow the module to change length. Increasing the length of x-cables leads to unfolding the module. The inversed action is used for folding the module. Length changes in spring elements (replacing actuated layer cables) are driven by cable actuation. Increasing x-cable length results in a contraction of spring elements corresponding to a decrement in the length of layer cables. After each actuation, a new equilibrium configuration is found based on the modified dynamic relaxation method. Equilibrium configurations are checked for strut contact. Deployment is thus based on a series of sequences of "*mechanism - equilibrium – constraint*". If strut contact is detected then the algorithm provides the details of the event. If deployment is completed successfully, then the deployment-path and the internal forces during unfolding and folding are given. This algorithm is summarized in Figure 4.

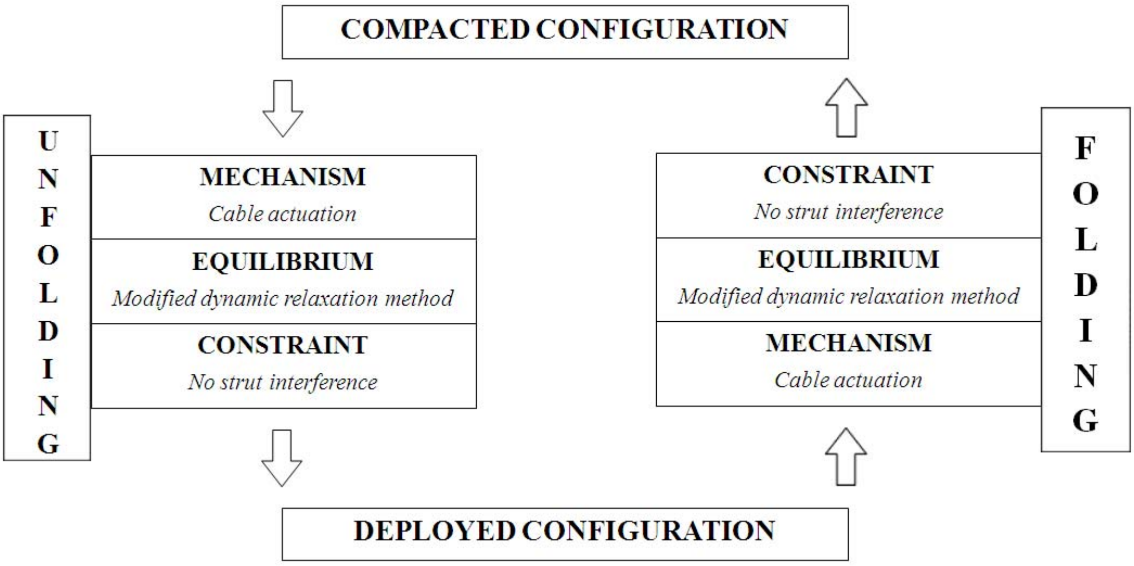

FIG. 4 – Illustration of the deployment-analysis algorithm

The deployment of a module made of aluminum struts and steel cables is analyzed using the deployment-analysis algorithm. Strut and cable cross-sections are set at 2.54 cm^2 and 0.03 cm^2 respectively. Spring elements have a constant of 20 N/cm and an initial length of approximately 66 cm. Figure 5 shows the evolution of internal forces during unfolding and folding for a single module. Structural elements are separated in actuated x-cables, spring elements (actuated layer cables), non-actuated x-cables and struts. Two types of struts are identified based on their internal forces. Strut types are in relation with ring-module topology. Figure 5 reveals that intermediate equilibrium configurations for unfolding and folding are the same. Internal forces in all structural elements increase with folding and decrease with unfolding. This trend is an effect of spring action as spring elements elongate with folding and contract with unfolding. Internal forces in actuated cables are lower compared with non-actuated elements. Finally, no strut contact is observed during unfolding or folding.

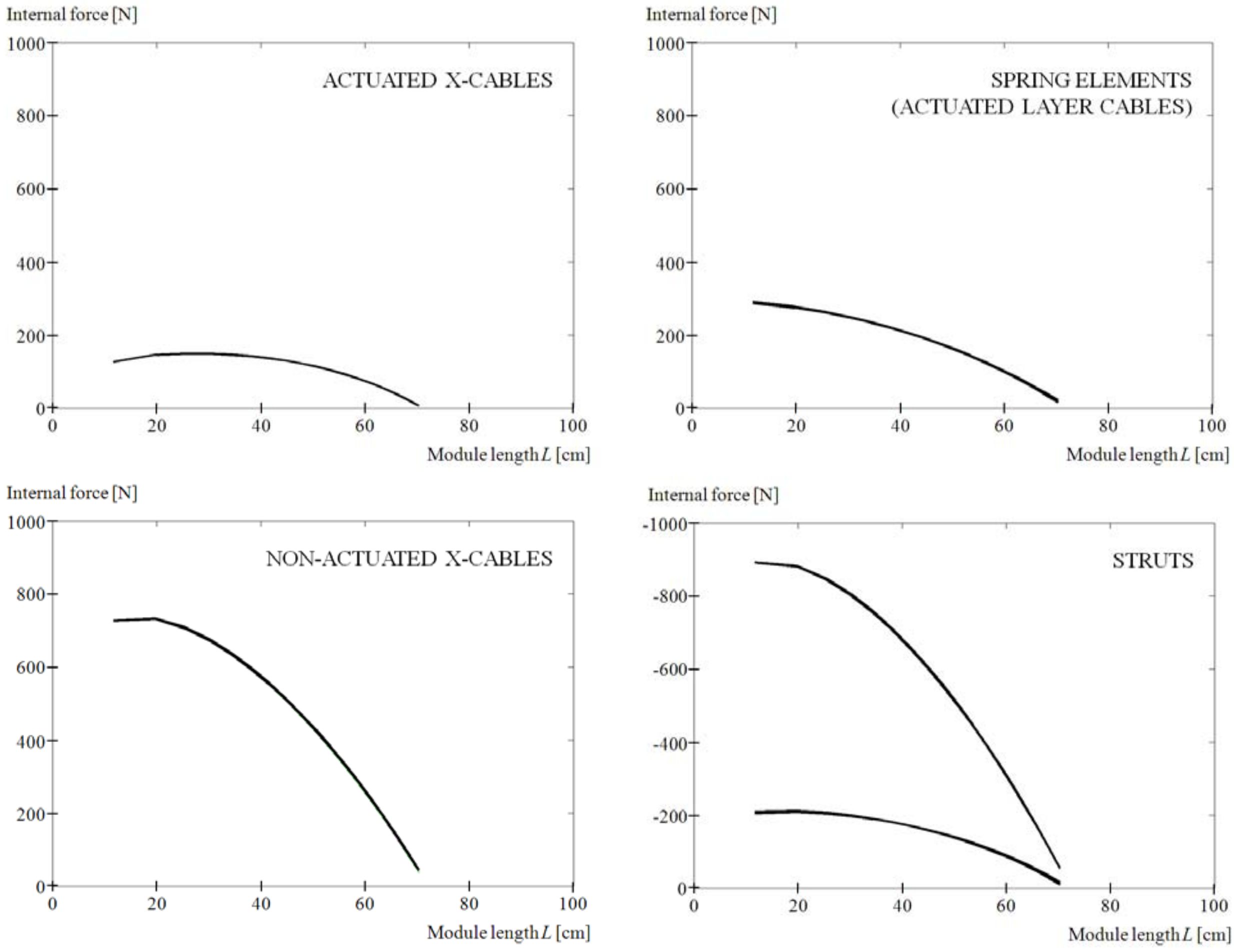

FIG. 5 – Internal force evolution in the pentagonal ring module during deployment

5 Discussion

The deployment of a pentagonal ring module is analyzed in this paper. Although deployment motion can be described using three geometrical parameters: L, θ and R (translation, rotation and dilation of the pentagonal faces), no explicit relationship between the parameters exists for deployment. The deployment-solution space is defined based on avoiding strut contact. A deployment path with minimum contact risk was identified. The path requires the actuation of all 30 cables for a single module. Furthermore, a deployment path with only 20 actuators was found based on observations on the path with minimum contact risk. The number of actuators is further reduced to 5 with the use of continuous cables and spring elements. Deployment was successfully validated without strut contact in a small scale physical model including both continuous cables and spring elements.

The deployment of a pentagonal ring module controlled by the proposed actuation scheme is composed of a series of equilibrium configurations. Furthermore, deployment motion is entirely controlled by cable actuation. Large actuation steps in x-cables result in unstable configurations while small actuation steps are computationally expensive. Moreover, spring elements are important for maintaining ring-module topology during deployment. Spring characteristics affect the stability of the system. Low values of spring constant combined with large values of initial spring length do not provide sufficient stiffness to the system resulting in unstable configurations. On the contrary, large values of spring constant combined with low values of initial spring length induce large internal forces that may exceed element strength during deployment. Therefore, actuation-step size and spring characteristics are important parameters for deployment.

Spring elements also affect the energy in the tensegrity system. Spring elements contract during unfolding and elongate during folding. It was found that the energy stored in spring elements during folding can be used for unfolding the module. Consequently, only folding requires an external energy supply. This finding was validated experimentally on the small scale physical model.

Finally, a single actuation step and a single spring constant were applied in actuated elements for this study. Different actuation steps and different spring constants could be considered for each actuated element. This may result in better control of the structure during deployment.

6 Conclusion

The conclusions from this study are as follows:

- The deployment of pentagonal ring modules is feasible through cable control.
- Continuous cables and spring elements can be used to reduce the number of actuated cables.
- Actuation steps and spring constants are critical parameters for deployment.
- Energy stored in spring elements during folding can be used for unfolding.

Work in progress includes the experimental validation of structural behavior of the module during deployment. Furthermore, a prototype of the tensegrity bridge will be built and studied experimentally.

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FIG. 1 – Giens sous le soleil