Toward development of a biomimetic tensegrity footbridge

N.Veuve, S.D. Safaei and I.F.C. Smith

Abstract—**Biomimetic structures interact with their environment, change their properties, learn and self-repair, thereby providing properties that are similar to living organisms. Interactions with the environment involve unique challenges in the field of computational control, algorithms, damage tolerance, and structural analysis. Tensegrity structures are pin-jointed structures of cables and struts in a self-stress state. Tensegrity structures are suitable for active control since the shape of the structure can be changed by changing the length of the elements. Consequently, they are good candidates for biomimetic structures. This paper describes research that is moving toward a case study of biomimetic behaviour of a deployable tensegrity footbridge. This footbridge is made of four modules. Each module is composed of pentagonal circuit-pattern including interconnected struts in a ring configuration that can be folded if cable lengths are changed. Various actuator combinations can be selected for deployment. This property is particularly interesting for biomimetic structures since a single shape change can be achieved many ways. Methodologies for deployment and folding of tensegrity footbridge via combinations of spring and cable clustered actuation are described. Analytical predictions are compared with test results of a near-full-scale tensegrity footbridge. Strategies for folding and deployment are different. A continuous cable and spring configuration is feasible for deployment of tensegrity footbridge. Since the deployment behaviour is non-linear and since deformed geometry as well as joint friction influences the deployment pattern, pre-defined control commands cannot provide the desired deployed position. Active deployment control is thus justified.**

I. INTRODUCTION

Biomimetics involves developing solutions inspired by nature. Many cases of biomimetic civil structures exist [1, 2]; mostly because their structural *shape* mimics a natural shape. However few structures reproduce *behaviour* that is inspired by nature. Biomimetic structures interact with their environment, change their properties, learn and self-repair, thereby providing properties that are similar to living organisms. Interactions with the environment involve unique challenges in the field of computational control, algorithms, damage tolerance, and structural analysis.

Tensegrities are spatial, reticulated and lightweight structures. They are composed of struts and tendons. Stability is provided by a self-stress state between tensioned and compressed components. Since tensegrity structures change shape easily with changes in element length, they are good candidates for active and deployable structures [3]. In several studies, e.g. [4-7], tensegrities have been proposed as deployable booms for space missions. Fest et al. [8] employed telescopic struts to investigate the active control behaviour of a five-module tensegrity structure. Dalil Safaei et al. [9] modified the bending stiffness of 20 m Snelson and prism type of tensegrity booms by employing a few actuators. Biomimetic properties of active tensegrity structures have been studied previously for a non-deployable structure [10, 11].

Recent research has revealed that a hollow-rope deployable tensegrity configuration (Figure 1) that has been adapted from a design proposal by Motro et.al [12] is a viable structural system for pedestrian bridges of spans around 20 m [13-14]. An active ¼-scale tensegrity structure is the experimental focal point of this study of biomimetic properties. Integration of continuous cables [15] over nodes and strategically located low stiffness elements (springs) [16] are providing unique opportunities for studies of low-power deployment with all actuators at the supports [17].

This paper describes an experimental and analytical study of the feasibility of a clustered-cable spring configuration for deployment of a tensegrity footbridge. More specifically, the influence of joint eccentricity, friction and non-linearity on deployment behaviour is examined with a view to determine the effectiveness of predefined control commands.

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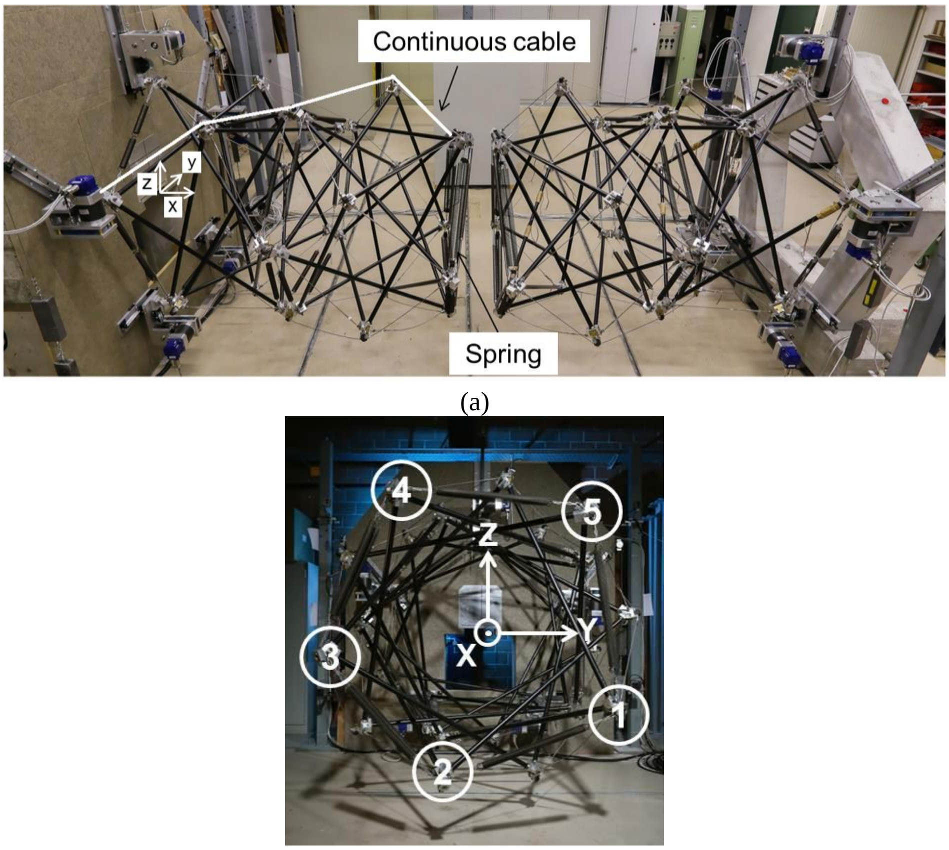

(a)

(b)

Figure 1: (a) Side view (b) front view with node numbering of near-full-scale tensegrity footbridge

II. DEPLOYABLE TENSEGRITY FOOTBRIDGE

A 1/4 scale model has been designed, manufactured and assembled in order to study deployment behaviour of two halves that meet at centre-span (Figure 1). Each half is composed of 15 springs, 5 continuous cables, 30 struts and 20 cables of which five are continuous active cables. Active cables start from nodes connected to the support and end at front nodes. The structural weight of each half is approximately 100 kg. Both ends move in rail-support systems as the circular end shape reduces in diameter during deployment. Struts are made of steel hollow tubes with lengths of 1.35 m, diameters of 28 mm and thicknesses of 1.5 mm. The steel grade of the struts is S355 with a modulus of elasticity of 210 GPa. Cables have a diameter of 4 mm and are made of stainless steel with a modulus of elasticity of 120 GPa. The value of spring stiffness at the support layer is 0.02 kN/cm and is 0.029 kN/cm for other layers. The footbridge has 25 joints per side, including 5 inter-module joints and 5 support joints. Joints are based on fork-to-fork design with additional components for continuous cables and for the inter-module connection. Position measurement provides the opportunity for closed-loop control and this has been performed with an optical tracking system that focuses on the front nodes (1-5 in Figure 1).

III. EXPERIMENTAL TESTING

Figure 2 shows snapshots of the deployment motion of one side of the near-full-scale tensegrity footbridge. Deployment and folding has been performed through changing the lengths of active cables and each actuation step is defined in terms of a set of length changes. Due to self-weight, the length changes of active cables are not equal.

Test results are systematically compared with numerical predictions. Dynamic relaxation (DR) with kinetic damping [18] is employed for incremental static analysis. The inputs to the program are current configuration, pre-stress, axial stiffness of the elements and loading state. Pre-stress values are obtained through deformation measurements of the cables using a tension measurement instrument. During deployment, the shape of structure changes from a compact state to an expanded configuration. The goal is to have both halves start from a compact configurations (folded), deploy and then become connected without human interaction. An acceptable difference between desired position and real position for connection of the joints is 1.5cm for this structure.

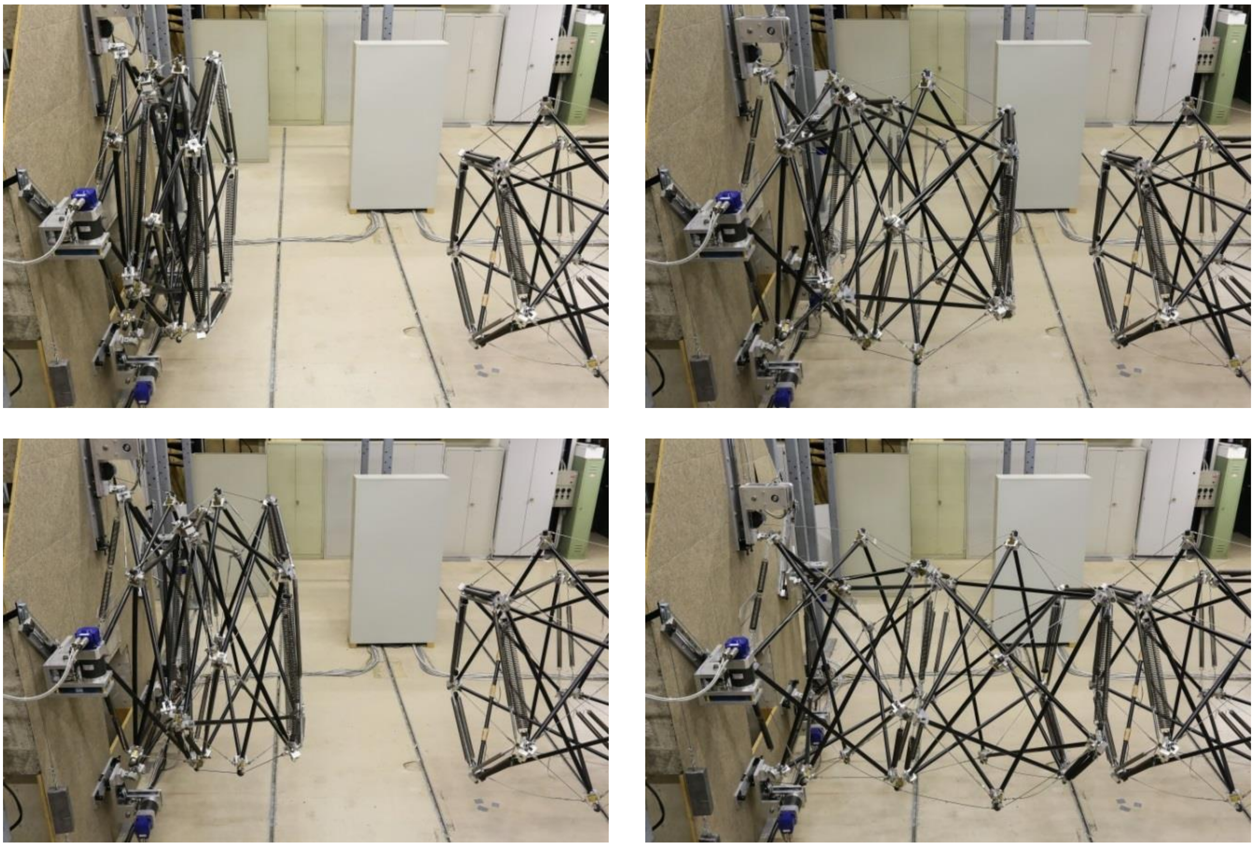

Figure 2: Snapshots of the deployment motion of the near-full-scale active deployable of one half of the tensegrity footbridge

When the footbridge is folded, eccentricities of the joints result in strut bending (Figure 3). This phenomena was not observed with earlier study of a single module at 1/10 scale [14].

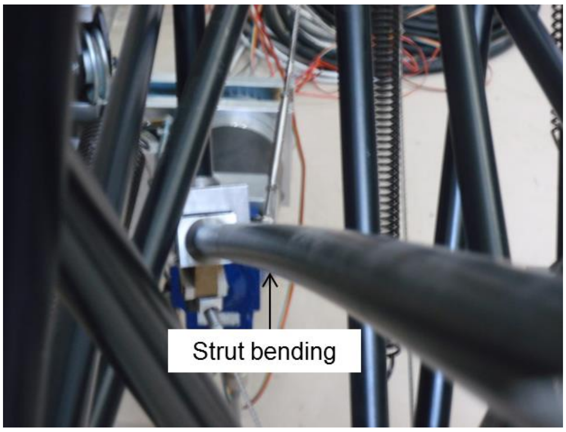

Figure 3: Bending of a strut due to joint eccentricities when the structure is folded. Bending was not observed during an earlier study of single module at 1/10 scale.

Spring stiffness influences the command sequence for deployment. Figure 4 illustrates that for a low spring stiffness, length change at the deployment stage where strut contact occurs is lower than for a higher spring stiffness. Another conclusion is that in addition to topology, deformation is a parameter that influences deployment.

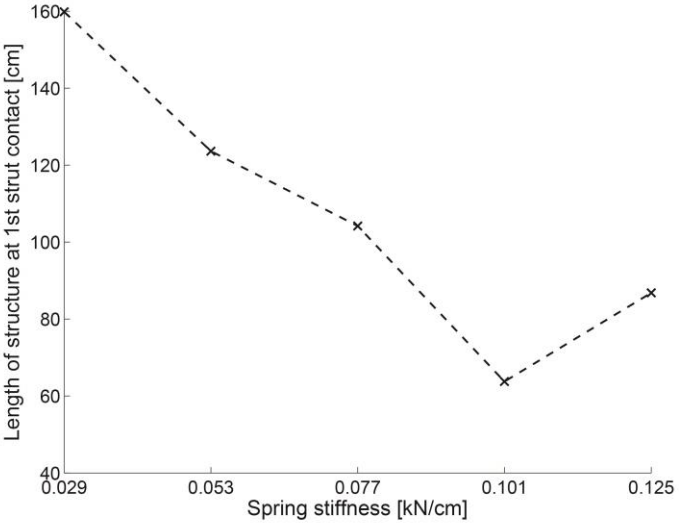

Figure 4: Structural length change for various values of spring stiffness

Through comparing numerical analyses with test results, it is concluded that accurate prediction of deployment requires more sophisticated models than those involving friction-free dimensionless joints. Table 1 displays the comparison between numerical analysis and measurements. Position changes due to lengthening of all active cables simultaneously and superposition of one at a time are not equal. Since such superposition is unsuccessful, deployment behaviour is geometrically non-linear.

Table 1: Position changes of front nodes along the direction of deployment (x-axis, see Figure 1) for a 10 cm length increase of active cables.

		Position change of node [cm]						
		Active cable 1	Active cable 2	Active cable 3	Active cable 4	Active cable 5	Superposition	All active cables simultaneously
Node 1	Analysis	3.9	3.1	4.8	-0.1	-4.9	6.8	9.1
	Measurement	4.1	0.6	1.7	1.1	-3	4.4	7.9
Node 2	Analysis	-4.2	5.6	3.1	0.8	-0.6	4.7	10
	Measurement	-2.9	1.6	2.5	2.3	0.1	3.6	-
Node 3	Analysis	-0.1	-1.5	4.2	0.5	3.1	6.3	11.1
	Measurement	-0.7	0	2.8	1.9	1.5	5.5	9.0
Node 4	Analysis	2.2	1.5	-0.9	0.8	2.6	6.1	9.4
	Measurement	1	0.5	0.2	3	1.9	6.6	8.4
Node 5	Analysis	2.7	3.3	1.2	-0.4	2.4	9.1	8.2
	Measurement	1.8	-0.3	0.8	0	1.2	3.4	6.6

Our study has shown that active control is required for connection of both halves of the tensegrity footbridge, since the behaviour of the structure is not reproducible in each cycle of deployment. Figure 5 shows the relative position change of Node 4 with respect to the average position over 10 cycles of deployment and folding. Deployment and folding cycles are performed with equal length changes of all active cables. There is significant variability; position of Node 4 changes when the same control commands are applied. Such variation is most likely due to the variable effect of friction at the joints. At full scale, this variation is expected to be **at least four times greater**. Since pre-defined control commands would not result in reproducible deployment behaviour, real-time active control for each deployment cycle is justified.

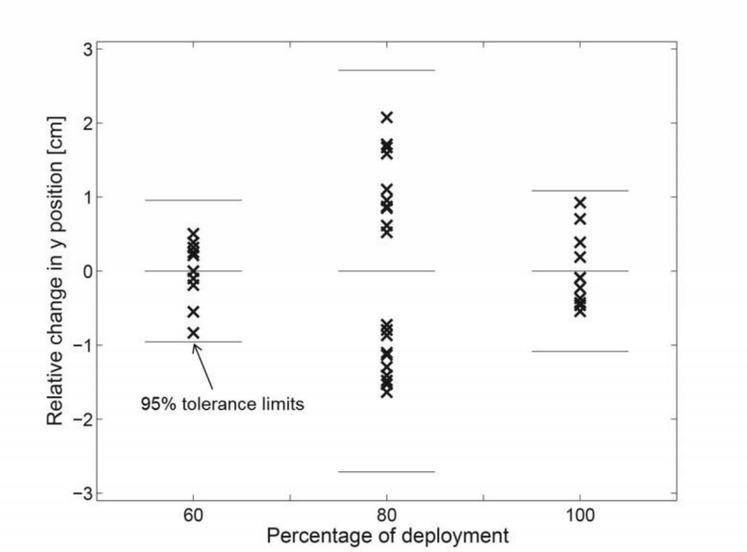

Figure 5: Relative change of y position (lateral movement, Figure 1) for Node 4 over 10 cycles of folding and deployment. Average values of lateral movement and their 95% tolerance limits are shown as horizontal lines.

IV. DISCUSSION

Continuous cables provide only partial control over element positions and subsequent deployment. Since active cables can be either lengthened or shortened, two commands per cable are possible at each front node. Additionally, when active cables are slack during deployment, there is reduced control over their connected nodes. A command strategy for continuous cables should be determined to avoid this.

In this study, there was no control over the length of springs during deployment and springs contain no forces at the end of deployment. In further testing and analysis, the initial conditions of the structure will be modified to ensure that springs retain a predetermined force at the end of deployment.

V. CONCLUSIONS

Experimental testing verifies that a continuous cable and spring configuration is feasible for deployment of tensegrity footbridge. The deployment behaviour is non-linear and the deformed geometry influences the deployment pattern. Eccentricity and friction within the joints influence the structural behaviour. Therefore, pre-defined control commands cannot provide the desired deployed position. These factors support the need for active deployment control. Future work involves improving modelling through including joint dimensions and estimating friction.

VI. REFERENCES

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