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Kinetic Hybrid Structure: Design and Motion Planning

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Abstract

The interactive relationship of society, technology and architecture has increased the demand on our built environment for kinetic structures that are capable to respond to changing external loading, functional and environmental conditions. Within this broader frame of consideration, the development of a reconfigurable hybrid structure is presented in the current paper. Hinge connected members, stabilized through a secondary system of struts and continuous diagonal cables with closed circuit compose the planar primary system. The kinematics of the structural system is based on the application of the effective 4–bar method, by using a sequence of 1-DOF (degrees of freedom) motion steps through modification of the cables' length. Motion planning is conducted through simulated models and is based on structural and kinematic criteria, in order to adjust the systems' joints to the desired values during the motion steps involved in any respective transformation sequence. The active control system applied for the reconfiguration sequences includes position sensors installed on the individual joints to provide feedback information, a minimum number of only two single motion actuators located at the structural supports, as well as hydraulic linear actuators installed on each strut. Specified criteria evaluate the kinetic behavior of the prototype according to the static braking torques, the cable axial forces and relative length variation. Following the construction design and motion planning of the kinetic structure, integration aspects of an adaptable tensile building envelope are discussed in the last part of the current paper.

Keywords

Adaptable structures; reconfigurable mechanisms; motion planning; envelope structure.

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Introduction

The interactive relation of society, technology and architecture expanded the area of research, design and application of static structures aiming at transformability and adaptability. The necessity for an architecture that is not static, instead it has the ability to adapt in time and change through systems with embedded kinetic mechanisms was initially demonstrated by Zuk and Clark (1970). The design philosophy of kinetic architecture aims at the development of timely transformable buildings or components with variable mobility, location, or geometry as to differing external loading, functional and environmental conditions (Fox, 2001). Especially significant in terms of the kinetic operability is the development of the structure in two aspects by ways and means: The structural mechanism that enables different geometrical configurations of the lightweight components through among others, folding, sliding, expanding and transforming in size and shape, and the output system that directs the structure towards specified transformations, through pneumatic, chemical, magnetic, natural or mechanical processes. Undoubtedly, interaction comprises the main characteristic of a system in order to recognize, control and respond to different external stimuli, instead of simply following any respective linear patterns of locomotion. Types of interactive architectural spaces outlined by the convergence of kinetic systems and embedded computation, enriched with capabilities of reconfiguration, adaptation and automatization of the physical change (Fox and Kemp, 2009). In this frame, the human body may be considered as the most representative example. As Fox pointed out, a kinetic environment without computation is like a body without brain: incapable of moving. Inextricably linked to biological survival is the capability of adaptability, which addresses issues of transformation and optimization in response for accommodating changing variables. In numerous applications, major part of the structure can be reduced through the ability of a singular system to facilitate multi-uses via transformative adaptability. In this aspect, Buckminster Fuller favoured through "Ephemeralization" reduction of material (Krausse and Lichtenstein, 2000). Robert Kronenburg illustrated the advantage of such systems in that, buildings that use fewer resources and adapt efficiently to complex site and programmatic requirements are particularly relevant to an industry, becoming increasingly aware of its environmental responsibilities (Kronenburg, 1997).

In structural terms, minimum self-weight is directly related with aspects of structural modularity, in limiting the complexity of the system and supporting constructability, connectivity, in producing a complete structural system on modular basis, loading, in providing feedback about load transmission with changes in stiffness, and shape, in accurately testing the geometrical shape limits of the structural system. From a static systems' point of view, tensegrity structures, i.e. self-stressed systems composed of tension and compression members (Pugh, 1976), may achieve minimum self-weight and controllable high stiffness values. Tensegrity structures combine parts mutually supportive in such a way that the compression members do not touch one another, but press outwardly against nodal points in the tension network to form firm, triangulated, prestressed, tension and compression units (Snelson, 1965). Such member structures have the ability to transform in space, while enabling optimized conditions in the mass and load transfer. Furthermore, discontinuous compression, as in classical tensegrity systems, may not always be necessary, whereas more efficient static structures can be achieved, if compression elements are allowed to join (Robbin, 1996, pp. 25-37). Such typologies may further lead to hybrid systems. In principle the latter are defined through linkage of different components in parallel and/or in series that are combined to resist forces by developing a specific mechanical behavior due to their different resisting nature (Schlaich, et al., 2005). The potential of hybrid systems lays in the synergetic possibilities emanating from exploiting the systems disparities: reciprocal compensation of critical stresses, system-transgressing multiple functions of individual components and increase in rigidity through opposite systems deflection (Engel, 2009). Even though

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the development of optimized lightweight structures is highly acknowledged in research and applications, their transformation into kinetic systems follows in most cases linear, sequential processes of development within respective multidisciplinary teams of operation, rather than non-linear, iterative ones in an interdisciplinary context. Linear, sequential modes of development have as a result in most cases member structures, i.e. planar and spatial trusses and hybrid systems, stressed in compression, tension and bending, with respectively articulated joints and embedded mechanical actuators.

An example of structural joints' activation for obtaining controlled flexibility is the "Kinetic Tower", a development of the movable guyed mast vision of Frei Otto (Kilian, et al., 2006). The resulting outrigger system of rhomboid shaped core units and vertical interconnecting tension-only members provides different spatial bending shapes through integrated dampers at the joints. An adaptable structure with integrated hydraulic actuators as primary compression diagonal members comprises the planar truss with lower horizontal elastomeric tubes, presented in Merali and Long (2010). Further developments in this direction are the Variable Geometry Truss, a planar or spatial member structure with embedded hydraulic actuators (Miura and Furuya, 1985), an adaptable aluminium tensegrity structure presented in Sterk (2003), and a tetrahedral truss with a number of actuator diagonals of shape memory alloy (Sofla, Elzey and Wadley, 2009). In the prototype of the "Muscle Tower" of six actuated trapezoidal vertically positioned tensegrity units, the actuators are in place of the tension members (Hwang, et al., 2006). The structure demonstrates high flexibility due to possible elongation, shortening and rotation of the units. Active tensegrity structures of struts and cables are further analyzed in Fest, et al. (2003) and Sultan (2009).

The above-mentioned projects identify design strategies of replacing main components of the structure with actuators. Consequently depending on the actuators number used and their specific characteristics, the structures overall weight and the energy consumption for their kinematic reconfigurations are disadvantageously affected. The design and analysis of the kinetic hybrid structure presented in the current paper reflexively addresses these considerations with regard to the integrative development of the systems static and kinetic operability. For achieving optimal load-bearing and energy performance, the transformability of the prototype structure is envisaged to arise primarily from the inherent integrative composition and dual capabilities of its members, than exclusively from the mechanical control system. The development refers primarily to the hybrid nature of the structure on one side and the application of the effective 4-bar method for its kinematics by using a sequence of 1-DOF motion steps through modification of the cables' length on the other side. In this way, reduced self-weight of the structure, dual capabilities of its members with regard to their static and kinematic operability and minimum number of actuators with reduced energy consumption are possible. Previous work conducted by the author in this direction refers to an adaptable spatial tensegrity structure presented in Phocas, Kontovourkis and Matheou (2012). The proposed reconfiguration concept of the system was based on general motion planning principles introduced in Christoforou, Müller and Phocas (2012) and Christoforou, et al., (2013).

The prototype structure presented in the current paper builds upon a previous proposal made by the author on an adaptable planar hybrid structure and motion planning concept of multi-body articulated systems (Matheou, Phocas and Christoforou, 2013). The

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hybrid structure consists of hinge connected beams and a secondary system of struts and diagonal cables. The system is initially analyzed in its static behavior with regard to the secondary members' geometrical and mechanical characteristics. The proposed reconfiguration concept requiring only two motion actuators tensioning each corresponding cable at the structural supports as well as hydraulic brakes at the joints, and the selection of an optimal motion pattern are demonstrated through a simulation example. Finally, two structural alternatives are proposed for the building envelope integration, so that the membrane units may follow elastically respective shape alterations of the primary structure.

Structural System Development

The typological development of the adaptable hybrid structure clarifies decisive geometrical and mechanical characteristics of the secondary members and their connections through a comparative static analysis of hinge connected horizontal beams with all joints conservatively considered to be moment free, Table 1. A two-hinge supported beam with span of 17.5 m, system: A-1-1, is initially modified into eight, hinge connected beam members with individual lengths of 2.5 m and 1.25 m at the edges. The members are stabilized through a secondary system of continuous struts with overall length of 1.0 m and diagonal cables connecting adjacent upper and lower strut points to the beams at the respective mid-spans, system: ST-1-1. The diagonal cables may also comprise continuous members between adjacent upper and lower strut points, system: ST1-1-1, and rotating discs may be applied at the cable-strut joints, system: ST3-1-1. In the latter system the cables obtain a closed circuit, meaning that in any transformation, the resulting alteration of the diagonals length is ideally zero. The geometrical characteristics of the struts are further modified to accommodate the kinematics of the system. The total length of the members is set to 1.5 m, whereas their effective length above the beam axis amounts to 1.0 m, system: ST3.1-1-1. Finally a refinement of the kinematic mechanism of the system is achieved with pulley elements at the respective joints and continuous cables, system: WM.

The sections of the members have been designed for a vertical uniform load of 2.5 kN/m, based on Eurocode 3. The beams consist of pairs of interconnected UPN320 sections facing outwards and positioned at a relative horizontal distance of 12,5 cm. The struts consist of rectangular sections with dimensions of 85/40/3.2 mm and the cables diameter amounts to 40 mm. Nonlinear analysis of the systems has been conducted with the Finite-Element software program SAP2000. The cables have been modelled as frame objects with zero compression limits. No prestress has been assigned to the members for enabling a direct comparison of the results. The rotating discs have been modeled as compositions of two short-length frame objects, each assigned with large stiffness values to represent the real property of a mechanical discs shaft. The absolute maximum internal forces developed in the members, maximum axial force Nmax, shear force Qmax, and bending moment Mmax, and the systems deformations f, are presented in Table 2.

Compared to A-1-1 system of reference, the first three alternatives have a significant increase of the maximum shear force of the primary members, of on average 73 %. In addition the contribution of the secondary system in the load-bearing behavior of the structure is reflected by the development of the respective axial forces in the members.

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Table 1. Typological development of planar hybrid system.

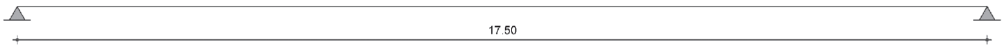
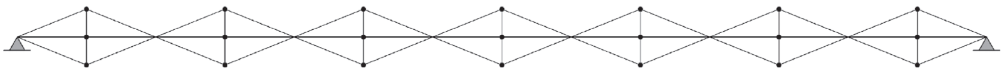
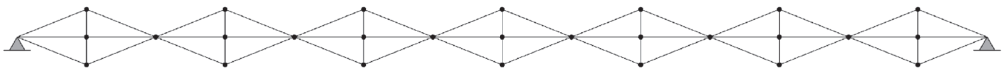
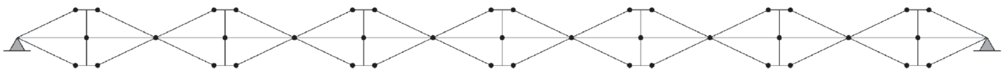
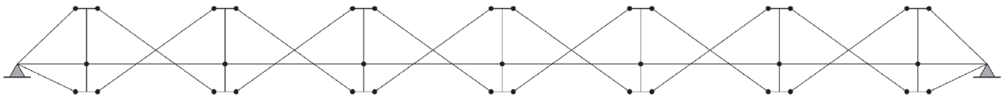
Type	Structural system
A-1-1	
ST-1-1	
ST1-1-1	
ST3-1-1	
ST3.1-1-1	

Table 2. Static behavior of the planar structural systems.

Type	Structural member	N_{max} [kN]	Q_{max} [kN]	M_{max} [kNm]	f [cm]
A-1-1	Beam	-	29.61	129.42	15.37
ST-1-1	Beams	112.91	110.51	135.49	16.56
	Struts	221.21			
	Cables	298.01			
ST1-1-1	Beams	90.30	110.26	135.20	16.53
	Struts	220.91			
	Cables	297.92			
ST3-1-1	Beams	104.49	110.93	135.99	16.19
	Struts	222.19			
	Cables	279.22			

Table 3. Static braking torques, T_i, axial cable forces, N, and relative cable length variation, Δl.

Sequence	$T_{i,\ max}$ [kNm]	$N_{1,\ max}$ [kNm]	$N_{2,\ max}$ [kN]	Δl_{max} [cm]
1 Type A	19.29	19.63	15.24	-8.00
1 Type F	18.87	19.31	11.91	-8.00
2 Type B	19.61	19.01	13.95	-10.00
4 Type D	19.64	19.05	11.48	-7.00
5 Type F	20.13	19.60	13.79	-11.00
6 Type B	20.05	19.55	12.21	-6.00
-2 Type E	34.53	19.25	19.72	-8.00
-2 Type F	29.69	17.09	14.37	6.00
-6 Type E	33.64	19.56	19.31	-6.00
-6 Type F	34.86	15.98	12.07	-6.00

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The maximum bending moment of the primary members increases only slightly, by on average 4.74 %, as well as the maximum deformation, by 6.87 %. The differentiation of the strut lengths as to the beam axis followed in ST3.1-1-1 proves to be disadvantageous for the structure resulting in a high deformability. The replacement of the rotating discs with pulleys in WM improves the load-bearing behavior of the system only in terms of uniform axial force distribution in the continuous cable members. The stability of ST3.1-1-1 and WM under vertical loading was verified in the frame of the succeeding respective motion analysis with the software Working Model. In the kinematic model of WM-System the transfer of motion driven by respective modifications of the cables length is realized through a hydraulic brake system and a pair of diagonal links symmetrically-installed on either side of each strut, Figure 1.
The linkage effectively ensures a centering of the struts while the corresponding joint angles vary.

Spatial Structure

The spatial structure follows general configuration principles of member structures with hierarchy in one direction. For ensuring spatial operability, especially in cases of non-symmetrical motion sequences between the primary structures, the horizontal structure needs to be geometrically variable. Therefore the secondary compression members consist of telescopic tubular steel sections of variable length, Figure 2. The compression members are connected to the primary beams over flat steel diagonals and elastomeric washers at the joints with the beams. The secondary diagonals consist of tension-only members with closed circuit, i.e. continuous cables connected at the end-compression members at a fixed and an electromagnetically controlled joint. In this way, once a new position of the primary elements is obtained, the horizontal members are redefined in their length and the diaphragm at the roof plane is ensured.

Motion planning

The planar kinematic mechanism, n−bar linkage of WM, has the capacity to develop different reconfiguration schemes. The supports provide one link to the linkage and the remaining kinematic chain consists of (n−1) members. In general, a planar n-bar linkage has (n−3) DOF and complete control of its motion requires equal number of actuators to be installed. However, installing many actuators on the system increases the overall structure's weight, structural deformations and cost. Moreover, operation will be energy inefficient given that the system will have to move about its own massive components. Therefore, it is proposed to use two single motion actuators at the structural supports corresponding to each one of the cables, as well as electromagnetic brakes corresponding to each one of the remaining articulated joints. By selectively locking (n−4) joints at a time, the mechanism is reduced to an "effective 4–bar" (E4B) mechanism that will have 1−DOF, Figure 3. A group of consecutively locked joints formulates an "effective link". By using the available actuators, any joint angle of the E4B linkage can be adjusted to its desired value and from then on it remains locked until a reconfiguration is completed. For each successive step of the control sequence a different E4B linkage is defined and one angle is adjusted. The final E4B realization is used to adjust the last remaining four joint rotations. Assuming that during every step one joint adjustment is fully completed the overall reconfiguration of the n–bar requires a total of (n−3) steps.

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Figure 1.
Primary structure unit of WM-System.

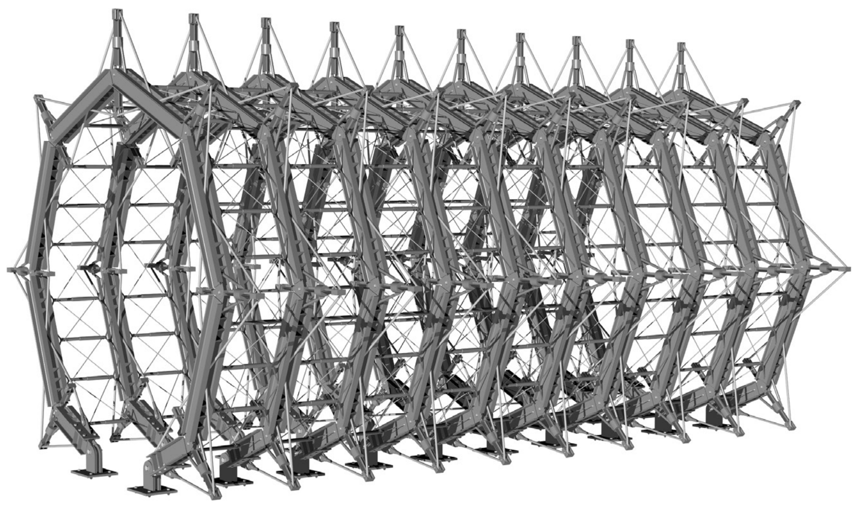

Figure 2.
Spatial structure.

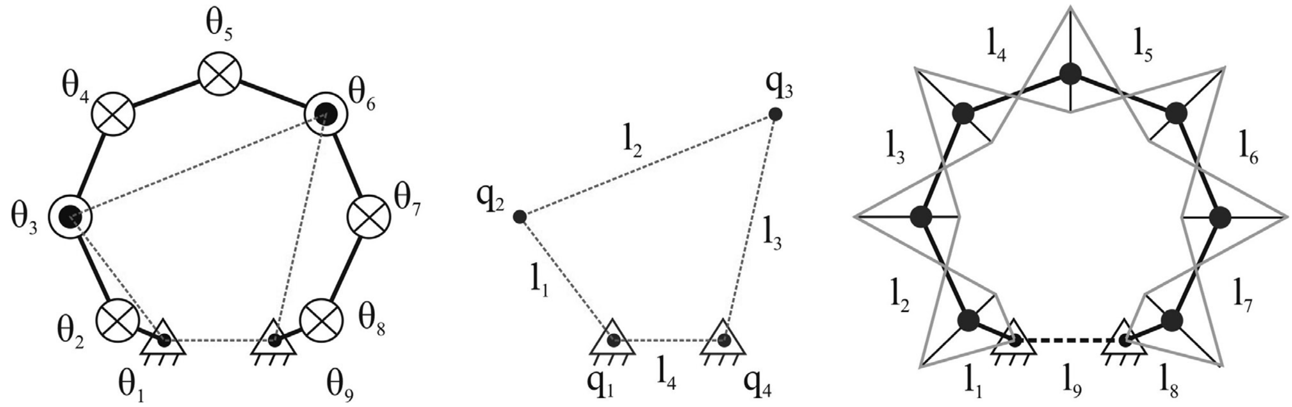

Figure 3.
The effective 4–bar concept (⊗: locked joint, ⊙: unlocked joint, △: pivoted–to–the–ground joint) and the cables actuation approach.

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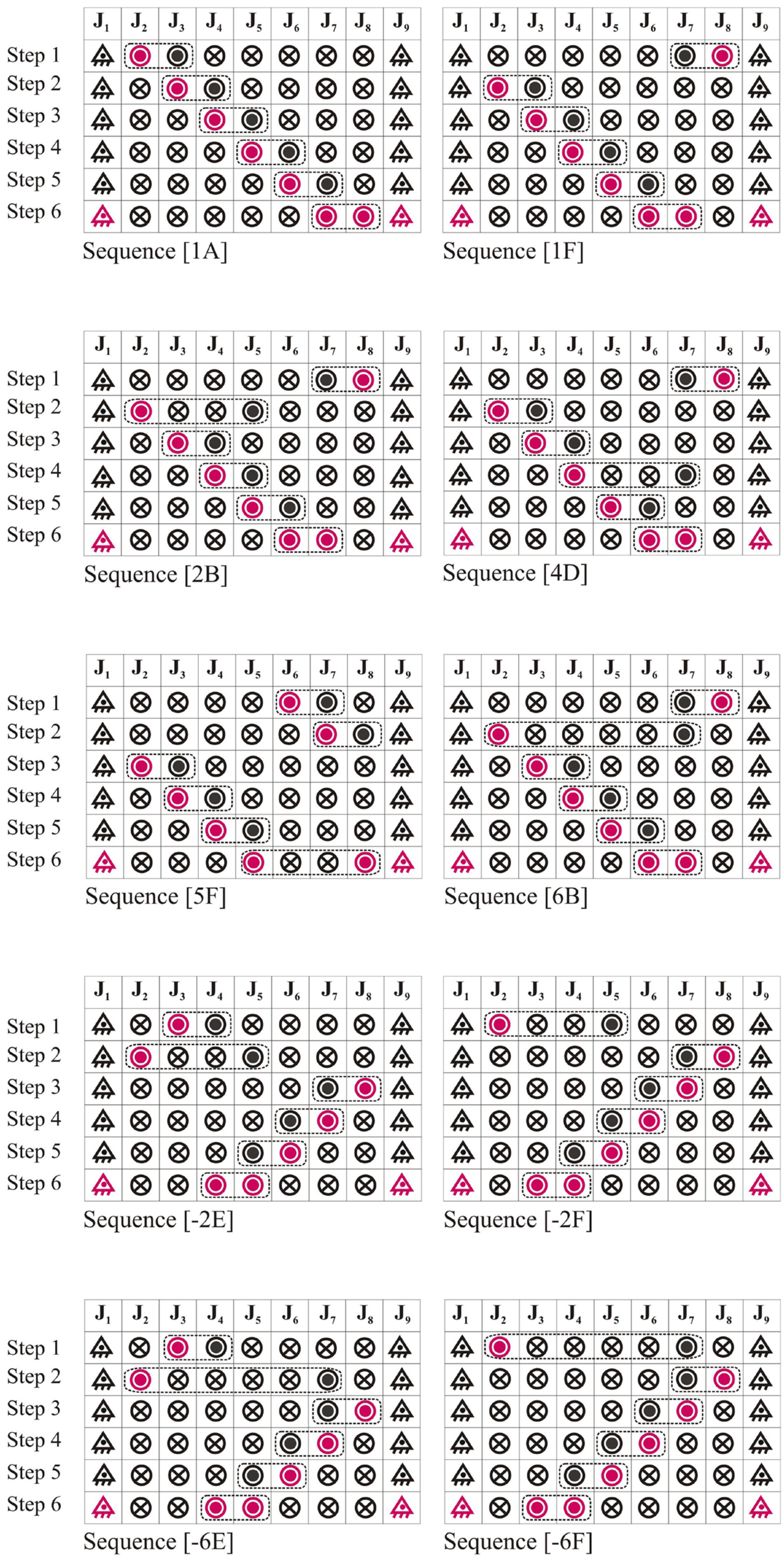

Figure 4.

Feasible control sequences for implementing the required shape adjustment (⊗: locked joint, ⊙: unlocked joint, △: pivoted-to-the-ground joint, symbols in red color represent the currently adjusted joints).

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Motion patterns

The motion planning of the system is based on the E4B concept. The 9–bar linkage configuration considered in the simulation example is composed of perfectly rigid primary members. The initial position (Figure 5, left column) of the symmetric system has joint angles defined by the corresponding joint rotations vector, Θi= [156, 135, 135, 135, 135, 135, 135, 135, 156]T degrees. The target configuration (Figure 5, right column) is given by Θf= [164, 133, 125, 138, 140, 138, 125, 133, 164]T degrees. The link lengths follow the geometrical prepositions of the structural system, their mass amounts to 297.5, 6.0 and 178 kg for each 2.5 m long beam, strut and an approximately 20 m long cable respectively. Given the initial and target configuration of the system, intermediate stages define various possible motion patterns and an optimal one may be selected on the basis of specific criteria, e.g. required actuator forces/torques, tension forces of the cables.

Moreover the following requirements had to be satisfied for the specific prototype simulation example: (i) Both pivoted-to-the-ground joints always remain unlocked; (ii) No link can move below the horizontal ground level; (iii) A flattening of the cables joint angles practically deprives the system from the mechanical advantage required to develop motion of the joint angles. Therefore a respective upper limit of 1750 of any unlocked cable joint angle was set in the analysis for avoiding infeasible sequences; (iv) Any motion sequence, clockwise or counterclockwise, requires two consecutively unlocked joints, or two, or four locked joints between any unlocked ones, so that the cable actions on the primary system do not compete with each other. Taking into account the operability of the system, there exist ten feasible motion sequences of six adjustment steps each, shown in Figure 4. The simulated reconfiguration results for the ten feasible sequence types are shown in Figure 5.

Control criteria

The braking torques in the primary joints, the cables' axial forces and relative length variation between the struts in each motion sequence type prescribe the actuators requirements and provide criteria for selecting the most appropriate sequence. The respective maximum values of the motion sequence types are shown in Table 3. Type F of sequence -2 develops the lowest values of maximum torques. The lowest tension forces of the cables are developed in type F of sequence -6. Types B, F, E and F in sequences 6, -2, -6 and -6 respectively yield smaller variations of the cables' length. Therefore, type F of sequence -2 would be the choice of preference for realizing the reconfiguration case example.

Envelope Structure

At the structure level the envelope should enable optimized lightweight of the material, structural efficiency, capability to cover relative large span spaces with only elastic deformations, without stress interactions with the primary structure (Knippers, et al., 2011). In addition the envelope structure is required to be flexible in order to accommodate for cases of dissimilar configurations assumed by any adjacent n-bar linkages that constitute the primary member structure. In the specific case example, any adjacent THV-membranes, Terpolymer of Tetrafluoroethylene- Hexafluoropropylene-vinylidene fluorid, are interconnected through horizontal double-paraboloid shaped surface elements of higher elasticity. The membrane units have initial overall dimensions in plane of 1.0 x 2.3 m and

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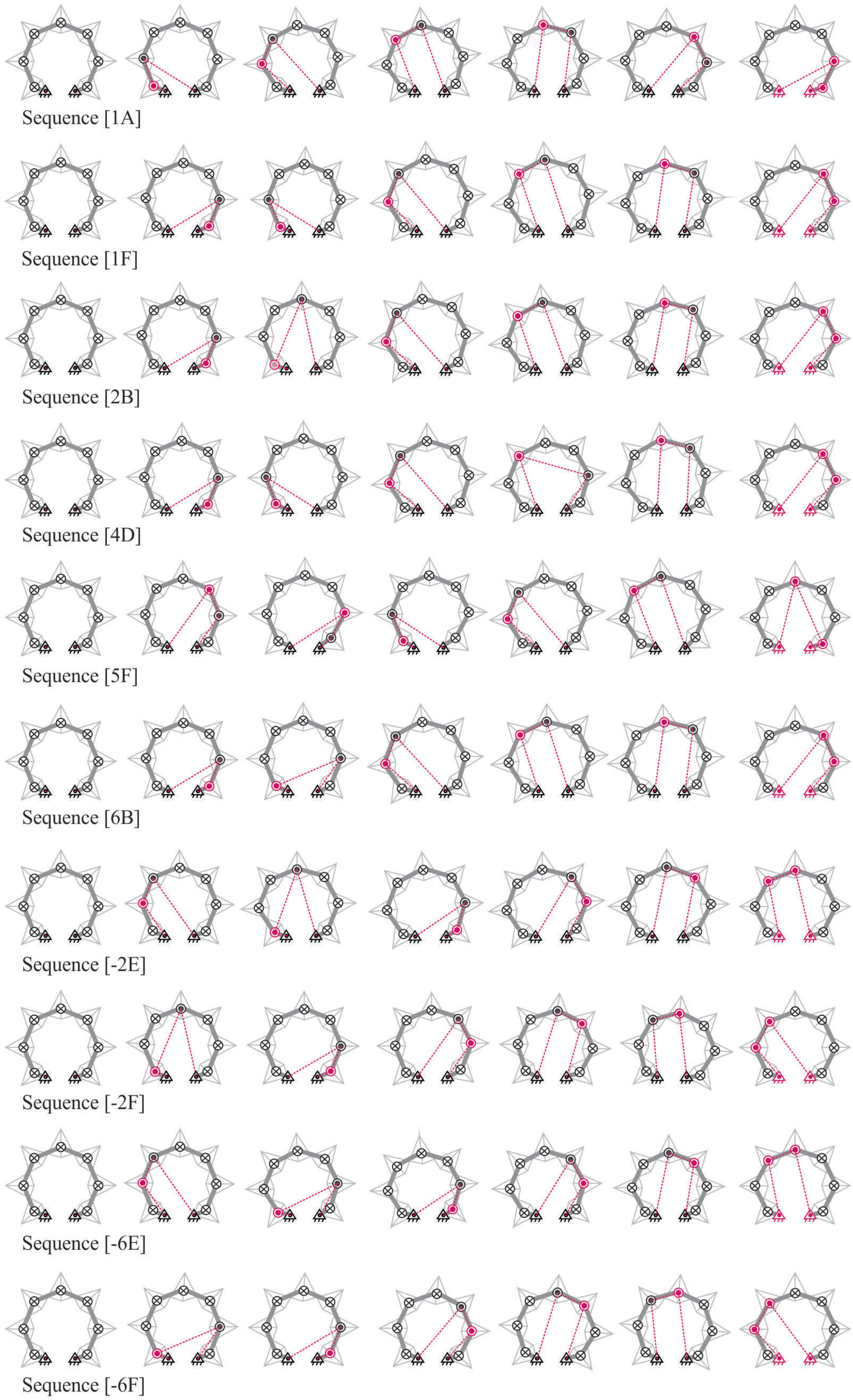

Figure 5.

Simulated stepwise changes of the 9–bar linkage for the required shape adjustment.

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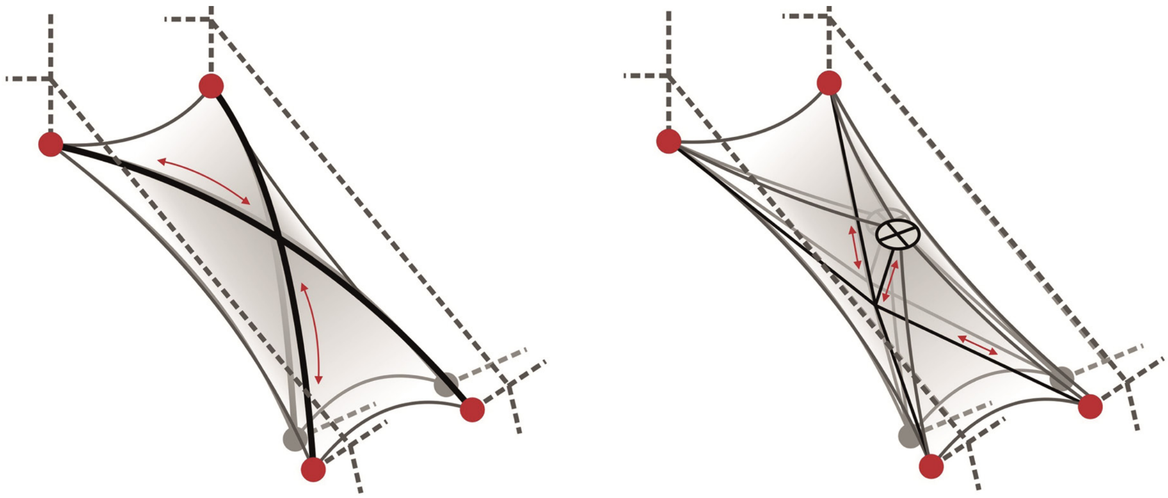

Figure 6.

Adaptable envelope structure concept enabling passive responses to reconfigurations of the primary structure (left) and active control for improving stress conditions in the membrane (right).

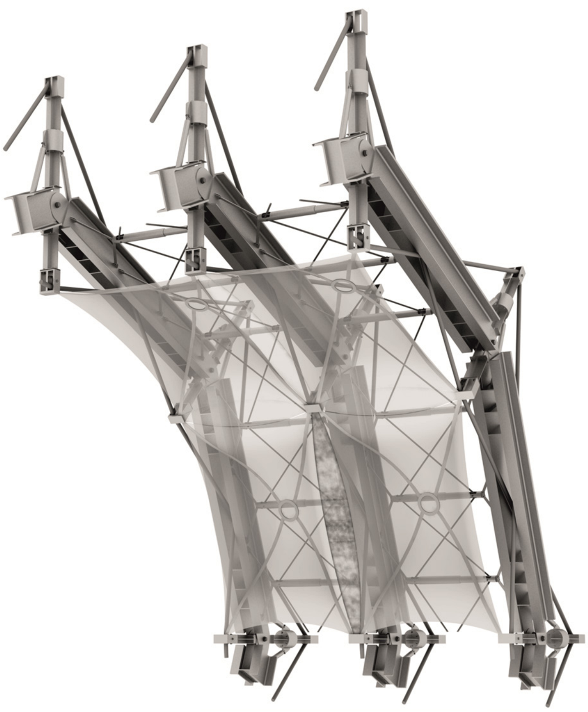

Figure 7.

Passive adaptable envelope system with bending active members.

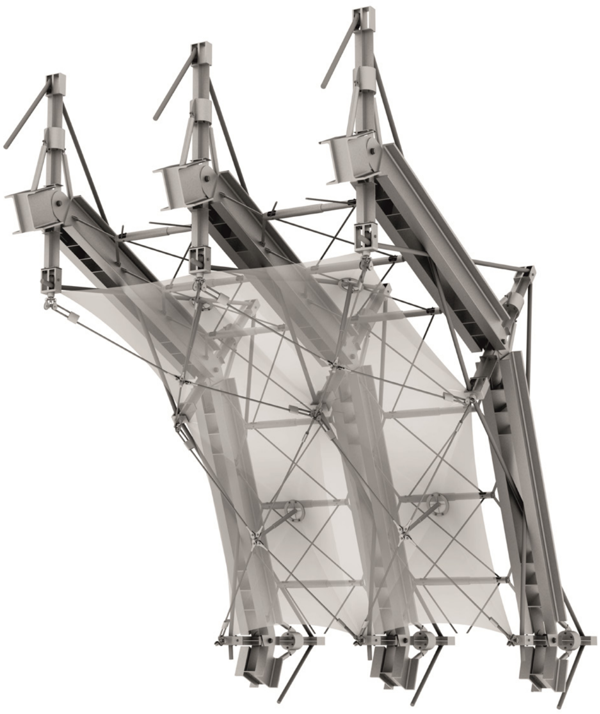

Figure 8.

Active adaptable hybrid envelope system.

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paraboloid curvature radius of 20-25 cm. The envelope system is positioned at a distance of approximately 30 cm underneath the primary structure for preserving continuity in the cover material. The membrane units are to be supported on a dedicated secondary structure rather than being directly affixed to the members of the primary structure. The secondary structure is supported on short-length auxiliary links located at the primary strut joints, and the membrane double curved surfaces, at their edge corners and middle points. Conceptually this means that the envelope system exploits the best structural qualities inherent in the tensile material and therefore the latter becomes an integral part of the envelope system, Figure 6.

Passive Envelope System

Following a passive structural concept, any adjacent strut joints are connected to bending active members that form scissor-type configurations in the horizontal planes. The members are curved on their weak section axis, in the perpendicular direction, so that relative alterations of their projected length induced through the kinematics of the primary members, are followed by their own respective bending deformations, Figure 7. This structural arrangement passively responds to the motion of the primary members. The membranes with double curved saddle shaped surfaces accordingly adjust their shape resulting from the position of their respective point supports.

Active Envelope System

By replacing the bending active members with double curved anticlastic membranes and integrating a secondary system of tension-only members with closed circuit and struts of telescopic tubular steel sections, the membranes act as primary components of the hybrid structure, Figure 8. In any operational mode the hybrid structure acts together with regard to the load transfer. The introduction of axial forces in the secondary members enables a stiffness related decrease of the tensile forces in the membranes. While the primary structures change their shape, the envelope structure will actively respond with a modification of the cables and struts length. Of-course, throughout the transformation shapes of the system each interacting envelope unit may obtain its own initial shape and stress based on its position within the global system. The active system is expected to ensure a uniform stress distribution in the membrane material.

Conclusions

A hybrid structure of hinge connected primary members and a secondary system of struts and continuous cables with closed circuit that inherently enables static operability and kinematic transformability has been presented in the current paper. The interdisciplinary modes of operation followed throughout the prototype development included a parametric analysis of the static systems, construction design of the structural members and connections, motion planning of the kinematics, as well as a conceptual development of the adaptable tensile envelope structure. The synergistic static and kinematic characteristics of the hybrid system and its motion planning through application of the effective 4–bar method provide a reliable and optimized reconfigurable system. The structure may obtain different geometrical reconfigurations according to external criteria of the users and the environment by following the transformation paths specified throughout its motion planning, whereas in between transformation stages from an initial to a target

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configuration define respective temporary transformation phases. Although the transformation phases constitute only transition intervals with regard to the usages of the building, the reconfiguration envelope implies the high flexibility made possible for the transformability of the structure through the control method proposed herein.

Further interdisciplinary work is necessary for the development of automated optimally efficient motion trajectories according to the building operations. This involves also the development of appropriate control system architectures that would indicate the various functions that the system will be required to perform, the functional relationships between them and their hierarchy. The flow and processing of information within the system will also need to be specified for the structure to become interactive. This includes among other, the particular information that the system will expect from its environment, the form in which this information should be provided, as well as the information the system itself will return to the users regarding its current status.

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