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CONCEPTUAL DEVELOPMENT AND KINEMATICS INVESTIGATION OF AN ADAPTIVE BUILDING ENVELOPE PHOTOVOLTAICS SYSTEM

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Abstract. An adaptive lightweight building envelope system with integrated thin-film photovoltaic modules mounted on aluminum substrates is presented in its conceptual development and investigated in its kinematics. A structural unit of a cable net spanning an aluminum frame supports a secondary system of struts and continuous cables responsible for the support of the photovoltaic modules and actuation of the system. Any rotation of the struts through the control cables enables the photovoltaic modules to correspondingly adjust their position to the sun radiation. Several system alternatives are possible through connection of the secondary cables on the aluminum frame and the use of spring elements in reducing the number of actuators required. The development of the system is based on the design of the structural components, and the verification of its kinematics through a series of prototype models in 1:10 scale and an analysis of the planar systems.

Key words: Adaptive Envelope Structures, Hybrid Structures, Motion Planning, Photovoltaics.

1 INTRODUCTION

Presently, the construction sector is still responsible for more than 40 % of the overall energy consumption and provides a significant amount of 25-30 % of all waste generated in the EU. In order to avert this development and achieve a sustainable built environment, CO_2 emissions and recourses use need to be limited while maintaining fiscal growth. Innovative technological

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methods, tools and policies need to be implemented across the spectrum of the industrial activity to reintroduce a circular economy within the construction sector. This constitutes a paradigm shift from the traditional linear flow of materials, i.e., the "take-make-consume-dispose" growth model, toward a sustainable system, that reduces the use of resources, promotes secondary resource use and zeros negative environmental impacts. In this framework, adaptive building envelopes with integrated photovoltaics constitute a promising alternative towards a sustainable architecture development of an upgraded existing and technologically advanced new built environment. Contrary to traditional fixed-shape systems, their adaptability serves adjustments in response to the sun motion for increased energy production, improvement of the building energy efficiency and sun protection [1]. The benefits can have a direct impact on the users' comfort, the building operation performance, as well as the society in general, e.g., energy savings.

The most common approach applied up to date in the conceptual development of adaptive systems with photovoltaic modules is based on transformable tensegrity structures [2]. A transformable skylight tensegrity system of six units with sliding panels of photovoltaic cells and plexiglass substrate is presented at conceptual level in [3]. The individual panels may slide towards the centre of the unit through cable actuation to create an open position. A design solution for the integration of rotating photovoltaic cells to a membrane roof structure is presented in [4]. The transformable tensegrity structure consists of a stable membrane roof and rotating struts in span direction that are interconnected below the membrane over continuous cables of variable length. The struts support photovoltaic cells above the membrane, which follow the path of the sun. The application of tensegrity structures for the design of active solar façades of smart buildings was investigated in [5], and the typological design of transformable units supporting solar panels is presented in [6].

In improving the adaptive behavior of adaptive photovoltaic systems, minimization of the self-weight of the structure and the photovoltaics gain at first place significance. In particular, thin-film photovoltaic modules, such as Cu(In, Ga)Se2 (CIGS), offer the advantage of flexible shapes, low self-weight and life-cycle advantages with regard to the embodied energy [7], when compared to traditional silicon-based photovoltaic modules. Related research results have demonstrated that thin-film photovoltaic modules can attain efficiencies similar to traditional modules [8, 9]. The development of an adaptive solar façade prototype of thin-film photovoltaic modules is presented in [9]. The lightweight thin-film photovoltaic modules placed on aluminum substrates are supported on cantilever elements fixed to a cable net spanning a stainless-steel frame. Soft-pneumatic actuators are integrated into the cantilevers providing rotations of the modules to attain various positions. The specific prototype development constitutes a first example of an adaptive building envelope photovoltaic system, even though, based on multiple actuators embedded within the system.

In further improving the adaptive envelope system, a reduced number of embedded control components and actuators is required, as well as maximization of the flexibility and controllability of the system [10]. Further practical challenges include the design of the structural joints and related constraints of the actuators to be employed [11]. In reflecting these aims, the current paper refers to the conceptual design, experimental verification and kinematics analysis of an adaptive unitized prototype envelope system with integrated thin-film photovoltaic modules placed on aluminum substrates. The system shape and the photovoltaic modules orientation adapt to the sun movement, in optimizing energy production and under certain circumstances, daylight (shading) performance. The conceptual development of the prototype system is based on four design alternatives that reflect on the process in achieving increased structural simplicity, flexibility in the kinematics and a minimum number of actuators. The next section describes four design alternatives and presents the corresponding structural components assembly. The following section refers to the physical prototypes of the system in small scale 1:10 and highlights practical implementation issues on the kinematics of the designs. This section is followed by a kinematics analysis of two basic planar systems. The last section of the paper includes the conclusions of the study.

2 SYSTEM CONFIGURATION

A lightweight structural unit of a cable net spanning an aluminum frame supports a secondary system of struts and continuous cables responsible for the support of the photovoltaic modules and actuation of the system, as shown in Fig. 1 for an initial system position corresponding to absolute vertically facing photovoltaic modules. The structural unit has axial dimensions of 540 cm width and 365 cm height. It contains twenty photovoltaic modules of 66 cm width and 50 cm height each. The secondary cables are responsible for the actuation of the system through their own relative length modification in providing respective rotations of the struts on the two orthogonal planes, i.e., vertical and horizontal plane. Since the photovoltaic modules are rigidly connected to the strut components, any rotation of the struts enables the photovoltaic modules to correspondingly adjust their position to the sun radiation. Practically, same positions of all photovoltaic modules on each orthogonal plane correspond to parallel sun rays prevalent on site. Therefore, all parallel actuation cables suffice to modify their length equally within the system for any uniform inclination of the photovoltaic modules to be obtained. This condition relates to the objective for a reduced number of actuators to be employed on the structure, so that the self-weight of the lightweight system is practically preserved in its kinematics. In this framework, different system alternatives investigated in the preliminary design phase refer to the secondary cables' configuration, their connections on the aluminum frame sections and the control components employed.

The basic configuration refers to pairs of rotating actuator units and pulleys installed at both ends of each secondary cable, on each side (front and back side) of the structural unit, S01, Fig. 1a. In this basic system configuration, each secondary cable is independently controlled in its length through the associated stepper motor. A total number of twenty actuator units would be required on each side of the structural unit. The number of actuator units is reduced, when each pulley row on each side of the structural unit is interconnected and their rotations are provided by an axis of rotation element controlled at one end by a single rotating actuator, S02, Fig. 1b. In this system alternative, all parallel secondary cables on each side of the structural unit are collectively controlled in their length through the associated stepper motor. A total number of four actuator units would be required on each side of the structural unit. Further reduction of the number of actuator units is possible, when both corresponding secondary cables on each side of the structural unit comprise a single cable element and all parallel ones on both sides of the structural unit are actuated together, S03, Fig. 1c. The secondary cables are wound up around a pair of pulleys at one end with reverse relative rotations and routed over a single pulley at midcourse. The pulley pairs in each respective row are interconnected and their rotations are provided by an axis of rotation element controlled at one end by a single rotating actuator. A total number of two actuator units would be required for the structural unit.

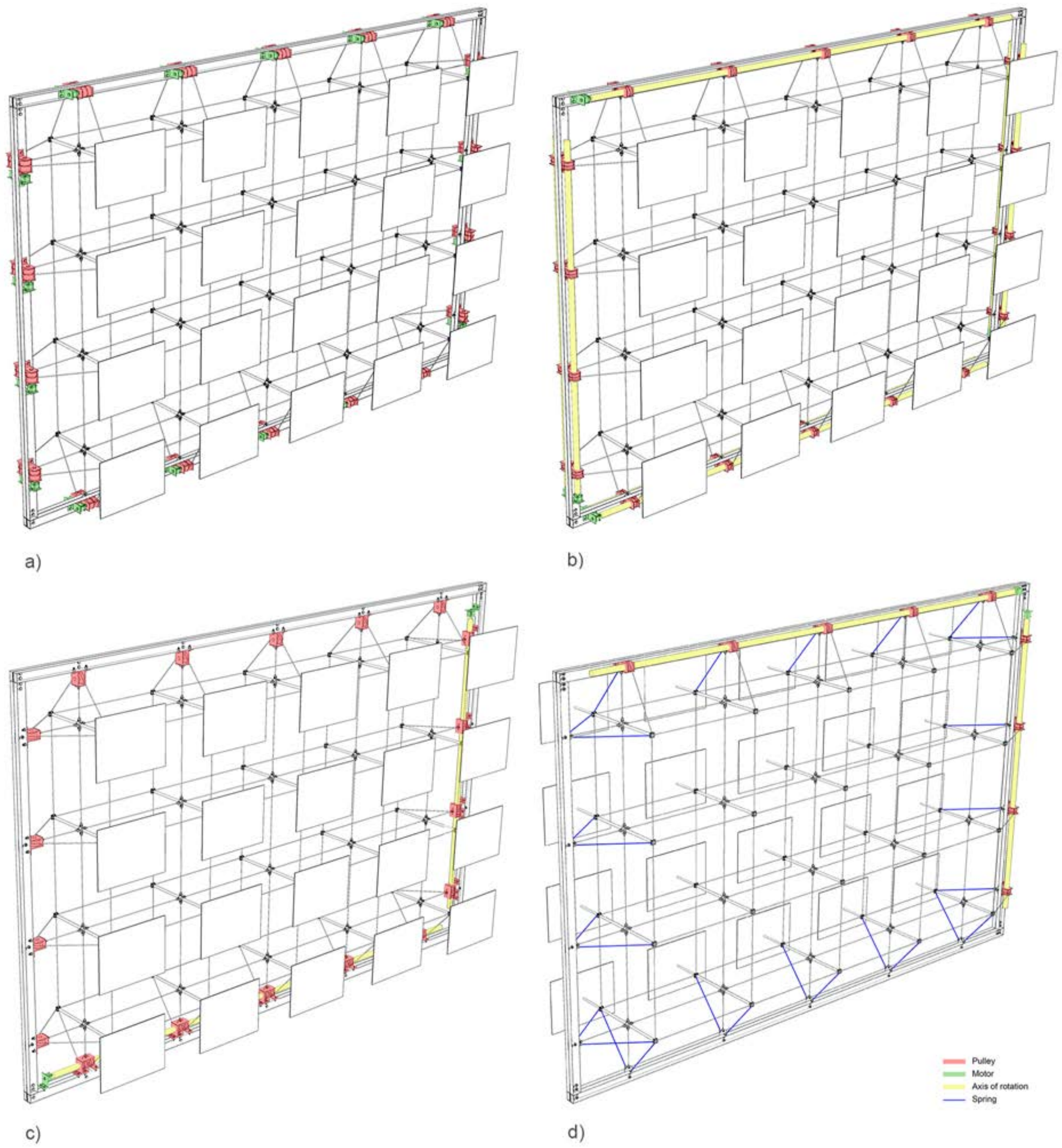

Figure 1: System design typologies: a) S01 with secondary cable segments associated to single pulleys and

actuator units at each end; b) S02 with interconnected pulleys through axis of rotation elements and single actuator units, c) S03 with secondary cables and pulleys pairs with reverse relative rotations and interconnected pulleys, d) S04 with spring elements and interconnected pulleys (rear view)

A further system alternative is possible based on the use of spring elements, S04, Fig. 1d. In this case, each secondary cable is anchored to the frame section of the structural unit at one end, and wound up around a pully at the other end. The first segment of the cable, spanning between its anchorage to the frame section and the first strut is replaced by a spring element. The corresponding cable on the other side of the structural unit is anchored to the frame section of the structural unit at both ends, while both, initial and last respective segments of the cable are replaced by spring elements. Again, the interconnection of the pulleys in each respective row and their collective rotations by an axis of rotation element are controlled at one end by a corresponding single rotating actuator. As in the previous system alternative, two actuator units are required for the structural unit.

2.1 Structural and Control Components Design

The design of the structural and control components and their connections is based on a modular composition of the prototype system, in order to enable its easy assembly and disassembly. The primary frame members of the structural unit consist of double UPN 80x40x5 mm aluminum sections placed back-to-back to enable easy connectivity of the primary members and the cable net through connecting steel plates inserted in-between. The primary members of the structural unit are interconnected through steel plates inserted at the joints' areas of the frame. The cable net with 5.0 mm cables' diameter is anchored to steel plates inserted perimetrically in-between the primary members in S1, S2 and S4, and connected to the encasement elements of the pulleys in S3. The cable net is connected at the cross points to ball-in-ball joint elements. The struts consist of aluminum round hollow sections of 60/4 mm dimensions and have a total length of 1.0 m. They are composed of two members of 37.5 and 62.5 cm length each, with one end connected to the inner ball element of the joint elements and the other end over cable clamps, to the secondary cables of 10 mm diameter and variable length and the photovoltaic modules respectively, Fig. 2a. The struts joints to the secondary cables on both sides of the structural unit are at 75 cm axial distance to the central ball-in-ball joints. The photovoltaic modules are supported at a distance of 25 cm to the equilateral joints of the secondary cables to the struts. In all system alternatives, the rotating actuators are directly placed on the primary frame sections in preventing any self-weight increase of the lightweight system. Each system alternative is appropriately configured to implement the actuation method corresponding to the secondary cables configuration and their connections, as well as the control components employed.

In the basic system configuration, S01, individual pulleys of 80 mm outer diameter are connected to the primary section webs on both sides over steel angles. The rotating actuator units are placed next to the pulleys and interconnected to the latter through the axis of rotation elements. The actuator units are supported by steel angles connected to the primary section webs, Fig. 2a. In S02, the pulleys in each row are interconnected through an axis of rotation element of 50 mm diameter that passes through the elements and is connected to a single actuator unit at its end. The actuator units' configuration and connections are similar to the previous system, Fig. 2b.

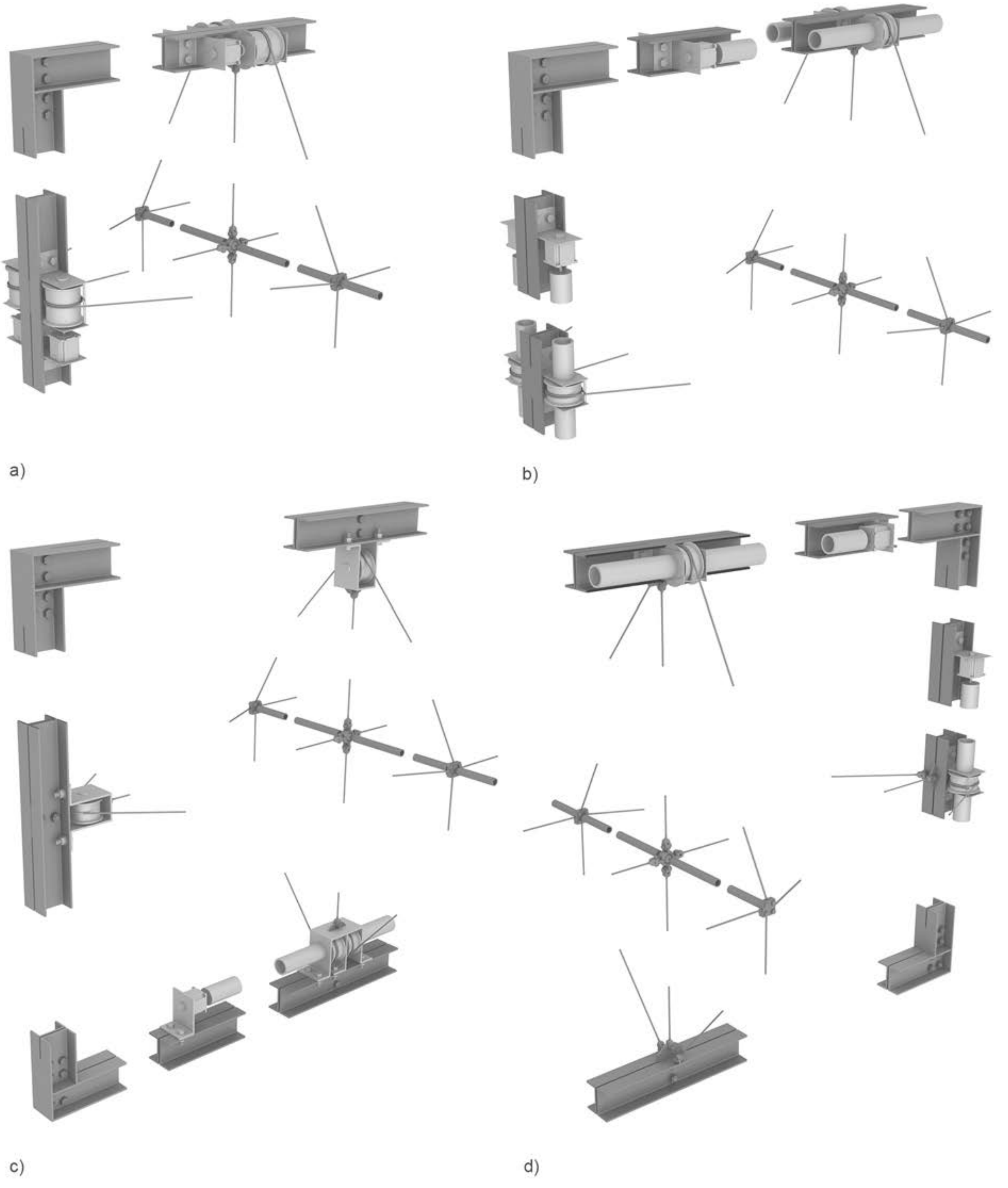

Figure 2: Structural and control components design: a) S01; b) S02; c) S03; d) S04 (rear view)

In S03, the pulleys are placed on the inner side of the structural unit. They are supported on steel frame elements that are connected to the flanges of the primary sections. The cable net is anchored to the encasement elements of the pulleys. Additionally placed on the inner side of the structural unit are the actuator units and the corresponding axis of rotation elements. The actuator units are supported by steel angles connected to the flanges of the primary sections, Fig. 3c. In S04, the spring elements are anchored to the flanges of the primary sections and the pulleys are connected over steel angles to the webs of the primary sections, according to the design connections in S02. The actuator units' configuration and connections are also similar to S02, Fig. 3d.

3 PHYSICAL MODELING

The three system alternatives with reduced number of actuator units, namely S02, S03 and S04, were realized in prototype models in scale 1:10, Fig. 3. Aim of the experimental study was to demonstrate the feasibility of the concept, gain an insight in the kinematics of the systems and highlight practical implementation issues. The models are based on a modular composition of the components to enable easy assembly and disassembly and were appropriately configured to implement the system alternatives. The primary frame and the connecting parts of the pulleys consist of full rectangular wood profiles, while the struts and rotating axes, of full round wood profiles. The pulleys consist of polymeric material and were 3D printed. The photovoltaic modules are made of rectangular cardboards. Synthetic rope was used for the primary and secondary cables passing through the pulleys that bends easily and is practically inextensible. The cables are simply routed through the struts, the pulleys and rotating axes to establish their corresponding connections. The kinematics of the systems was managed manually through rotations of the respective rotating axis elements.

Figure 3: Isometric view of experimental systems S02, S03 and S04

S02 proved to be straight-forward in its kinematics, provided that no friction develops in the pulleys of the system. The high degree of flexibility as to the individually controlled secondary cable segments on both sides of the structural unit has rather limited benefit for the given task, i.e., pulling of the parallel cable segments on one side of the structural unit, requires that the respective members on the other side are also actuated to remain stretched throughout the process. This is to be managed by the actuator pairs employed on both sides of the structural unit. In actual scale conditions, position accuracy is to be provided through a closed-loop controller with direct position sensory feedback on the joints of the system.

Unification of the associated secondary cable segments of the structural unit to single cable elements and collective actuation of all parallel ones on both sides of the structural unit, as followed in S03, enables respective reduction of the actuator units employed. This case evidenced to the most for the secondary cables to remain stretched. Following rotation of the axis element, a slight pulling of the associated cables was necessary, so that they could be correctly wound up around the pulleys. In actual scale conditions, pretension in the cables is necessary, in order to prevent slack of the members during the transformation process and ensure smooth transition between consecutive positions of the system.

In S04, the spring elements' mechanical characteristics are decisive for the kinematics of the system. Rotations of the photovoltaic units in one direction involve elongation of a single spring element and respective contraction of the other two for each corresponding secondary cables pair, and vice versa. The initial position of the system is ensured through stiffness tuning of the spring elements. The latter relates to the self-weight of the elements and is further on decisive for providing equilibrium of the photovoltaic modules in their respective positions. In actual scale conditions, the cable elasticity is also expected to have a coupling effect on the kinematics of the system.

4 KINEMATICS ANALYSIS

The planar vertical system alternatives S02 and S04 were analyzed it their kinematics with the software program Working Model 2D, Figs 4, 5. The struts are pin connected at their actual connection points to the cable net. The secondary cables pass through the strut ends and the pin supports of the system defined below and above the struts. In S02, one of the secondary cables is connected at its lower end to an active linear actuator that is responsible for the kinematics of the system through its displacements. The other secondary cable is connected at its upper end to a linear actuator that exerts a force of 1N, in order for the cable to remain stretched throughout the process. The remaining two ends of the secondary cables are connected to spring elements of stiffness characteristics of 10 kN/m. In S04, the three end segments of the secondary cables are replaced by spring elements of stiffness characteristics of 5 kN/m that are directly connected to the lower and upper pin support of the planar system. Thus, in S02, the support elements of the secondary cables, while in S04, the spring elements are responsible for the equilibrium of the system in any discrete rotational position of the struts. In both cases, a respective displacement of the active actuator results in pulling of the secondary cable for inducing rotation of the struts. Thus, in each reconfiguration step, the struts target angle is obtained through the corresponding actuator's displacement according to its initial position.

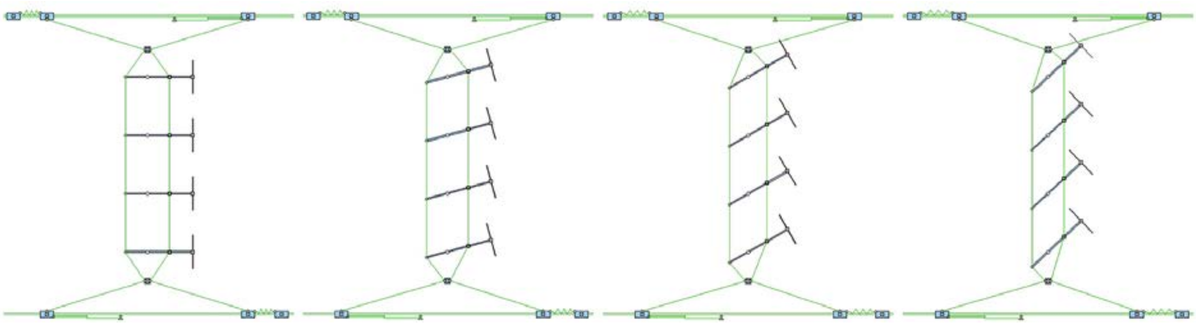

Figure 4: Kinematics model of system S02 in its initial position and struts target rotational position of 15, 30 and 45° degrees to horizontal axis

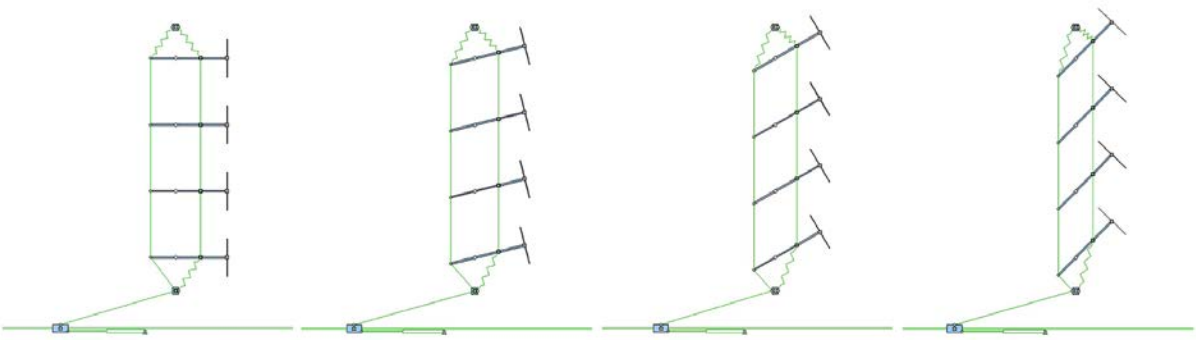

Figure 5: Kinematics model of system S04 in its initial position and struts target rotational position of 15, 30 and 45° degrees to horizontal axis

The analysis considers the self-weight of the members and their mechanical characteristics (i.e., aluminum sections of 69.6 GPa elastic modulus and 241.3 MPa yield strength, cables assigned to steel S450 of 24.82 GPa elastic modulus). The analysis was based on numerical integration of the model, based on the Kutta-Merson method. The respective time step was automatically adjusted during the simulation. The kinematics of the system were examined from an initial horizontal configuration of the struts to three discrete positions corresponding to a respective parallel anticlockwise rotation by 15, 30 and 45° degrees. The analysis results for all three reconfiguration steps of the systems are presented in Table 1.

Table 1: Kinematics analysis results of the vertical planar systems S02 and S04; Struts angle position (P), maximum actuator displacement (Δl_{max}), actuator power (P_{max}), cable axial force ($N_{c,max}$), spring axial force ($N_{s,max}$)

System	P [degrees]	Δl_{max} [m]	P_{max} [W]	$N_{c,max}$ [kN]	$N_{s,max}$ [kN]
S02	0-15°	0.08	216.78	4.11	-
	0-30°	0.17	216.78	7.35	-
	0-45°	0.26	216.78	9.76	-
S04	0-15°	0.08	95.07	3.12	1.67
	0-30°	0.17	95.07	5.39	3.36
	0-45°	0.26	95.07	7.74	5.01

The actuator displacements for the respective strut target angles are independent of the system employed. The maximum power of the actuator required for the members rotation develops already in the first step for both systems, S02 and S04. The maximum power of the actuator in S02 is by 128 % higher compared to S04. These values are indicative for the required capacity of the actuator to complete the reconfiguration task in each respective step. The maximum active cable force increases according to the strut target angle opening. While in the initial reconfiguration step, a maximum cable tension force of 4.11 and 3.12 kN develops in S02 and S04 respectively, the maximum inner force in S02 increases by 36 and 26 % compared to the one in S04 by the completion of the second and third reconfiguration step respectively. The maximum spring axial force in S04 amounts to 54, 62 and 64 % of the inner cable force in S04, in each corresponding step. The kinematics analysis proves that S04, which is characterized by higher simplicity in its composition and components employed, also has lower requirements with regard to the actuator work and the tension forces in the active cable. Of-course, the results of this preliminary analysis depend strongly on the stiffness of the spring elements set. A calibration of the respective stiffness values requires consideration of the load-deformation behavior of the structural system under wind-loading acting on the photovoltaic modules.

5 CONCLUSIONS

The present paper refers to the conceptual development of an adaptive unitized prototype envelope system with integrated thin-film photovoltaic modules placed on aluminum substrates. The development of the prototype system aims at achieving simplicity, flexibility in kinematics and a reduced number of actuators employed. Four design alternatives have served as representative for the development of the system, with regard to its composition and kinetic behavior, which has been initially investigated in small scale physical prototypes. A kinematics analysis of two basic planar systems referred to the mechanical requirements on the actuators and the active cables. The current study demonstrates the feasibility of the kinematic concept and provides a comparative assessment of the structural behavior of the system alternatives. Furthermore, the prototype system is envisaged to provide mass-customization and optimum designs with regard to architectural, structural engineering, kinematics, control and energy performance criteria leading to an affordable and widely received technology towards a sustainable built-environment.

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