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Design, motion planning and control of a reconfigurable hybrid structure

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ABSTRACT

Compared to traditional fixed-shaped structures, reconfigurable structures may provide various advantages with regard to space utilization, building form optimization and energy efficiency. The purpose of this study is to present the development and kinematic behavior of a reconfigurable hybrid structure. Hinge-connected beam members, stabilized through a secondary system of struts and continuous diagonal cables compose planar n-bar mechanisms arranged in parallel to formulate the spatial reconfigurable structure. The transformability of the system is based on the application of the 'effective 4-bar' concept using a sequence of 1-DOF motion steps through selectively locking $(n-4)$ joints of the primary members and modification of the cables' length. Different intermediate configurations depend on the motion planning, in order to adjust the system's joints to the desired values during the motion steps involved in the respective transformation sequence. The proposed control system includes position sensors installed on the individual joints to provide feedback information, two motion actuators located at the structural supports, as well as brakes installed on each individual joint. The control system manages the operation of the motion actuators and the brakes to realize the reconfiguration sequences through tensioning the cables. The paper reports the structure's design concept, motion planning and control. The implementation of the structural reconfiguration approach and related kinematics issues are investigated through a simulation example.

1. Introduction

The significance of buildings with variable geometry that adapt in response to external loading, functional and environmental conditions, has been widely acknowledged. At the same time, technological advances that took place in recent years have enabled kinematics to be implemented and tested in functioning prototypes for reconfigurable structures, which can adjust their shape [1]. Reconfigurability of structures establishes a framework that enables customization and optimization. In general, reconfigurable structures combine two elements: the structural system that may assume different geometrical configurations and the control system that implements the specified transformations.

In structural terms, minimum self-weight is directly related to aspects of structural modularity, connectivity, loading, and shape. In this respect, of special interest are tensegrity structures, i.e. self-stressed systems composed of tension and compression members [2]. Tensegrity structures combine mutually supportive parts in a way that the compression members do not directly contact one another, but press outwardly against nodal points in the tension network to form firm, triangulated, prestressed tension and compression units [3]. Such structures have the ability to transform in space and to enable optimized conditions in load transfer. Furthermore, more efficient tensegrity structures can be achieved, if their compression members are allowed to join [4].

Tensegrity structures may further lead to hybrid systems. In principle the latter are defined through connection of different components in parallel and/or in series, combined to resist forces by developing a specific mechanical behavior due to their different resisting nature [5]. 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 opposing systems deformation [6].

Kinetic systems have been studied during the past 25 years in the context of deployable structures. Relevant developments were primarily motivated by the need for space structures that can be compacted for launch and then deployed in space [7]. Deployable tensegrity structures may be transformed from a closed configuration to a predetermined expanded form in which they are stable and effectively transfer loads [8]. The transformation is achieved via alteration of the compression or tension members' length

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without consuming a lot of energy due to the systems' kinematic indeterminacy [9,10]. Relevant studies on the analysis of deployment mechanisms, folding concepts and shape control based on stress analysis are included in [11–14]. In general, control of the compression members becomes difficult to implement when the internal forces of the members are substantial and the required shape adjustments of the system are large. Furthermore, when actuation of the compression members is applied for deployment purposes, the structure may have no stiffness until it is fully deployed [15]. Therefore, alteration of the tension members' length proves to be a rather practical deployment method [16]. Symmetrical reconfiguration procedures in tensegrity structures through cable and torque control are presented in [17], and control of all cables of the structure based on the existence of an equilibrium manifold is described in [18].

Other common types of deployable structures include planar and spatial scissor-hinge elements. These have the ability to expand in both a horizontal and a vertical direction [19–21]. While such structural elements need additional stabilizing members like cables or other locking devices, self-stable structures can be achieved with the application of special geometrical configurations through additional inner scissor-like elements. A considerable advance in the design of such systems was made with the development of the simple angulated element and its geometrical principles [22,23]. However, scissor-like elements do not provide extensive flexibility, since their motions are limited between their open and closed states. In general, both tensegrity and scissor-like elements are not capable to achieve multiple shapes without altering the overall system's geometrical size and boundaries. A novel planar and spatial scissor-hinge mechanism that provides permanent structural transformability is proposed in [24,25].

In principle, the development of lightweight structures to obtain kinetic capabilities is primarily based on systems with articulated joints and embedded mechanical actuators [26]. 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 [27]. The resulting outrigger system of rhomboid-shaped core units and vertical interconnecting tension-only members provides different spatial bending shapes through dampers integrated at the joints. An adaptable structure with integrated hydraulic actuators as primary diagonal compression members is the planar truss with lower horizontal elastomeric tubes, presented in [28]. Further proposals in this direction are based on the 'Variable Geometry Truss' concept, a planar or spatial member structure with embedded hydraulic actuators [29], an adaptable aluminum tensegrity structure [30], and a tetrahedral truss with a number of actuator diagonals of shape memory alloy [31]. In the prototype of the 'Muscle Tower' composed of six actuated trapezoidal, vertically positioned tensegrity units, the actuators are in place of the tension members [32]. The structure demonstrates high flexibility to possible elongation, shortening and rotation of its units. Active tensegrity structures consisting of struts and cables are further analyzed in [33–36].

Although structures with embedded actuators in place of primary joints or members are usually designed to use a small number of components to achieve a maximum number of shape adjustments, implementation requires designers to deal with an increase of the structure's weight (depending on the number and characteristics of the actuators used), complex mechanisms and energy-inefficient operation. Minimization of the number of embedded actuators may be achieved through the so-called strut-routed actuation [37,38]. The actuators are linked to the active elements by running continuous cables through a series of connected struts and pulleys at the nodes. This strategy has the advantage of migrating the actuators outside of the structure, in order to prevent the additional mass and element size constraints of embedded actuation. Further improvements are possible by employing continuous cables and spring elements [39]. A deployable pentagonal tensegrity ring structure involving actuation of continuous cables and spring elements is studied analytically and experimentally in [40]. In general, application of continuous cables in tensegrity structures becomes less desirable as the number of controlled members increases, i.e. numerous active cables need to be routed through the same strut paths, and the issue of connection spacing becomes critical. The concept of continuous cables in tensegrity structures is only feasible with bar-to-bar connections [37].

From a control perspective, performing structural reconfigurations requires an appropriate control system with actuators, feedback sensors, as well as suitable motion planning and control algorithms. As the reconfiguration motions will make efficient use of resources, such as drive power, implementation of optimal control becomes relevant [15,41,42]. Direct analogies from the field of robotics involve well-established techniques used for the kinematic analysis and control of multibody articulated systems. Therefore, robotics may provide a framework for the analysis and control realization of reconfigurable structures. Robotically adjustable structures where not only the configuration but also the actual morphology of the system can change, were discussed in [36].

The design and analysis of a planar reconfigurable hybrid structure with hinge-connected members and continuous cables presented in the current paper is an extension of the aforementioned considerations, and aims at achieving conceptual simplicity on the structural typology and reduced energy consumption during reconfigurations. This work focuses on key aspects related to structural composition, load-bearing function, kinematics and control, all of which will constitute the basis for a practical implementation of the reconfigurable system. The development of reconfigurable structures requires a multidisciplinary design approach that combines various scientific aspects including architecture, structural engineering, kinematics and control.

The reconfigurable structure presented herein builds upon adaptable architecture concepts as well as approaches to motion planning and control of multibody systems previously developed by the authors [43–45]. The proposed structural system consists of hinge-connected beams and a secondary system of struts and cables, as described in the following section. A basic kinematics element of the system is the n-bar linkage, the characteristics of which are exploited for control purposes as detailed in Section 3. Following the proposed control concept, reconfigurations are performed based on appropriate control sequences, which is the topic of Section 4. The implementation of the reconfiguration approach is investigated through a simulation example in Section 5. Concluding remarks are provided in the last section of the paper.

2. Structural system

The basic reconfigurable structural system is a planar n-bar mechanism. A parallel arrangement of such systems forms a primary skeleton structure that supports a flexible membrane defining the building envelope, as shown in Fig. 1. The configuration of the individual n-bar linkages defines the overall shape of the building. Considered herein is an example of a mechanism composed of eight beams, interconnected with rotational joints that, together with the ground formulate a 9-bar linkage moving on the vertical plane. The overall span of the system is 17.5 m.

Preliminary investigations of the system's behavior were carried out through parametric nonlinear static analysis of different typologies, with regard to the geometrical and mechanical