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On Control Strategies for Responsive Architectural Structures

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Summary
The present paper considers control of responsive architectural structures for improvement of structural performance by recognizing changes in their environments and loads, adapting to meet goals, and using past events to improve future performance or maintain serviceability. The general scope of the paper is to discuss control strategies for responsive architectural structures, particularly reconfigurable architectural structures which can transform body shape, i.e. a transformation into more than one or two different shape alternatives.

Keywords: *kinetic structures, responsive architecture, control, multi-body dynamics*

1. Introduction

Responsive architectural structures follow a new trend emerging in architecture related to the physical movement of structural building elements that can result to the spatial movement of a structure as an entirety or just part of it. More particularly, this kind of architecture can be defined as buildings and/or building components with variable mobility, location and/or geometry. Structural solutions must be considered in parallel both the *ways* and *means* for kinetic operability. The *ways* in which a kinetic structural solution performs may include among others, folding, sliding, expanding, and transforming in both size and shape, see e.g. *The means* by which a kinetic structural solution performs may be, among others, pneumatic, chemical, magnetic, natural or mechanical. Shape control within architectural kinetic structures is a natural extension to the practice of engineering and architectural design. The knowledge needed for this builds upon two well understood foundations: 1) the long existing knowledge that building performance and function are intimately connected to the shape of built spaces; and 2) the relatively new idea that embedded computational systems may be employed to control shape in useful and beautiful ways. Structural shape control is of major interest within responsive architecture because it is the primary ingredient needed to produce building envelopes that change shape. The term *responsive architecture* was coined by Nicholas Negroponte in the late 1960s, when he proposed that architecture would benefit from the integration of computing power into built spaces and structures, and that better performing, more rational buildings would be the result. Little further work in the area was undertaken until the late 1990s when interest in tensegrity grew considerably. However, applications had more to do with the aesthetic shape of the building rather than it's functioning [1-4]. Research in the area of responsive architecture has had far more to do with the building structure itself, its ability to adapt to changing weather conditions and to take account of load, light, heating etc. This could theoretically be achieved by designing structures consisting of rods and strings which would bend in response to wind, distributing the load in much the same way as a tree. The present paper will consider shape control of responsive architectural structures. Control strategies that enable a structural shape to be moved and changed will be discussed. In order to reconfigure a structure from one shape to another, the forward and inverse kinematic problems will be considered.

2. Responsive architectural structures

Generally, kinetic structures in architecture can be defined as buildings and/or building components with variable mobility, location and/or geometry [5-7], i.e. kinetic architecture can refer to buildings or structures with variable location or mobility such as portable buildings like caravans, tents and prefabricated barracks [5-7]. However, it can also be buildings or structures with variable geometry or movement, i.e. soft form buildings with transformation capacity made by membrane structures, cable-nets pneumatic structures, or rigid form buildings with deployable, foldable, expandable or rotating and sliding capacity of rigid materials which are connected with joints [8,9].

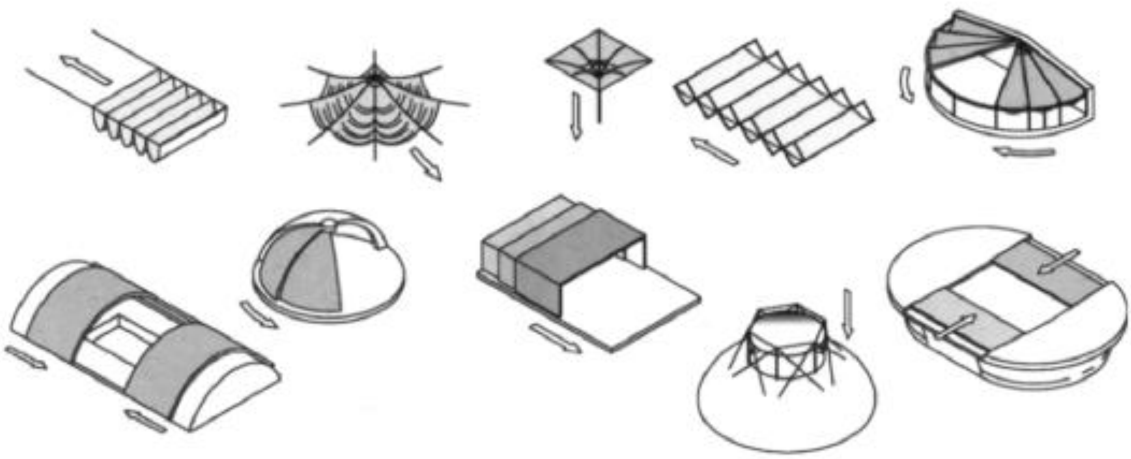

Figure 1: Types of various kinetic systems (Güçyeter 2004).

Kinetic structures can also be classified according to their structural system. In doing so, four main groups can be distinguished: spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, strut-cable (tensegrity) structures and membrane structures [10,11]. Much research has been done with respect to improve the efficiency of these kinetic structural systems which can facilitate a flexibility in building design and give rise to a search for responsive architecture which can physically convert themselves to adapt to the ever-changing requirements and conditions [1,3-4,10-11]. This could theoretically be buildings consisting of rods and strings which would bend in response to wind, distributing the load in much the same way as a tree. Similarly, windows would respond to light, opening and closing to provide the best lighting and heating conditions inside the building.

Kinetic structures can be defined as an *open-closed* or *extended-contracted* body shape, i.e. transformations occur between two body shapes [1,7] based on scissor-like elements such as those proposed by the key designers/researchers [12-14]. However, proposals for adaptive kinetic structures using scissor-like elements have been given, i.e. structures where transformations occur between more than two different shapes to constitute more flexible shape alternatives [2,15-16].

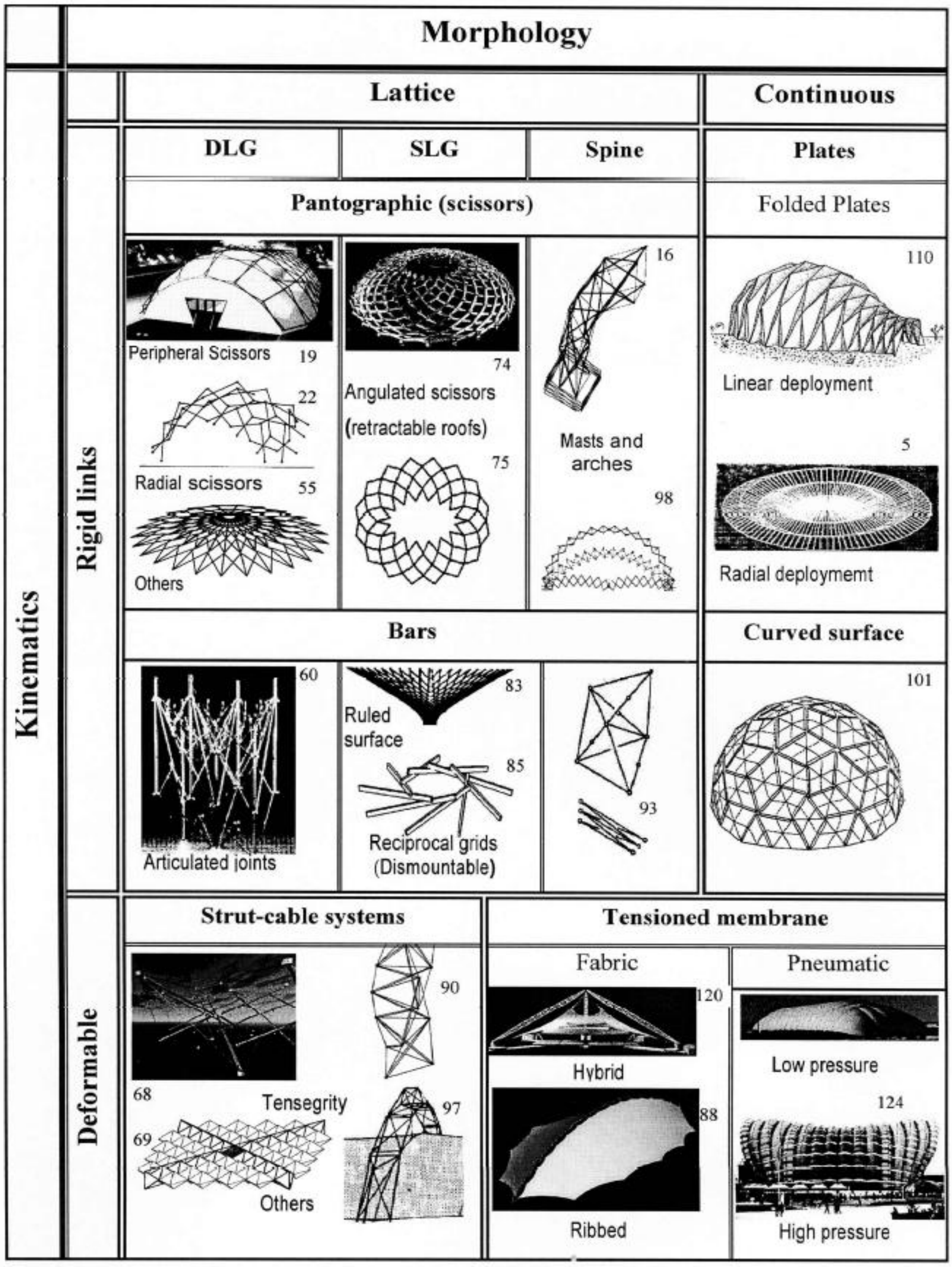

Figure 2: Deployable structures. Numbers indicate references in [10].

Tristan d'Estree Sterk of "The Bureau for Responsive Architecutre" and Robert Skelton of UCSD in San Diego have been working on shape-changing building envelopes using actuated tensegrity structures, i.e. a system of rods and wires manipulated by pneumatic "muscles" that serve as the building's skeleton, forming the framework of all its walls [2,3]. Within the projects sensor/computer/actuator technologies are used to produce a series of intelligent kinetic building envelopes that seek fresh relationships between ´building` and ´user`. These responsive buildings are covered by skins that have the ability to alter their shape as the social and environmental conditions of the spaces within and around each building change, see figure 3. New, more personalized relationships with space will inspire fresh interpretations of architecture. Finally relationships that emerge from the juxtaposition of experimental performance and responsive architecture could lead architects to new sets of ideas that uncover new possibilities within architecture as well as provide performance artists with spontaneous, unanticipated, and serendipitous moments that further artistic expression. Use of a modified scissor-hinge element combined with actuators was considered in [15]. A scissor hinge structure facilitates unique extension and rotation capabilities, and the modified scissor unit developed herein greatly increases the form possibilities for the structure. This modified scissor unit differs from common scissor units in the addition of two joints at a specific point in the mechanism. With the development of this modified unit, it is possible to change the shape of the whole system without changing the dimensions of the struts or the span. The proposed scissor structure is two-dimensional, but it is also possible to combine structures in groups to create three-dimensional systems. [16] presents a large-scale movable monument exhibited at the International Expo 2005, Aichi, Japan, as the first application of an adaptive structure using a VGT mechanism. This monument is composed of three identical movable towers comprising four truss members combined by VGT at joints.

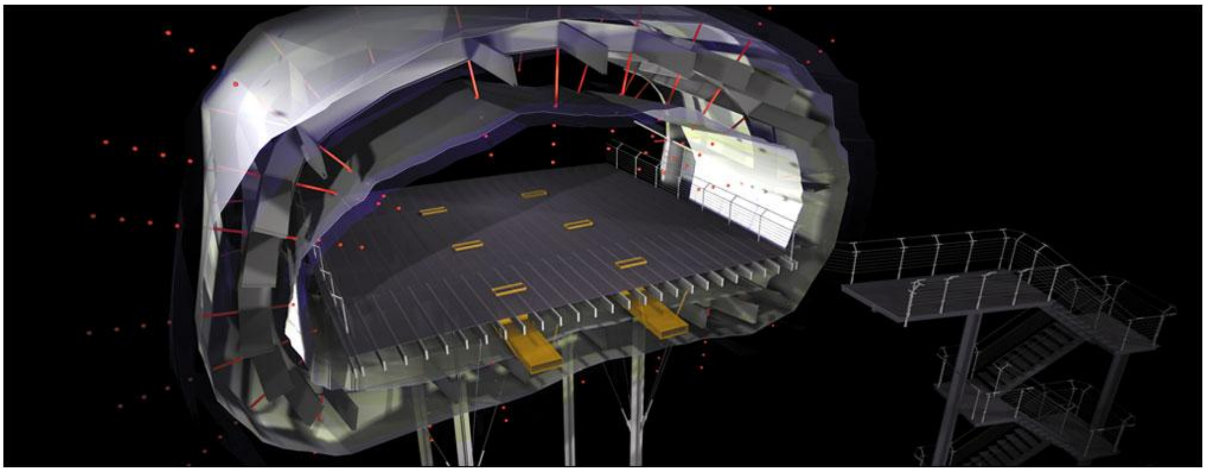

Figure 3: A responsive space [2].

3. Control strategies for responsive structures

In general a control system can be categorized as an *open-loop* or a *closed-loop* system. The *open-loop* system uses feed-forward control in order to actuate the mechanism, meaning that it responds to a control signal in a predefined way without taking the output into account. In opposite a *closed-loop* system uses a feedback system, where the input is adapted by measuring the output. The feedback goes through a sensor system that measures the output and provides the controller with an additional input signal. In [5, 17] these two fundamental concepts for control have be refined for responsive architectural structures as :

- *Internal control* where the degrees of freedom of the structure is controlled by mechanical constrains, such as rotational and translational joint constrains. In this category falls architecture that is deployable and transportable.

- *Direct control* where movement is actuated directly by one or several energy sources, such as actuators and motors. This is equivalent to open-loop control.

- *In-direct control* is the same as direct control, however, the energy source is now controlled by input from sensors in a closed-loop system.

- *Responsive in-direct control* is movement, where a control device makes an optimized decision on the actuated movement of the structure, based on input from numerous sensors. This is also referred to as optimized control.

- *Ubiquitous control* where movement is the result of many actuator pairs acting together as a networked whole. It is based on adaptive control laws that use measurements of the response to calibrate the control parameters.

- *Heuristic responsive in-direct control* implements self-learning capacity into the system, where the control system learns through successful experimental adaption. The system is optimized to the domain in which it operates, which is equivalent to adaptive control systems.

The *Heuristic responsive in-direct control* system could be the ultimate goal for a responsive architectural structure, i.e. intelligent kinetic structure which maintains and improves the structural performance during service life by e.g. recognizing changes in behavior and load, changing weather conditions, daylight, heating etc. and adapts to meet demands and using past events to improve future performance through learning and planning,

An outline of control strategies for responsive architecture has also been considered in [18], however none specific control approaches have been proposed.

3.1 Forward and inverse kinematics

An interesting control problem is related to reconfigurable architectural structures which can transform body shape, i.e. a transformation into more than one or two different shape alternatives. Two approaches can be used. 1) Forward kinematic is used to determine the position and orientation of every point on the structure from a set of generalized variables, while 2) inverse kinematic is used to find a set of generalized variables that places the structure in a new configuration.

If a multi-body reconfigurable structure is assumed to consist of rigid links the complete configuration of the multi-body can then be specified by a single generalized variable, namely $q = [q_1, q_2, \ldots q_n]^T$. If $p = [p_x\ p_y\ p_z]^T$ denotes the position of the *effector* (the main point of interest for the shape changes), the forward kinematic (FK) solution can be expressed as:

$$p = f(q) \tag{1}$$

f is a non-linear three-dimensional vector function. For inverse kinematics (IK), it is presumed that the *effector* is assigned a target position. If an *effector* is to be moved from one location to another, a set of DOF must be found so the resulting configuration of the manipulator places the *effector* at its target position. This requires that the inverse solution should be found in (1), which is a nonlinear equation. For a redundant structure, the functions involved are non-linear and a solution can be difficult to obtain even when it exists. Therefore, numerical methods have to be used to provide a stable solution to the general inverse kinematic problem. This problem will be considered in an accompanying paper.

4. Conclusions

The present paper has outlined fundamental issues related to control of responsive architectural structures. General typologies of kinetic architectural structures are presented followed by an outline of control strategies. Especially the principles of forward kinematic and inverse kinematics shape control are presented.

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