Directions for the design of energy efficient kinematics in adaptive solar building envelopes

Paolo Basso[1], Andrea E. del Grosso[2]

1 D'Appolonia S.p.A., Via S. Nazaro 19, Genova, Italy, paolo.basso@dappolonia.it, michele.mililli@dappolonia.it
2 University of Genova, Italy, andrea.delgrosso@unige.it

Abstract

The development of adaptive building envelopes is receiving increasing interest in contemporary architecture, as it strives to cope with several requirements such as energy saving and harvesting (or mitigating environmental actions), improving performance and, finally, aesthetics. Actual implementation fundamentally concerns external "skins" (i.e. adaptive facades), but internal "skins" (e.g. adaptive ceilings) may also be developed.
The engineering aspects related to the above developments are quite complex and involve different behavioral models to be merged within the adaptive strategy.

In the present paper, a study is presented that concerns the conception of an adaptive origami-like solar skin. The main design issues in managing the kinematics of the envelope are then identified and the envisaged solutions, to be developed in the next stage of the research, are discussed.

Keywords

building facade, adaptive skins, morphing skins, optimization, energy harvesting

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1 ADAPTIVITY CONCEPTS IN CIVIL STRUCTURES

When the concept of adaptivity is related to the field of civil structures, specific issues, such as the factors of scale and time, have to be considered. Contrary to what happens in mechanical engineering, automotive engineering or space engineering where structures are often much lighter and considered to be in motion, it is unlikely that a civil structure is able to change its configuration in a very short time. Dimensions, mass and the presence of people are typically going to constrain the possible range of accelerations and velocities, not to mention displacements and trajectories of the moving elements. The human threshold of motion perception is a consistent example of such a limitation (Iannucci & Fontanazza, 2010). Consequently, the adaptive behavior cannot belong to, nor come from, all the elements of the structure at the same time. Specifically referring to buildings, the existing proposals involving structural adaptivity are in fact usually focused on the internal and/or external envelope – i.e. the "building skin" (Del Grosso and Basso, 2010; Trubiano, 2013; Karanouh and Kerber, 2015).

Restricting adaptivity to the building skin means that mechanisms develop exclusively at the boundary, thus reducing kinetic inconsistencies with the internal space and possibly allowing a main static structure to be the core of the building. This, in turn, implies that adaptivity tends to come from mechanisms distributed all over the envelope in order to provide a better change of shape, and a consequent distribution of the actuators is also expected.

The envelope then plays an interface role in the most of the environmental actions, both externally (e.g. wind) and internally (e.g. people walking). More generally, this interface role is exploited with respect to all those excitations, other than loads, which have effects that are "shape-dependent". Such an excitation is, for instance, the sunlight, as shown in Fig 1.

This aspect makes it possible to take advantage of the same adaptive system to improve different performances of the building and it perhaps represents the most relevant feature when comparing structural adaptivity with more traditional control approaches.

Another specific aspect in the civil field is related to the morphology of the adaptive structure which is implicitly constrained by necessities of the building skin. In particular, the building skin is always required to be a watertight and rigid surface, but it is not trivial to constrain a multi degree of freedom (MDOF) system to maintain these two properties throughout the morphing process.

Besides the main functionality aspects, it is also worth noting the potential of adaptive structures to complement the aesthetics and the organic nature criteria of modern architecture, and thus provide contextual motivations for their implementation. These considerations are not of secondary importance as they indirectly enforce the adoption of sensing and actuation devices in buildings and make their costs more attractive to contractors and stakeholders.

In the present paper, a Finite-State Control (FSC) strategy, recently developed by the authors, is presented for the design and control of MDOF-adaptive envelopes. Starting from the FSC strategy general description (Section 2), a suitable representation of the building skin structure for its application is provided in Section 3. Section 4 of the paper instead focuses on specific aspects for the efficient application of the FSC strategy to solar envelopes, namely the solar energy harvesting potential and the energy minimization of the kinematics actuation. Finally, the paper draws some conclusions concerning the achievements and the future plans of the research.

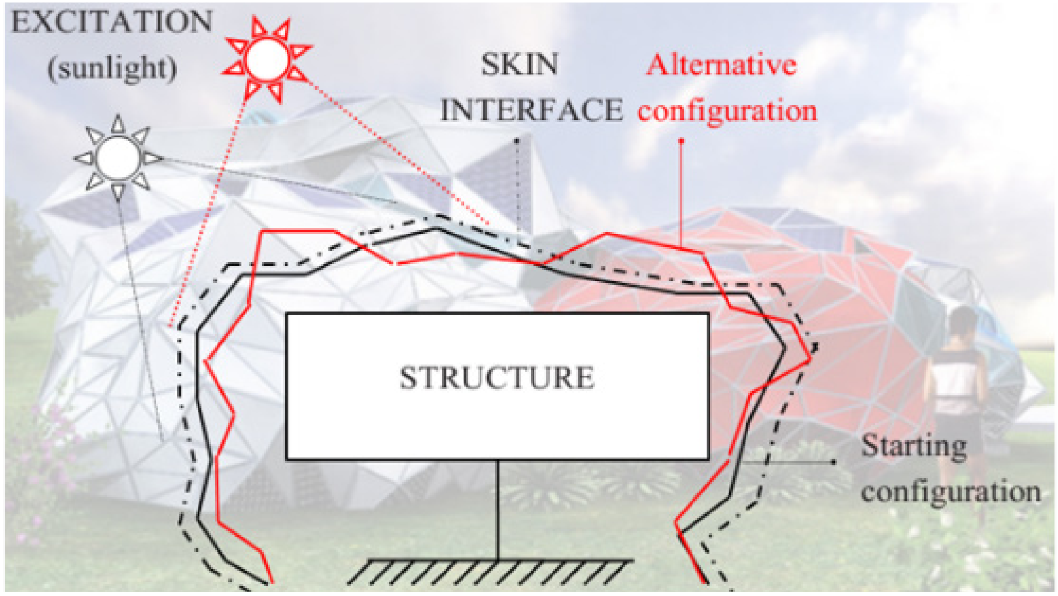

FIG. 1 The "building skin" as the interface to non-structural design drivers (e.g. sunlight).

2 FINAL STATE CONTROL

The FSC is a general procedure for the design of adaptive structural envelopes (Del Grosso & Basso, 2012; Del Grosso & Basso, 2013). The procedure is a basic combination of two main parts: a meta-heuristic optimization process, which aims to discover new optimal configurations – i.e. finite states – according to some defined purpose, and a gradient-based optimization process that acts as a constraint for the kinematic compatibility maintenance. Finally, a topology optimization process, which aims to decrease the number of degrees of freedom (DOFs) of the structure while retaining its ability to achieve the optimal configurations, is proposed as an integration of the finite states selection.

The main advantage of the FSC is that a set of optimal configurations (i.e. finite states) are investigated during the design phase to partially or totally avoid the computational cost of the real-time control. The strategy can handle any kind of system that can be associated with the framework representation as provided in Section 3 of the paper. The framework representation is central to the strategy development, mainly because the matrix analysis of frameworks is used to control the kinematic properties of the envelope.

A scheme of the FSC is summarized in Fig. 3, with emphasis on the key steps of the constrained optimization process. The key steps are, namely, the optimization of the different configurations of the envelope (finite states selection), the post-optimization of the framework topology and the management of the actuators' location. The initial framework to optimize G0 has to be equivalent to a triangular mesh. The choice of this initial mesh is determinant to achieve a good result. The most important parameter in this sense is the density of the mesh – i.e. the number of nodes and edges. A coarser mesh has, in fact, fewer possible configurations compared to a denser one but more DOFs to manage. Moreover, the mesh should represent a real envelope made with real panels which always have limits in the range of possible measures. The topology of the initial mesh – i.e. how the edges are connected – is another important factor because it constrains the "folding" process. It is, for instance, important to start with a symmetric pattern if the mesh is expected to fold symmetrically. Topology and density of the initial mesh could then be part of the whole optimization process, though on the other hand these two elements are also fundamental to the definition of the envelope appearance. Consequently, regarding a building facade, roof or internal ceiling, these turn out to be architectonical parameters in the majority of cases. Therefore, the topology and density of the initial mesh are left outside the optimization process here since they are considered a direct choice of the designer.

3 FRAMEWORK REPRESENTATION

A framework, from the structural engineering point of view, can be defined as a discrete set of one-dimensional elements in three-dimensional space, connected at their ends to points called nodes. Frameworks are therefore general enough to represent a huge variety of structural systems such as, for instance, trusses, cable-nets, tensegrities, membranes, reciprocal frames, etc.

In order to make the FSC applicable, two more characteristics have to be associated with the generic framework definition provided above. The first is related to the internal restraints that are assumed to be pin-joints. The second is a further specification of the topology of the framework. Specifically, the framework will be assumed to be “single-layer”, which means that whatever projection on a plane would result in no intersections of the edges, except in correspondence of the nodes. A pin-joint single-layer framework, like the one in Fig. 2, is usually a multi degree of freedom (MDOF) system, which allows different compatible configurations to be obtained by reciprocally rotating edges around nodes. Such a particular system has thus a great potential for structural applications as an adaptive building envelope since:

- the pattern of the system can be filled with rigid panels to achieve a watertight and rigid surface;
- mechanisms are purely geometric, i.e. they do not rely on the elasticity of materials and robust kinetic structure in a larger scale under gravity can be realized;
- the transformation from one configuration to another can be controlled by a limited number of degrees of freedom enabling a semi-automatic deployment of the structure.

In a system of this kind, the number of DOFs depends on the topology and geometry of the pattern. The triangular pattern, for instance, is the most frequently used but with such a pattern the number of DOFs increases along with the number of nodes. On the contrary, a quadrilateral pattern results in no DOFs or a maximum of 1 DOF when the pattern is singular (Koiter, 1984). A main issue is then to design a pattern which optimizes the number of DOFs and then to define their location and, consequently, the optimal type, number and location of the actuators. A limited number of DOFs simplifies the mechanism control and can result in an actuation process with reduced energy requirements. On the other hand, too few DOFs could overly restrain the adaptability of the structure, depending on the set objective. Moreover, a high number of DOFs that are based on reciprocal kinematic relations among the system parts makes the real time control of this kind of structure not insignificant.

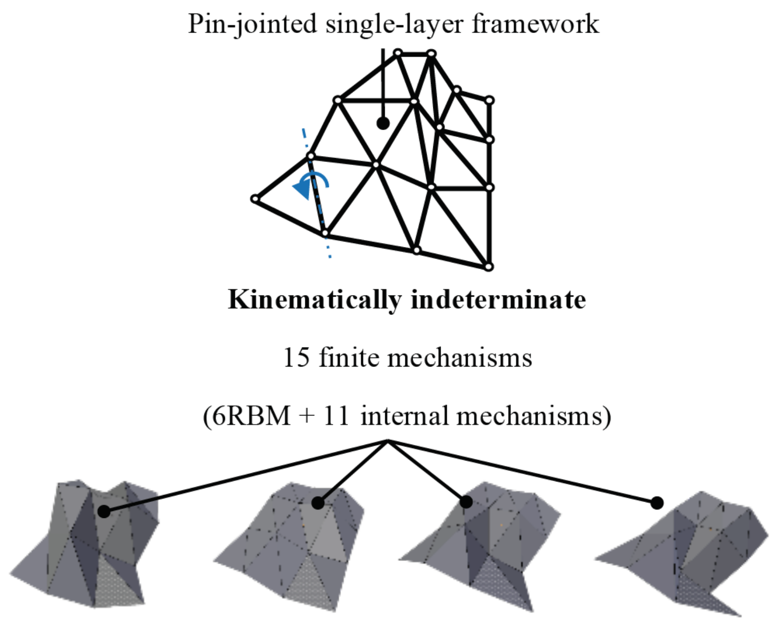

FIG. 2 MDOF pin-joint single layer framwork.

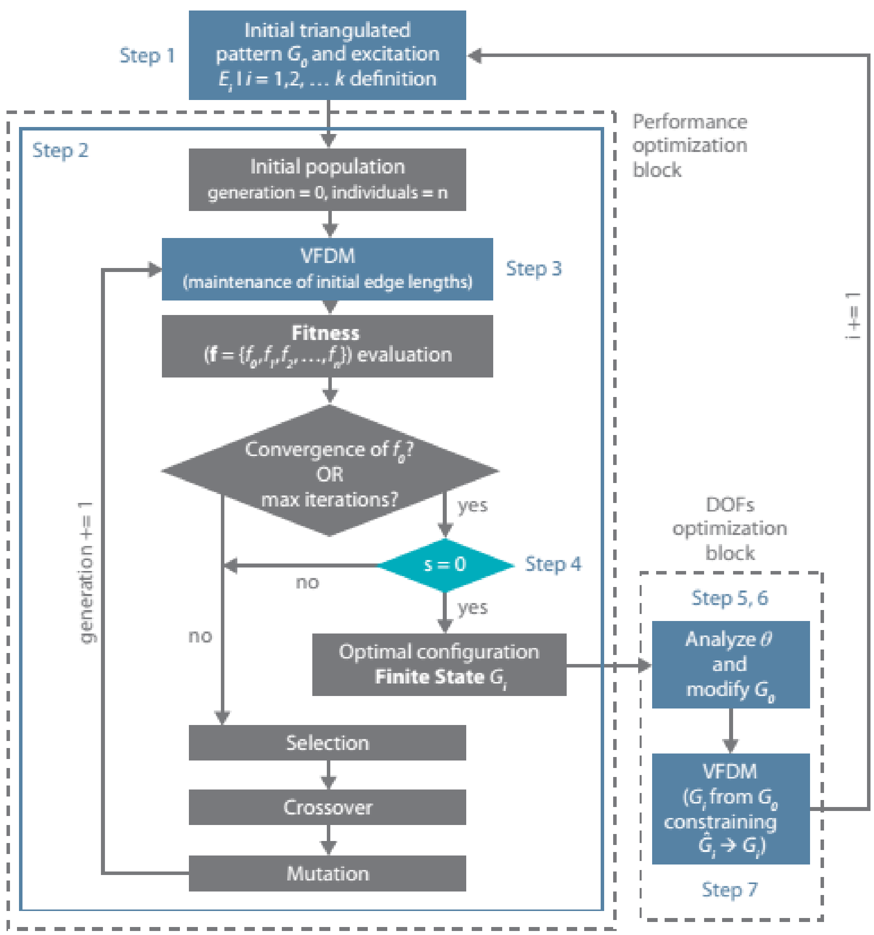

FIG. 3 Flowchart of the optimization process.

4 DEVELOPMENT OF A COST-EFFECTIVE SOLAR SKIN

The key point in the design of an adaptive envelope is to quantify its benefit by comparing it to a static approach. However, due to the complexity of the subject, to date research on MDOF adaptive envelopes has mostly focused on the viability of the different analyzed solutions and advantages and disadvantages are usually reported only qualitatively (Tachi, 2010; Tachi, 2013).
Since the research developed by the authors currently focuses on the conception of a new kind of adaptive solar envelope, i.e. an envelope with the characteristics of a rigid origami mechanism and an integrated solar energy harvesting process, the quantification of the achievable energy gain becomes the measure of the product's effectiveness. Therefore, the energy balance is the difference between the energy consumed by the actuation system and the exploited solar energy. The final aim is thus to overcome the main barriers identified for the integration of solar technologies in the building envelope, i.e. performance and aesthetics (Prieto, 2017), through the conception of a dynamic skin which could handle an increment of the energy harvesting potential and a major freedom of design.
Starting from these considerations, the proposed actions that enable this energy efficiency advantage are discussed hereafter.

4.1 LIGHTWEIGHT MULTI-PANE GLAZING UNITS WITH ENERGY HARVESTING POTENTIAL

To achieve lightweight envelopes is the first step in reducing the energy consumed by the actuation process. On the other hand, an energy harvesting process should be included in the envelope design in order to obtain a positive energy balance from the actuation. Finally, the envelope insulating and transmittance properties have to be comparable to the best alternatives on the market.
Using these considerations as a starting point, based on the combination of transparent and translucent curtain walls with ETFE membranes and optional PV membranes or advanced solar thermal concepts, the idea is to develop a new range of higher optical, thermal performance and a lower weight component. Some internal glass layers are replaced with lightweight transparent foils expressly treated (e.g. plasma and low-E coatings) in order to exceed the current level of performance of glass panels through a cost effective solution and a minimum quantity of material. The use of foils can drastically reduce the risk of breaks in the intermediate layers, realized using standard float glass, due to a high temperature difference (over 55K) within an individual glass pane. In addition, multi-pane (more than 3-pane) glazing units are built of complex glazing systems with outer, inner, intermediate, and expansion glass panes that vary optically. Reflective coatings and transparent PV membranes are integrated to enhance energy harvesting; an example of such a functionality can be seen in the High Insulating Solar Glass (HISG) developed at the National Taiwan University of Science and Technology (Fig. 4). In this case, the principle is that incoming radiation encounters the PV membrane to generate energy and then reflects back on to the PV membrane to maximize energy harvesting. This contributes further to heat insulation.

The concept can be further integrated into a high-efficiency thermodynamic facade, comprising an air-driven heat pump and an external air-gap which would act as a solar thermal collector, for the distributed supply of heat and air conditioning to buildings. One of the innovations of the proposed concept is the capability to use the heat from the surrounding environment to fulfil the heating and air conditioning requirement of the rooms. This system could incorporate a heat recovery device to generate an all-in-one device for the HVAC needs of a medium sized room. The external aesthetics & appearance of the system will be similar to a ventilated facade, and a small-sized internal terminal unit. This modular approach can be broken down into a range of semitransparent components introducing different finishes and levels of transparency for the cell, moving from membranes to crystalline cells integrated in a thinner outer glass layer.

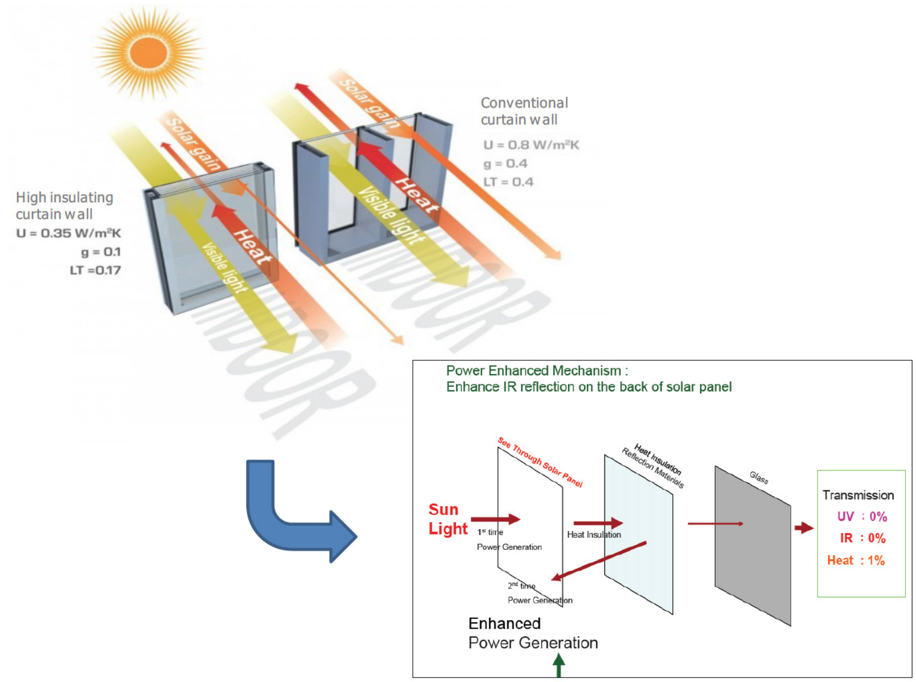

FIG. 4 Scheme of the High Insulating Solar Glass (HISG) concept. Image courtesy of Prof. Young - National Taiwan University of Science and Technology.

4.2 ACTUATION ENERGY MINIMIZATION

Low-energy actuators are important in minimizing the total energy consumption during actuation. However, an even more problematic but neglected issue is represented by the actuators network topology, i.e. the number and placement of the actuators in the framework. The difficulty with this issue is that it is directly related to the framework dimensions, to the envelope mechanism, and to the optimization of the energy harvesting process. Moreover, an optimal actuators distribution: a) minimizes the trajectories leading from one configuration to another; and b) minimizes the stress ranges in the skin's structural elements, for improving fatigue life. Consequently, the actuators network topology must be part of the whole optimization process of the envelope (steps 5 to 7 in the FSC flowchart – Fig. 2).

The number of actuators needed to manage the morphing process of an adaptive framework depends on the number of finite mechanisms within the framework and the type of actuators used. Here, the actuators are assumed to be linear and to be linked both to the adaptive envelope and to a supporting structure through pin-joints and through fixed joints respectively, as shown in Fig. 5. Every actuator belonging to this type that is correctly placed on a node of the framework constrains a maximum of three mechanisms. An incorrect placement may generate self-stress states leaving some of the mechanisms untouched. Therefore, the location of the actuators must be chosen carefully in order to control all the mechanisms.

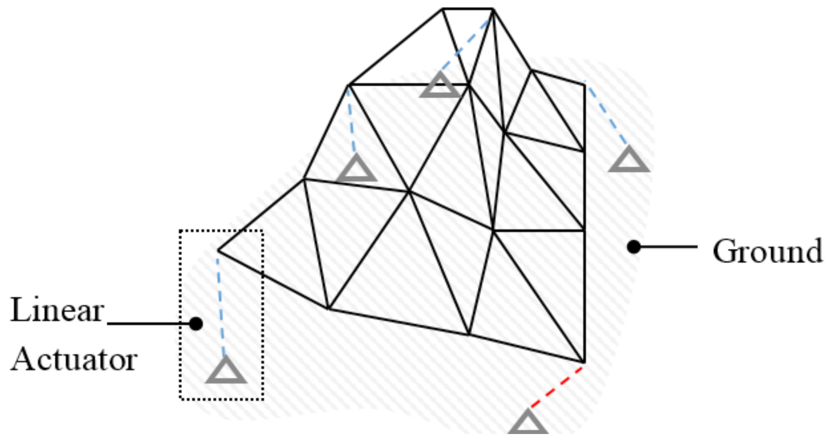

FIG. 5 Scheme of an adaptive envelope linked to a supporting structure by linear actuators. Actuators are pin-jointed both to the supporting structure and to the envelope.

This concept is better illustrated by comparing Fig. 6a and Fig. 6b. Note that the two frameworks have the same number of nodes, the same number of edges and also the same edge lengths. Moreover, the number of mechanisms (m = 11) is exactly the same when assuming the framework is unconstrained in the 3D space. But in Fig. 6b, if no actuators are placed at node 7 and node 7 is unconstrained, it is not possible to manage the face 4-7-8 rotation around the edge 4-8. This does not happen in Fig. 6a because of the different topology of the pattern. The above example leads to the first important conclusion, which is that no nodes with connectivity ≤ 2 can be left unconstrained or not actuated.

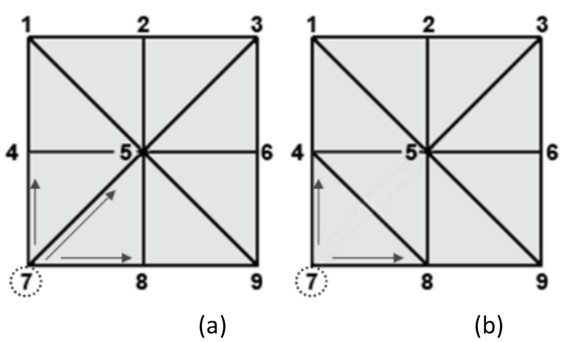

FIG. 6 (a) and (b): two frameworks with the same number of nodes and edges but with a different pattern topology. In (b) node 7 has connectivity ≤ 2 and needs to be controlled directly.

The second important observation is that actuators and constraints should be placed first on nodes that are not directly connected to one another. For instance, still looking at Fig. 6, it turns out that a minimum of four actuators/restraints are needed to control the 11 mechanisms and at least one self-stress state is expected (3 DOFs ´ 4 actuators – 11 mechanisms = 1). The only group of four nodes which can be selected avoiding nodes inside the same group to be connected to each other is the one composed by nodes 1, 3, 7 and 9. Controlling these four vertices through pin-joint restraints or actuators results in zero mechanisms and only one self-stress state of the framework. Every other combination of four nodes, assuming the same kind of restraints/actuators would end up with more self-stress states.

Inverse kinematics can then be used both to plan and to verify the actuation process. The inverse kinematics of the framework can be controlled by the Moore-Penrose generalized inverse of the Jacobian of the non-linear vector equation representing the geometry constraints (constraint equation). The constraint equation for a pin-joint framework reads:

$$\boldsymbol{\Omega}\ (\mathbf{x},\mathbf{y},\mathbf{z}) = [\mathbf{l} - \mathbf{l}_0] = \mathbf{0} \quad (1)$$

where l is the vector of the edge lengths at the current step and l0 is the vector of the initial edge lengths. Eq. (1) can be written in terms of the Cartesian nodal coordinates:

$$\boldsymbol{\Omega}\ (\mathbf{x},\mathbf{y},\mathbf{z}) = (diag(\mathbf{Cx})^2 + diag(\mathbf{Cy})^2 + diag(\mathbf{Cz})^2\ )^{1/2} - \mathbf{l}_0 = 0 \quad (2)$$

where C is the incidence matrix of the framework and x,y and z are the vectors of the nodal coordinates.

Eq. (2) yields an underdetermined system, by exploring the solution space for which it is possible to obtain variations in the configuration. Valid shapes are found by perturbing the nodal coordinates according to the nullspace of the Jacobian $J = \left[\frac{\partial \boldsymbol{\Omega}}{\partial \mathbf{x}} \middle| \frac{\partial \boldsymbol{\Omega}}{\partial \mathbf{y}} \middle| \frac{\partial \boldsymbol{\Omega}}{\partial \mathbf{z}}\right]$.

The solution is calculated using the pseudoinverse of the Jacobian as follows:

$$d\mathbf{u} = (\mathbf{I} - J^{+}J)d\mathbf{u}_0 \quad (3)$$

where du0 represents the initial perturbation and I is the identity matrix. Eq. (3) finds the valid perturbation closest to du0 by orthogonal projection to the solution space. An integration of this infinitesimal motion has to be executed and, for each step, the residual has to be eliminated (e.g. Newton-Raphson method).

It is worth noting that considerations are limited to geometric ones and elastic or plastic behavior of the structure with specific materials is not analyzed. With reference to Eq. (3) the perturbation vector Du0 = [Dx1, Dx2, …, Dxn] T1xn is then built from the zero vector $\Delta u0 = [\Delta x1, \Delta x2, \ldots, \Delta xn]^{T}1xn$ by substituting the zero values corresponding to the "actuated" nodes with the distance between the node at the current position and the node at the target position.

5 CONCLUSIONS

Differences concerning the applicability of adaptive structures to engineering problems of different fields have been discussed. Of particular interest for potential civil applications are MDOF envelopes which are generally characterized by a high reciprocity in the behavior of their parts. The resulting constrained MDOF kinematics are not inconsequential when attempting to achieve optimal configurations through real-time control. The proposed FSC strategy focuses on adaptive envelopes which can be associated to single-layer frameworks and is based on the "a priori" exploration of the design space in order to reduce the computational cost during the real-time control of the structure. In order to apply the FSC to the design of a new kind of solar building envelope, the paper has presented the identified issues and the next key-steps that will be addressed.

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