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Responsive Plant-inspired skins: A review

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Abstract: Sun-shading Plant-inspired skin can use plant actuation principles to develop reversible motions. This paper will triangulate the intersection between plant actuation principles, their morphology and low energy strategies, to integrate the underlying mechanisms in responsive dynamic shading skins. This paper will investigate the non-autonomous reversible plant movements to develop elastic kinetic solar screens. New approach of soft mechanics found inspiration in plant movements for pliable structures in architecture. Interestingly, global flexibility is often achieved through the adaptive behaviour of plant that change its morphological features by acting as living hinges and allowing for elastic deformations. These motion patterns are found in nastic structures which are very promising as natural actuators. By studying how plant species take advantage of mechanical, compositional and structural gradients to perform mobility with minimal energy use, it is possible to learn how to integrate these properties into the design of kinetic shading solar screens. The focus of this review is to understand the soft mechanics approach and its applications on responsive shading skins. A critical review of the current progress in mechanical properties and actuation principles of nastic plant movements is illustrated.

Keywords: Responsive skins, Plant movements, Biomimetics, Deployable structures, Actuation

Introduction

The urgent demand for more energy-efficient and sustainable architecture is leading to a growing interest in kinetic skins that can adapt to changing environmental conditions (Fiorito *et al.*, 2016). The term 'Kinetic skins' has come to be used to refer to building envelopes capable of configuration changes due to their geometrical, material and mechanical properties (Adrover, 2015). Recent literature shows that most environmental kinetic facades are based on mechanically operated systems. A mechanical system, such as Al Bahr Towers in Abu Dhabi, has the disadvantage that it is complex to build, difficult to maintain and require high energy consumption (Reichert et al., 2015). Lately, more recent attention has focused on two approaches that have the potential to simplify mechanical designs utilized in kinetic skins, Biomimicry and Smart materials.

Plant tissues have the capability to adapt to constantly changing environmental conditions even when their cells are dead. This is achieved through iterative feedback loops, which sense, record, inform and instruct the fibre composite to alter their current configuration towards an optimized one (Mingallon and Ramaswamy, 2012). By studying how plant species take advantage of mechanical, compositional and structural gradients to perform mobility with minimal energy use, it is possible to learn how to integrate these properties into the design of kinetic shading solar screens.

Moreover, Investigation of new responsive smart materials could be an efficient replacement to simplify mechanical actuation (Reichert et al., 2015). Material embedded actuation can alter their morphology under external stimulation and adapt autonomously to their respective environmental conditions (Schaeffer and Vogt, 2010; Reichert et al., 2015). Smart materials have permanently reversible properties which can be triggered by external stimulus such as temperature (Schaeffer and Vogt, 2010). For example, Shape memory alloys have great potential to act as a servo-actuators to design low-tech responsive skins. The activation temperatures of Embedded Shape Memory Alloys can be achieved in hot arid climates through direct solar contact and can be applied for responsive solar shading skin. This paper concentrates on the mechanical, compositional and structural constraints enabling plants to actuate their organs, summarizing current knowledge in how plants generate movement. It focuses on reversible plant movements to develop elastic kinetic solar screen.

Biomimetic Approach for efficient movement

Biomimicry is the study of imitating and mimicking nature, where it has been utilized by designers to help in solving human problems. Some designers and researchers argues that nature is the best, most influencing and the guaranteed source of innovation. Plants can be a promising inspiration source to learn soft mechanics (Schleicher et al., 2015). Suitable analogues can be developed into responsive motions production that could meet design as well as sustainability demands. Plants have evolved the capability to respond to a wide range of signals and efficiently adapt to changing environmental conditions. They perform mobility with minimal energy use, due to the fibre elasticity composition and integration of sensing and actuating capabilities into their system (Fiorito et al., 2016). In particular, the leaves and pedals bending and folding mechanisms demonstrate how the number of mechanical parts can be reduced by making use of flexible and elastic material properties and allow reversible deformations (Poppinga *et al.*, 2010; Schleicher *et al.*, 2015).

For biologists, the classification of plant movements is an important aspect to understand how plants develop morphogenesis (Boudaoud, 2010), and specially how they respond to environmental stimuli. Plant biologists distinguish between nastic and tropic movements. The movement in nastic responses is independent of the spatial direction of a stimulus, whereas tropic movements are influenced by its direction (Burgert and Fratzl, 2009; Schleicher, 2016)**.** Generally, Nastic movements occur due to the swelling and shrinking of motor cells and result in reversible movements that could be of high interest in responsive skin applications (Ueda and Nakamura, 2006; Poppinga *et al.*, 2010). In order to understand how plants' movements develop in general, they will be analysed on different levels: mechanical, compositional and structural systems.

Actuation mechanisms in Plant Movements

Numerous studies have attempted to classify plant movements. Poppinga et al. (2010) developed wide-ranged matrix focused on actuation systems found in active or passive nastic plant movements in response of environmental stimuli. The study distinguished between autonomous and non-autonomous movements as well as the active and passive. Non-autonomous movements are mostly reversible deformations caused by a release of stored elastic energy in pre-stressed structures or are initiated by external mechanical forces.

Similarly, (Schleicher, 2016) distinguished between frequently encountered drivers like external loads, growth processes, hydraulic mechanisms, and elastic instabilities.

Accordingly, a more detailed structure of nastic non-autonomous reversible movements is given as shown in figure 1. Reversible Plant movements can be actuated either hydraulically in active way by turgor changes, or in passive way by hygroscopic swelling and shrinking. Other mechanisms use the release of stored elastic energy after an external trigger or by direct application of mechanical forces. The next section will discuss the actuation mechanisms derived by external loads, hydraulic mechanisms, and elastic instabilities.

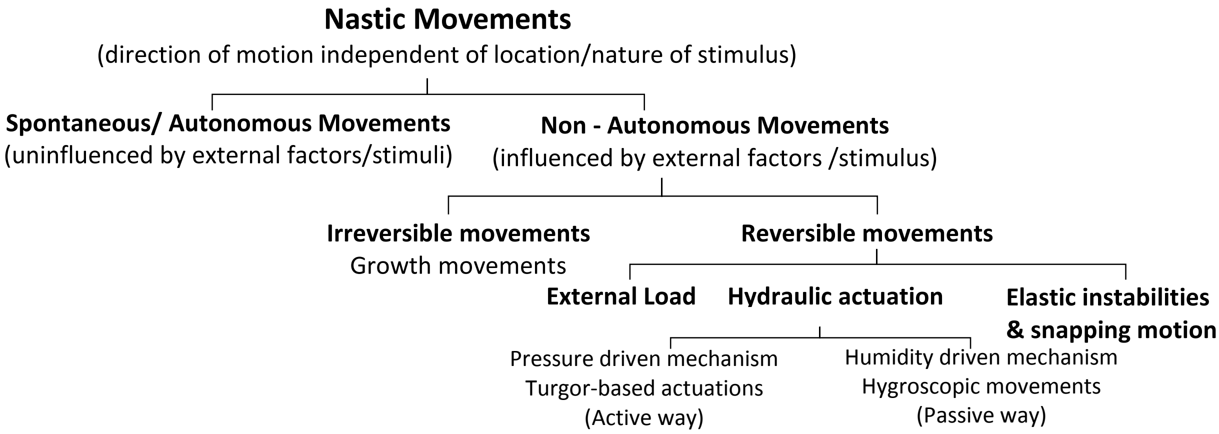


Figure 1. Classification of nastic plant movements.

External loads

The motion of plants can be a response to direct application of mechanical forces. This movement follows an external influencing factor passively rather than been driven by the plant itself. Different loads can act on a plant, such as flowing water, wind gusts, contact with pollinating insects, or attacks of natural predators. According to the plant's composition, an outer drive can either cause an immediate deformation or be diverted to trigger secondary transformation processes (Schleicher, 2016). For example, the movement of the Bird-of-paradise due to the pollination mechanism is triggered by a locally applied load at a specific point as shown in figure 2 (c).

Hydraulic mechanisms

Hydraulic mechanisms in plant movements can be actuated either actively by turgor changes that lead to reversible movement or passively by hygroscopic swelling and shrinking. *<u>Osmotic actuation:</u>* Osmotic actuation is a ubiquitous plant-inspired actuation strategy that has a very low power consumption but is capable of generating effective movements in a wide variety of environmental conditions (Sinibaldi *et al.*, 2014). Living plant cell can generate an internal hydrostatic pressure (turgor pressure) by maintaining an osmotic gradient between its cytoplasm and ambient environment (Li and Wang, 2016). Variations in turgor pressure enable plants to perform volumetric changes and rapid movements (Burgert and Fratzl, 2009; Schleicher, 2016).The pressure driven, water based actuation mechanism in plants is closely related to the hydraulic and pneumatic actuators that are attractive for morphing applications in adaptive structures (Li and Wang, 2016). For example, Mimosa pudica exhibits a rapid, defensive response to external stimuli, closing its leaves and bending its pulvinus. Motor cells, divided into flexor and extensor cells on the ventral and dorsal side of the leaf as shown in figure 2 (a), respectively, regulate the volume and shape according to their relative turgor pressure (Guo *et al.*, 2015).

<u>Hygroscopic shrinking or swelling mechanism:</u> Other than the pressure driven mechanism, plants also exploit a humidity driven mechanism to achieve shape change and actuation. Plant cell wall is a hydrophilic material, so it will shrink in volume due to evaporation when it is exposed to dry atmosphere. This process can occur in both living cells and dead cells in the sclerenchyma tissues (Li and Wang, 2016). For example, a change in the relative humidity causes a closed, tightly packed Pine cone to open gradually. The mechanism relies on the bilayered structure, the active outer layer of tissue, closely packed long parallel thick-walled cells respond by expanding longitudinally when exposed to humidity and shrinking when dried, while the inner passive layer does not respond as strongly as shown in figure 2 (b) (Reyssat and Mahadevan, 2009). But to be consistent with the scope of this review, this mechanism is only applicable in humid climates.

Elastic instabilities and snapping motion

Elastic instabilities and snap-buckling effects are methods for translating small stimuli into large and amplified movements. Snap-buckling effects speed up movements beyond the limits imposed by simple hydraulic mechanisms. These elastic instabilities are special mechanical failure modes characterized by a sudden deformation of a structural element withdrawing from high tensile or compressive stresses by deflecting into a less strained but geometrically deformed state. In particular carnivorous plants like the Venus Flytrap seem to have mastered that technique (Schleicher, 2016). Interestingly, a kind of "memory" appears to be involved in the leaf closure (Ueda and Nakamura, 2006). The main source of the fast closure is the bistable, doubly curved structure of the leaves, which snap-buckle to reverse their Gaussian curvature upon closing as shown in figure 2 (d) (Guo *et al.*, 2015).

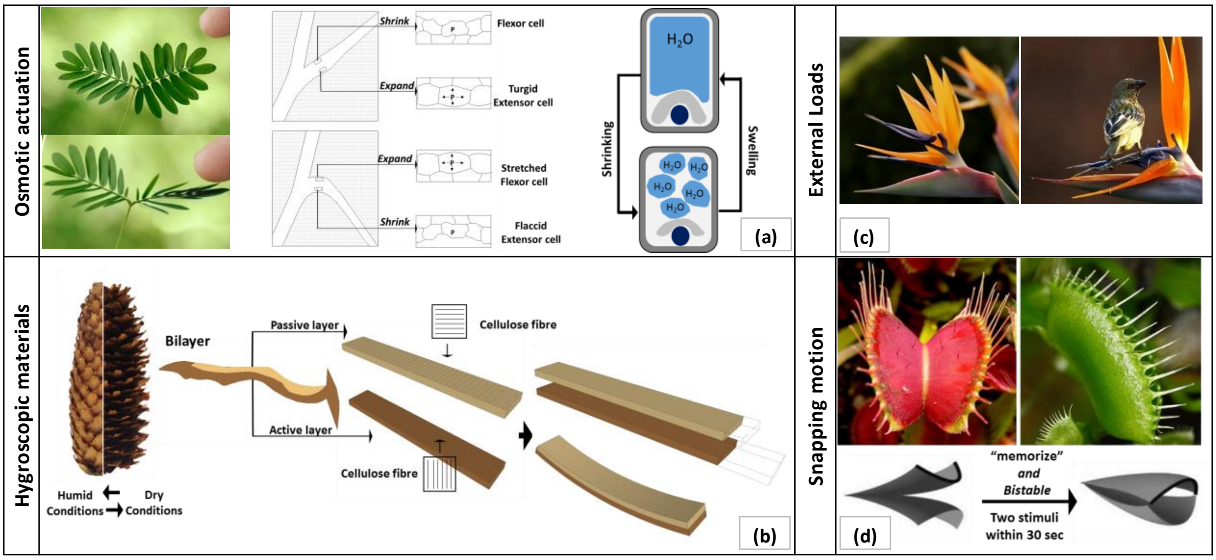


Figure 2. Reversible movements in the plant kingdom.

Compositional features

Plants have also evolved to strategically combine various physiological features with different actuation mechanisms to achieve sophisticated movements (Li and Wang, 2016). Material self-organization is a processes present in the formation and adaptation of biological tissues. They are responsible of the resultant high performance, found in natural fibre composites, to deal with unprecedented environmental conditions (Mingallon and Ramaswamy, 2012). They have the ability to create gradients of tissue, cell or cell wall properties to create actuator-type "smart" materials. The organ deformation is controlled at various levels of tissue hierarchy as shown in Figure 3, which are: Geometrical tissue organization at the micro-level, and Cell size, density and Cell wall polymer composition at the macro-level as shown in Figure 4 (Burgert and Fratzl, 2009). The composition and the geometry of cellular patterns influence the complexity of the actuation system, the folding directions and the reversibility of the system.

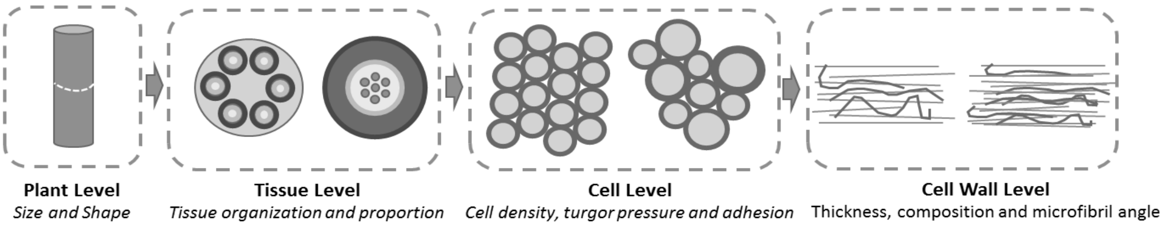


Figure 3. Hierarchy of mechanical parameters influencing plant movements.

Cellular organization (micro-level)

Plant materials are made up of plant tissues, either simple tissues, or complex tissues, each with their own structure (Gibson, 2012). Plant tissues are essentially close-walled cellular solids, which are well known for providing better stiffness and strength to density ratios as compared to their constituent solid materials. Cellular organization could also facilitate movements (Li and Wang, 2016). The cellular structure of plants varies, from the largely honeycomb-like cells of wood to the closed-cell, liquid-filled foam-like thin-walled parenchyma cells and to composites of these two cellular structures, as in arborescent palm stems. Honeycombs have prismatic cells which can be periodic (often hexagonal, but sometimes rectangular or triangular) or random (as in Voronoi honeycombs. Foams have polyhedral cells, typically without a repeating unit cell. Open-cell foams are solid at the edges only, while closed-cell foams have solid faces (Gibson, 2012). Integrating the cellular feature and osmotic pressurization mechanism can provide the ability to achieve differential pressurization for more complicated deformations (Li and Wang, 2016).

Fibrous cell wall materials (macro-level)

Plant cell walls are fibrous in nature, non-homogenous membrane, consisting layers of four basic building blocks: cellulose (the main structural fibre of the plant kingdom) hemicellulose, lignin and pectin. Each fiber has a complex, layered structure consisting of a thin primary wall encircling a secondary wall. The secondary wall is made up of three layers and the thick middle layer determines the mechanical properties of the fiber (Kalia *et al.*, 2011). Although the microstructure of plant cell walls varies in different types of plants (Gibson, 2012), all cell walls are composites of cellulose fibrils and a partially cellulosic matrix material, assembled into three major architectures: parallel fibrillar, sheet-like, and bulk. Microfibrillar angle is defined as the angle between fiber axis and microfibrils, and it was found to be a crucial factor in determining the mechanical properties of plant organs (Kalia *et al.*, 2011). For example, In bilayers, differential swelling of neighbouring tissues with dissimilar microfibril angle and/or degree of matrix swelling leads to reversible shape changes (Brule *et al.*, 2016). In summary, Cellulose orientation in plant cells direct organ actuation.

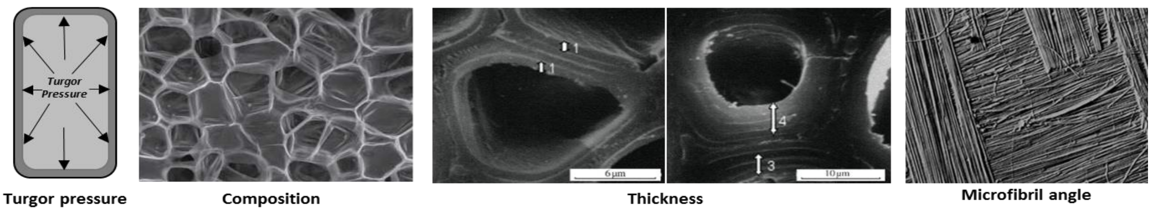


Figure 4. Cell and cell wall level.

Structural systems in engineering

The employment of elasticity within a structure facilitates not only the generation of complex geometries, but also create elastic kinetic structures. Plants' flexibility, represent a compliant mechanism that reduces the number of mechanical parts by an integrative design (Schleicher, 2016). (Howell, 2001) defined Compliant Mechanisms as mechanisms that gain their motion from the deflection of elastic members and transforms the kinetic energy to strain energy in the members and then transforms it back to the kinetic energy (Howell, 2001). Compliant mechanisms combine strength with elasticity and gain some of their mobility from flexible members deflection rather than only from movable joints (Howell, 2001; Schleicher, 2016). In pliable systems the deformation behaviour of individual elements is constrained by their neighbouring elements. The linking of these elements allows the transmission of forces and torque (Schleicher *et al.*, 2011). Thus the deformation of one element will result in the deformation of the adjacent element. This relationship can be used to build up a cascading deformation movement. Pliable structures are based on elastic deformation as well as on the fact that it can convert between different stable configurations (Vergauwen *et al.*, 2017).

Bending-active structures are pliable constructions, which generate their geometrical form and their system rigidity by elastically deforming their members (Schleicher *et al.*, 2011). Bending-active structures, defined by Lienhard as structural systems that include curved beam or shell elements which base their geometry on the elastic deformation initially planar configuration. Yet, most bending-active structures are designed to bear loads and to be stiff only in their final configuration (Lienhard, 2014). Some researchers combine folding (plastic deformation) and bending (elastic deformation) using Curved-line folding to design efficient kinetic system. Curved-line folding is the act of folding paper along a curved crease pattern in order to create a 3D shape. (Vergauwen *et al.*, 2014) demonstrates how the choice of the composition of the crease pattern, the curvature of the creases and the Length–Thickness Ratio affect the resulting kinetic system (Vergauwen *et al.*, 2014). In addition, (Vergauwen *et al.*, 2017) introduced the secondary layer principle (Bilayering) to perfectly control the folding motion by changing the distance between the two layers, which drive the layers to tension and pull into the desired position. On the whole, the selection of the composition, the structural behaviour and material have a great responsibility on the actuation system.

Applications of kinetic solar shadings

Some projects linked kinetic design with biomimicry; from the selection and investigation of plant movements to the abstraction methods which were developed to translate plant movements into hinge-less elastic kinetics for deployable structures.

(Project A) The Flectofin® façade was developed by a team; from Plant Biomechanics Group (PBG) and the Institute of Building Structures and Structural Design (ITKE). A sun-shading system for complex building facades was inspired by the elastic deformation behaviour of the Bird-Of-Paradise flower. It is based on the valvular pollination mechanism of the Bird-Of Paradise flower. The logic of curved line folding was discovered accidentally from manufacturing tolerances but is understood as a key to the function of the mechanism. The curved-line folding kinematics was informed by the rapid trap closure mechanism of the carnivorous waterwheel plant (Lienhard *et al.*, 2010; Lienhard *et al.*, 2011; Lienhard, 2014).

(Project B) The Thematic Pavilion at the EXPO 2012 trade-fair in Yeosu, Korea was inspired by the Flectofin® concept. It was proven that up-scaling of the basic principle is possible. It is magnified to the large scale of 108 individual GFRP lamellas with varying heights that are deformed by controlled buckling. The facade can therefore adapt to light and physical building conditions.

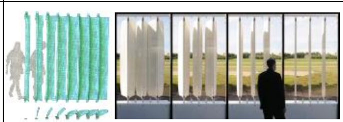
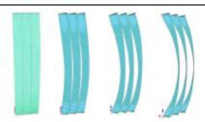
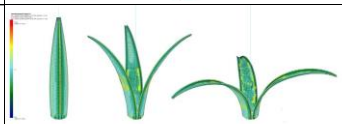
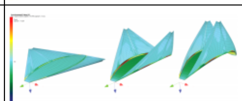
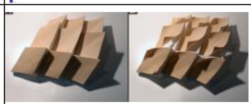
(Project C) was inspired by Aldrovanda vesiculosa. This aquatic carnivorous plant has a quick and reversible snapping motion. The movement is hydraulically driven by a central surface with a midrib, which cause a bidirectional change (Schleicher et al., 2015).

(Project D) The Lily mechanism was inspired by the compliant mechanism in the flower of Lilium casablanca (Liliaceae). The movement of the plant organ is based on unidirectional changes at the periphery caused by differential edge growth. Since the movement driver is based on internal changes of the material state, a temperature-controlled actuator that enforces edge expansion was simulated (Schleicher et al., 2015).

(Project E) Hygroskin project is developed by another team from the Institute for Computational Design (ICD), Achim menges in collaboration with Oliver david krieg and Steffen Reichert, presented a comprehensive development of smart skins based on the biomimetic transfer of hygroscopic actuation of plant cones. The shape change of wood was utilized to develop humidity responsive, integrated technical system (Reichert et al., 2015).

(Project F) studied the same mechanism of hygromorphic (moisture-sensitive) materials by (Holstov *et al.*, 2015) to produce low-tech low-cost adaptive systems by deploying materials with embedded responsive properties. A prototype of a responsive umbrella canopy consists of triangular panels with 7 different types of active layers.

Table 1. Summary of Bio-inspired skin systems.

	Project name	Project	Plant-Inspired	Biomimetic Methodological Approaches	Actuation mechanism
Project A	Flectofin		Bird-Of-Paradise (Strelitzia reginae, Strelitziaceae)	‘Bottom-up-approach’	Valvular pollination mechanism
Project B	Thematic Pavilion				Elastic mechanism based on structural failure (buckling).
Project C	Lily Mechanism		Lilium casablanca	‘Bottom-up-approach’	Differential edge growth in the tepals
Project D	Aldrovanda vesiculosa		Aldrovanda vesiculosa (Droseraceae)	‘Bottom-up-approach’	Hydraulically driven by a central surface with a midrib
Project E	Hygroskin		Pine cone	‘Bottom-up-approach’	Hygroscopic actuation (shrinkage and swelling wood)
Project F	Hygromorphic responsive umbrella		Conifer cones (e.g. spruce and pine cones)	‘Top-down-approach’	Hygroscopic actuation (shrinkage and swelling wood)

Conclusion

The inability of contemporary adaptive skin systems to meet performance and cost efficiency requirements is a result of their excessive dependence on mechanical components which is associated with increased complexity and cost. In contrast, plant-inspired skins present an alternative approach of soft mechanics which provide opportunities for design of low-cost low-tech adaptive skins achieving dynamic behaviour by means of passive response. The current study has provided an understanding for the response mechanism of plants and principles for selection of their configuration. A number of morphological and compositional parameters affecting plant movements have been discussed across multiple scales ranging from tissues to cells and cell walls. The core principles of bi-layering have been extracted and discussed to develop Plant-inspired hinge-less kinetic skins. Future research could focus on development of efficient strategies; such as Bi-stability for practical application.

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