THE APPLICATION OF AN ADAPTIVE SOFT STRUCTURE FOR LIGHTWEIGHT FACADES

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Building façades play an important role in the performance of buildings. They define the architectural aesthetics of buildings and separate the occupied indoor space from the outdoor environment. Historically, façades were considered to be a load-bearing structural element and limited in their functionality and adaptability to environmental changes. The application of bio-inspired strategies to building façades that are derived from principles found in nature offers more flexibility and adaptability to the external environment. This research presents a bio-inspired adaptive façade system that is derived through the biological analysis of a deformability mechanism, namely, turgor-based actuation, found in plant movements. The adaptive prototype module inspired by a nastic movement is composed of two lightweight triangular plates connected to pneumatic artificial muscles that control folding and unfolding of the device by pressurization. Finally, the application of adaptive modules in a building façade is simulated via computational 3D modelling. The simulation analysis shows the possibility of creating a system from numerous modules that can create a rich palette of typologies resulting in a gradient of openings. This could be an appropriate solution for an external shading device or as regulator for air ventilation and light transmission.

Keywords: Biomimetic, Plant-inspired, Pneumatic actuation, Plant adaptation.

1 INTRODUCTION

The façade on a building is an extended buffer between the interior space and exterior environment. It defines the architectural aesthetics and plays an important role in controlling energy consumption in the building. Historically, the façade has been considered a primary load-bearing structural element that acts as a thermal barrier to prevent heat gain. The building envelope integrates about 80% of the outside environment (Etman et al. 2013); thus, the façade is no longer only an interface between the inside and outside of building. It must be designed as an adaptive layer that provides more flexible space, thermal comfort, and adaptability to changing conditions. For these reasons, implementing adaptive solutions can enhance the performance of building façades and potentially reduce the energy demand of the whole building (Badarnah 2017).

In biology, adaptation is the behavioral process living organisms use to survive in their surrounding environment. This process can be observed in nature, both in animals and plants, that have unique mechanisms that enable them to adapt to extreme environmental conditions easily. The imitation of adaptive strategies used by these organisms has been mostly applied in building façades where the skin is dynamic and responds to the external environment to create more sustainable and energy efficient buildings. For example, the use of a kinetic shading façade inspired by tree organisms and behavior in Council House 2 in Melbourne provides an energy savings of 82% and reduces artificial light and mechanical ventilation by 65% (Radwan et al. 2016).
Because of the high potential of applying biomimetic approaches to architectural designs, this paper presents research on a kinetic façade system that is derived from nastic movement in plant. The adaptive prototype module is composed of two lightweight triangular plates that are foldable by pressurization. Finally, the application of adaptive modules in a building façade is simulated via computational 3D modelling.

2 PLANT-INSPIRED MECHANISMS

Architects and designers have taken inspiration from nature to solve particular design problems. Several terms have appeared to describe the flow of ideas from nature to technical solutions, such as bio-inspiration, bionics, biomimicry, and biomimetics. All these terms refer to the sciences that observe the form, the function, and natural ecosystems to produce sustainable solutions for humans by imitating or taking inspiration from them (Tavsan and Sonmez 2015). The biomimetic approach can be initiated by a problem-based strategy (top-down approach) or by a solution-based strategy (bottom-up approach).

Plants represent a minor part of biomimetics used in architectural design. Plants are known as sessile structures that are incapable of changing their location. Therefore, they must react to changes in environmental conditions, such as the light, humidity, temperature, and air quality, through adaptations that are categorized as static strategies or dynamic mechanisms (López et al. 2015). Static strategies refer to the multifunctional properties of plant leaves, for example, the hairy leaves of an Alpine snapdragon that are used for protection against excessive temperatures due to sunlight (Figure 1a). The dynamic mechanisms result from the responses of plants to external stimuli through movements, for example, the opening and closing of conifer cones due to changes in the humidity level (Figure 1b).

According to Sonnewald (2014), plant movements can be classified into tropisms and nastic movements. Tropism is the growth of a sessile plant in response to external stimuli depending on its direction, such as the heliotropism of Arctic poppy (Papaver radicatum) that moves toward the sunlight. In contrast to Tropism, Nastic movement is a non-directional response to external stimuli. Most nastic movements are often due to changes in the turgor pressure, for example, a thigmonasty in Mimose (Mimosa pudica) that folds its leaves within a few seconds of being touched.

Nastic movements, which are the focus of this work, are classified into two types. Autonomous movements are driven by motor organs, for example, the pulvinus. Non-autonomous movements are caused by the direct application of mechanical forces, and these can be subdivided into reversible elastic deformations and movements of a hinged organ (Poppinga et al. 2010). Unlike animals, plants convert hydraulic pressure into various types of movements of their organs.
(Stahlberg 2009). For instance, they generate a hydrostatic pressure through the process of osmosis to stiffen and stabilize their cells, tissues, or organs (Gibson and Ashby 1982). The hydrostatic pressure inside plant cells, known as turgor pressure, plays an important role in the processes of growth and organ movements and also provides a hydrostatic skeleton to support leaves and stems. This principle of pressure-induced stability was used in the development of pneumatic and tensairity structures (Luchsinger et al. 2004). The best-known example of plant movement caused by turgor pressure is pulvinus-actuated leaf movements. When there is an unequal concentration of solutes, such as sodium or potassium ions, in pulvinus cells, a substantial water flow results, resulting in a sudden change in the turgor pressure in pulvinus cells that leads to leaflet movements (Figure 2).

![Figure 2. Leaflet movements due to changes in the turgor pressure in the pulvini.](image)

3 BASIC MODULE PROTOTYPE

The unit module employs plants as a biological model for the development of an adaptive shading structure. The unit prototype is composed of two lightweight triangular petal-like plates of the same size. Each of them are covered with a polyvinyl chloride (PVC) fabric and connected to V-link steel supports that are used for lifting the plates. The other side of each V-link steel support is connected to an artificial muscle by a pinned connection, as shown in Figure 3.

According to the actuation mechanisms in plants, their cells develop and maintain a high internal turgor pressure by injecting solutes into a confined space that results in a large variety of hydraulic actuation mechanisms; these are known as “plant muscles” due to similarities to filament-based muscle movements (Taya 2003). Plants use this hydration mechanism as the basis for the movement of their organs. Similarly, a pneumatic artificial muscle (PAM) (Figure 4) is introduced as the actuation mechanism to control the folding of triangular petal-like plates.

![Figure 3. Unit prototype for adapting a façade inspired by the turgor pressure in plants (1. Triangular steel structure of petal-like plate, 2. Hinge, 3. Vlink – transmission arm, 4. Pneumatic artificial muscle, 5. Straight link).](image)
A PAM, also known as a McKibben artificial PAM, pneumatic PAM actuator or fluidic muscle (Gaylord 1958 and Yarlott 1972), is a tube-like actuator that is characterized by a decrease in the actuating length when it is pressurized. A PAM consists of a long synthetic or natural rubber tube that is wrapped by a double helix synthetic fiber netting and attached by metal fittings at each end. The use of a PAM to manipulate the system fulfills the requirements of possessing a light weight and flexibility.

Figure 4. Pneumatic artificial muscle drive mechanism.

4 CONTROL AND ACTUATION

The proposed adaptive façade in this work focuses on the effect of fluid pressure in the opening/closing mechanism, which was derived from plant movements. The mechanical deformation process occurs in two main parts in this module. The initiator of the movement mechanism is the central part, which consists of a PAM operated by pressurized air from an air compressor under the control of a microcontroller unit (MCU). When the muscle is pressurized, the sleeve with a rhomboidal mesh transforms the growing air pressure inside the tube into a longitudinal force. Consequently, the expansion caused by a longitudinal force leads to lifting of the wings (open position), as shown in Figure 5.

Figure 5. The opening and closing mechanisms.
5 RESULTS

According to the prototyping model analysis, the displacement test is conducted to determine the maximum displacement of the PAM at different pneumatic pressures and degrees of lifting. The artificial muscle connected to the V-link transmission arms acts as a pneumatic actuator that is pressurized by an air compressor installed 10 meters away from the control unit. When the PAM is pressurized by the air compressor, the pneumatic pressure tries to expand the PAM and transmit the longitudinal force to lift the triangular plates, resulting in the folding movement. The displacement of the triangular plates (in degrees) at various pneumatic pressures is shown in Figure 6.

![Figure 6. The displacement of the triangular plates at various pressures.](image)

The graph in Figure 6 shows the relationship between the applied pressure and resulting displacement of the lifting wings. The change in the degree of displacement is gradually increased with an increase in the pneumatic pressure, where 3 bars are sufficient for a maximum lifting angle of 55.3°. After 3 bars of pressure, the displacement remains constant, although the air pressure still increases.

The unit prototype can be installed as a part of a multicomponent system, as an individual module, or in combination with another element in a building façade. Thus, there is an opportunity for numerous configurations. Therefore, a rich palette of typologies and a gradient of openings can be created through the opening and closing mechanisms, which can provide shading for a building façade or function as a regulator for air circulation, as shown in the design proposal in Figure 7.

![Figure 7. Application as an external shading device.](image)
6 CONCLUSION

The building façade is the most important factor that determines the energy consumption of a building due to the vast surface area. Biological analogies or biomimetic approaches, such as plant adaptations, can provide innovative ways to increase the energy efficiency of buildings. Several recent studies show that a biomimetic façade can reduce energy consumption by 50% for all climate zones and in all building types (Webb 2022). Plants represent one of the main contributors to biomimetics in architectural design. Unlike animals, plants are tied to specific location. Therefore, they must adapt themselves to environmental changes for survival. For this reason, plant movements can be suitable role models for an adaptive façade.

The aim of this work is to present the unit prototype for an adaptive façade system derived from plant movements. The deformability mechanism and turgor pressure actuation found in plants are translated into design solutions for an adaptive façade. The unit prototype consists of two lightweight triangular petal-like plates, which were inspired by a plant leaflet. The plates can move by the actuation of a PAM; thus, the structure is light weight and flexible. The experiments are conducted to study the motion characteristics and performance of the façade system. A maximum displacement of 55.3° is obtained with an air pressure of 3 bars at the no external load condition. However, other aspects need to be further investigated, such as the actuation of the system, the wind load resistance and ventilation performance, to achieve maximum efficiency for an adaptive façade design.

References

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