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Plant-inspired compliant actuation

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Micro Abstract
Compliant systems with an integrated actuation allow adaption to varying requirements. In this context the cellular structure of plants is a valuable source of inspiration. Plant cells are hydraulic systems that can serve as actuators. Specialized motor cells change volume and shape depending on the internal cell pressure. Besides that the stiffness of parenchymatous plant tissues can change with turgor. Inspired by this a cellular pressure driven actuator capable of varying shape and stiffness can be developed.

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Introduction

Latest research in different fields of engineering suggests a shift from rigid body mechanics towards compliant systems to provide adaption to changing requirements with a reduced mechanical complexity. Kinetic structures usually consist of several rigid elements connected by hinges, which demand precise manufacturing and perfect alignment. This complex construction principle makes them prone to failure and requires intensive maintenance. An innovative approach to reduce the mechanical complexity of kinetic systems is the development of compliant systems. Here, the flexibility of the system is based on the elastic deformation of the material. Existing compliant shading systems are actuated externally and therefore posses elaborate support systems including motors or hydraulic cylinders, requiring additional space at the supports. To further reduce the mechanical complexity of the systems the actuation is proposed to be integrated into the elements. Also an adaptive stiffness of the systems is desirable to enable the structure to be able to bear high external loads and at the same time allow the elastic deformation of the structure. In this context plants are a valuable source of inspiration. Their hinge-less folding principles were already the role model for the development of compliant shading systems as the Flectofin® or Flectofold. Beyond that their cellular structure shows possibilities for integrated actuation and variable stiffness. Plant cells are hydraulic systems that can serve as actuators. Specialized motor cells change volume and shape dependent on the turgor, affecting also the stiffness of the plant tissue. Inspired by this, a cellular pressure driven actuator capable of varying shape and stiffness is developed.

1 Computational analysis of the biological role model

One example for turgor dependent actuator cells are the slow motor cells, also called bulliform cells. They are enlarged, thin-walled epidermal cells often arranged in groups on the adaxial side of the leaf, either over the whole width or as in the here examined example only close to the mid-vein. On the abaxial side, there are lignified strengthening tissues such as vascular bundles and sclerenchyma fibres. In rice, maize, wheat and other grasses bulliform cells are suggested

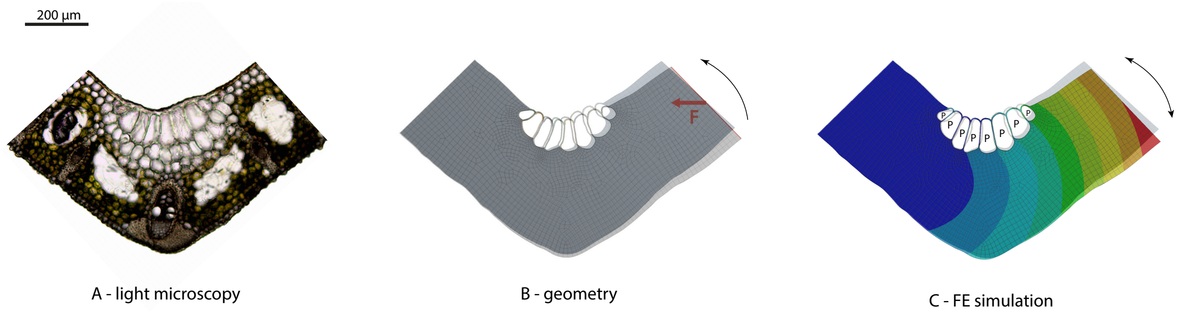

Figure 1. Process of transferring the geometry of bulliform cells of *Carex flacca* to a FEA simulation. A increase/decrease in cell pressure (P) leads to a opening/closing movement (C).

to be responsible for the joint-free movement of the leaves. During drought, the bulliform cells are assumed to shrink because of decreasing turgor pressure. Consequently, the two edges of the grass blade fold up towards each other. The folding up reduces the transpiration rates as it allows the creation of a micro-climate. As soon as sufficient water is available, turgor increases and the bulliform cells enlarge once again. This results in an opening of the leaves which guarantees higher exposure to solar radiation. [1, 2, 5]

The exact mechanics of this process, however, has not been described yet. A FE-model was used to further comprehend the role of bulliform cells in leaf movement (see Figure 1). In order to do so a fresh and unstained cross section of a leaf of *Carex flacca* was studied using light microscopy images and subsequently reconstructed by the usage of computer-aided design software. The 2D-geometry was extruded to achieve a 3D model which was then imported into a FEA tool (ANSYS® Academic Research, Release 16.2). The walls of the bulliform cells were represented by shell elements, whereat the averaged cell wall thickness was determined beforehand from the microscopy image with the help of an image processing program. The surrounding tissues are represented by one solid body whose assigned Young's modulus is three times lower than that of the bulliform cell walls. This ratio was derived from literature values for cell walls and tissue properties of different plant tissues.

Light microscopy images represent the leaf in an open position with fully turgscent cells. In the model an increasing turgor leads to a further unrolling movement of the leaf segment. The reduction of the turgor or shrinkage of the cells, represented by negative pressure values, proved to be less effective in causing changes in the leaf configuration. More likely, also in terms of plant physiology, seems a mechanism assuming the bulliform cells work against a pre-tensioned leaf thriving towards the closed position, so that a loss of turgor passively leads to a closing movement. In order to induce the necessary pre-stress, the geometry of the leaf segment in the closed position was approximated by applying an external load (F = 0.02 N) to bend the leaf section in the closing direction (see Figure 1 - B). The resulting stresses were then set to zero and the resulting geometry served as the basis for a new simulation where hydrostatic pressure was applied to the bulliform cells to imitate increasing turgor. This approach resulted for a given pressure change in the highest deflection.

The simulation shows that a change in cell shape caused by varying turgor can affect the configuration of a whole structure. This further suggests the hypothesis that bulliform cells are likely to be responsible for the rolling/unrolling of the grass leaf.

2 Technical transfer

The approach of using pressure dependent cellular systems for adaptive systems has risen the interest of engineers. The potential utilization of pressurized cellular structures for technical adapting systems has been investigated by several authors with a special focus on the application

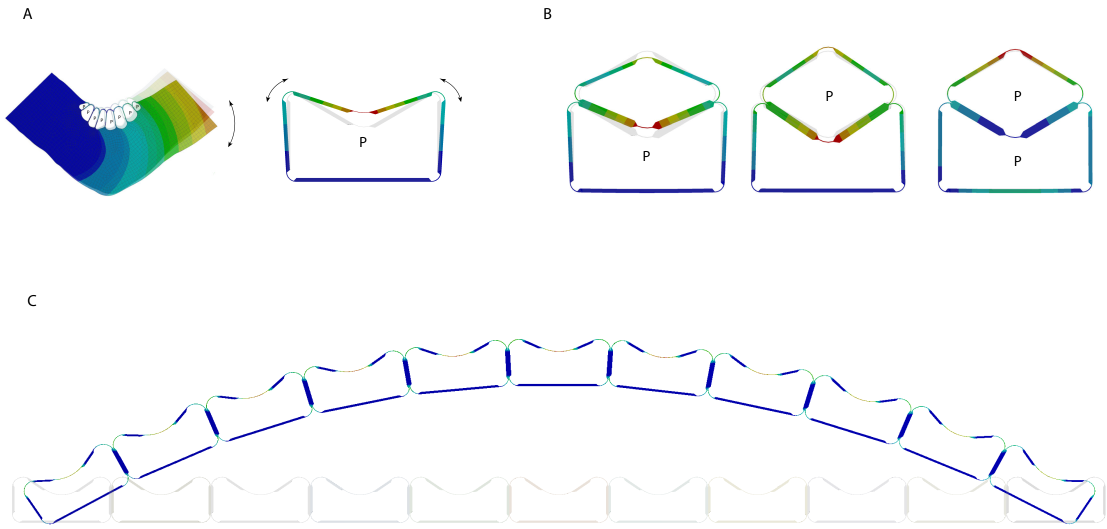

Figure 2. A - Transfer of the functional principle of pressurized cells to a technical cell. An increase in cell pressure leads to a change in cell volume and shape. B – The addition of a second counter acting cell allows the decoupling of internal pressure and cell deformation. C – Accumulation of the in individual cells in sequence leads to a bending actuator. (The width of each technical cell is 80 mm.)

in the field of morphing wings [4, 6, 8–11]. Cellular systems are suggested not only to be easier in control, but also to be more reliable, energy efficient and to exhibit a better strength to self-weight ratio. This investigation aims to use the plant-inspired functional principle of pressurized cellular systems as actuators for other compliant mechanisms that use e.g. folding techniques to enhance a certain actuation movement. Furthermore, it will be investigated how the pressure can additionally be used to also adapt the stiffness of the system. A change in stiffness dependent on the turgor is known for non-lignified plant tissues as the parenchyma and has been investigated in several studies [3, 7]. On the technical side Vos et al. [11, 12] also investigated pressure-adaptive honeycomb structures to alter the structural stiffness of a system.

As mentioned before for plants, reversible macroscopic movements are caused by changes in cell volume due to varying turgor. To transfer this principle to a technical structure a cell geometry needs to be defined in such a way that upon pressurization, it shows the desired movement. In the case of a bending actuator this cell shape can resemble similarity to the grass leaf segment with group wise arranged bulliform cells (Figure 2 - A). As the pressure in the cell increases, it aims to maximize its volume. For the technical cell in Figure 2 - A that leads to the tilting of the outer horizontal walls, which accumulated in a row of cells causes a bending movement of the whole structure (Figure 2 - C). To allow a proper connection, the stiffness of the straight cell walls needs to be high enough such that the internal pressure does not deform them. The reconfiguration of the cell is enabled by the compliant hinges. For the simulation and prototyping, glass fibre reinforced composites are chosen as cell wall material. It has to be mentioned that the size of the technical cells is thereby several orders of magnitude larger than that of the biological role model. An up-scaling of the cell-size is possible but affects the material selection and also the required cell pressures [8].

Assuming a cell with rigid cell walls and sufficiently compliant hinges a higher internal pressure results in a higher stiffness of the cell. This is due to the fact that at higher pressures more energy is needed to reduce volume and therefore the resistance to external loads is higher. However, with the proposed technical cell shown in Figure 2 - A, the shape also changes with pressure. This means that a higher stiffness can only be achieved in combination with a large deformation of the cellular actuator. By adding a counteracting second cell, pressure and deformation can be decoupled allowing for an increased stiffness also without a deformation of the cellular structure (Figure 2 - B).

Simulations of a horizontal cell row (using hydrostatic fluid elements representing the air inside the cells and being able to account for pressure-volume-coupling) show the higher resistance to external load at higher internal pressures. Figure 3 displays the simulation result for a cell row of six glass fibre composite cells (isotropic, linear-elastic material properties, E-Modulus: 15 GPa). One can see that dependent on the internal cell pressure, the deflection caused by an external load F (10 N) decreases by approximately 60% as the pressure is increased from 0.001 to 0.02 MPa.

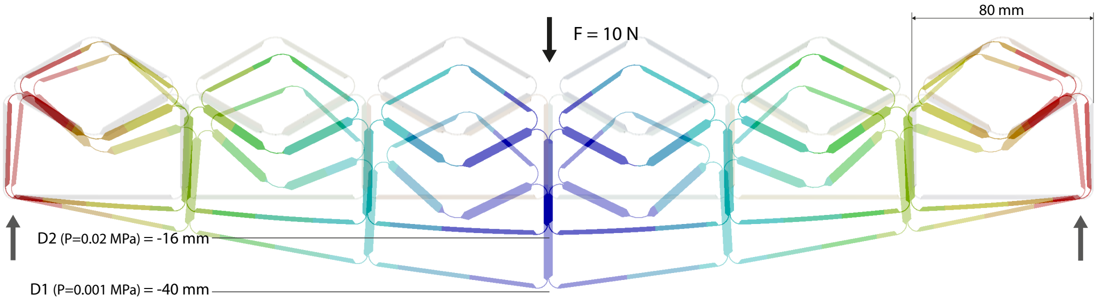

Figure 3. Deformation of a pressurized cell row due to an external load F. The higher the internal pressure the higher the system stiffness and lower the vertical deflection. (The width and depth of the cells are 80 mm.)

Conclusions

The investigated plant-inspired cellular structure is capable of creating convex as well as concave curvature. At the same time it can change its stiffness depending on the applied internal cell pressure. In a next step, the potential use of actuating compliant mechanisms and the adjustable stiffening effect on the overall structure will be investigated. This could, for example, enable the system to bear infrequent higher external loads occurring only during extreme conditions. This feature would allow to design the system less stiff to reduce the material usage and energy consumption during everyday operating conditions.

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References

[1] J. M. Alvarez, J. F. Rocha, and S. R. Machado. Bulliform cells in Loudetiopsis chrysothrix (Nees) Conert and Tristachya leiostachya Nees (Poaceae): Structure in relation to function. *Brazilian Archives of Biology and Technology*, 51(1):113–119, 2008.

[2] O. Betz, A. Birkhold, M. Caliaro, B. Eggs, A. Mader, J. Knippers, O. Röhrle, and O. Speck. Adaptive Stiffness and Joint-Free Kinematics: Actively Actuated Rod-Shaped Structures in Plants and Animals and Their Biomimetic Potential in Architecture and Engineering. In J. Knippers, K. G. Nickel, and T. Speck, editors, *Biomimetic research for architecture and building construction*, Biologically-Inspired Systems, pages 135–167. Springer, Cham, 2016.

[3] M. Caliaro, F. Schmich, T. Speck, and O. Speck. Effect of drought stress on bending stiffness in petioles of Caladium bicolor (Araceae). *American journal of botany*, 100(11):2141–2148, 2013.

[4] B. Gramüller, J. Boblenz, and C. Hühne. PACS—Realization of an adaptive concept using pressure actuated cellular structures. *Smart Materials and Structures*, 23(11):115006, 2014.

[5] A. Kadioglu and R. Terzi. A Dehydration Avoidance Mechanism: Leaf Rolling. *The Botanical Review*, 73(4):290–302, 2007.

[6] Q. Luo and L. Tong. Adaptive pressure-controlled cellular structures for shape morphing: II. Numerical and experimental validation. *Smart Materials and Structures*, 22(5):055015, 2013.

[7] S. B. Nilsson, C. H. Hertz, and S. Falk. On the Relation between Turgor Pressure and Tissue Rigidity. II. Theoretical Calculations on Model Systems. *Physiologia Plantarum*, 11(4):818–837, 1958.

[8] M. Pagitz and E. Kappel. Design of Pressure Actuated Cellular Structures. 2014.

[9] M. Pagitz, E. Lamacchia, and J. M. A. M. Hol. Pressure-actuated cellular structures. *Bioinspiration & Biomimetics*, 7(1):016007, 2012.

[10] S. Vasista and L. Tong. Design Considerations of a Pressure Driven Morphing Wing Structure. In *Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences*, pages 2174–2183, 2012.

[11] R. Vos and R. Barrett. Mechanics of pressure-adaptive honeycomb and its application to wing morphing. *Smart Materials and Structures*, 20(9):094010, 2011.

[12] R. Vos, R. Barrett, and A. Romkes. Mechanics of Pressure-Adaptive Honeycomb. *Journal of Intelligent Material Systems and Structures*, 22(10):1041–1055, 2011.