A methodology for transferring principles of plant movements to elastic systems in architecture

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HIGHLIGHTS

• Plant movements.
• Kinetic structures.
• Biomimetics.
• Facade shading.
• Compliant mechanisms.

ABSTRACT

In architecture, kinetic structures enable buildings to react specifically to internal and external stimuli through spatial adjustments. These mechanical devices come in all shapes and sizes and are traditionally conceptualized as uniform and compatible modules. Typically, these systems gain their adjustability by connecting rigid elements with highly strained hinges. Though this construction principle may be generally beneficial, for architectural applications that increasingly demand custom-made solutions, it has some major drawbacks. Adaptation to irregular geometries, for example, can only be achieved with additional mechanical complexity, which makes these devices often very expensive, prone to failure, and maintenance-intensive.

Searching for a promising alternative to the still persisting paradigm of rigid-body mechanics, the authors found inspiration in flexible and elastic plant movements. In this paper, they will showcase how today’s computational modeling and simulation techniques can help to reveal motion principles in plants and to integrate the underlying mechanisms in flexible kinetic structures. By using three case studies, the authors will present key motion principles and discuss their scaling, distortion, and optimization. Finally, the acquired knowledge on bio-inspired kinetic structures will be applied to a representative application in architecture, in this case as flexible shading devices for double curved facades.

1. Introduction

Contrary to the widespread notion that architecture focuses only on the planning of rigid and immovable structures, the increasing use of kinetic structures in our built environment proves that the border between building and machine has already been crossed. A closer look at how buildings are manufactured, constructed, and operated reveals that today’s living spaces have a considerable amount of moving parts and helpful devices that serve a large number of different tasks. Typically, these are mechanical systems that are implemented whenever there is a need for adaptation to internal or external factors through means of spatial adjustments. Once an actuating force is provided, they transform energy into movements that open, close, release, stop, direct, regulate, accommodate, counteract, control or fulfill many other functions. Examples range from simple small-scale applications like valves and flaps to medium-scale applications like doors, windows, blinds, louvers, and shutters to more complex large-scale applications like adaptable facades, retractable roofs, or folding bridges.

Similar to other areas in engineering, kinetic structures in architecture are usually based on the basic construction principles of rigid body mechanics. For design, one can therefore draw from the same engineering knowledge, scientific theories, and wealth of experience that has already provided the basis for...
many technical achievements. However, there are some profound differences between kinetic structures in industrial machinery and architecture [1]. Movable structures in architecture are usually produced in small quantities or uniquely designed and manufactured for every application anew. Furthermore, while mechanical devices in the automotive or aviation industry constantly evolve due to extensive test runs and prototypes of various scales, these custom-made architectural devices are already the final product and often have to function at the first attempt. All of these aspects sum up and cause inevitably high planning and acquisition costs. Besides these disadvantages, kinetic structures in architecture are confronted with some particular challenges, which not easily align with the fundamental construction principles normally used in machine design [1]. The traditional design approach prioritizes uniformity, regularity, and compatibility over individuality and adaptability. As a result, mechanical devices are usually conceptualized as mono-functional and standardized modules whose mechanics conform to a grid of orthogonal axes. A mechanical system like this, however, entails many limitations and is difficult to be applied in other than planar and parallel configurations. Here, adaptation can only be achieved at the expense of additional mechanical complexity, which results in heavy and maintenance-intensive structures. In summary, it can be said that the traditional approach of designing kinetic structures has created some hindering inertia that is difficult to reconcile with the increasing demand for individual technical solutions, as they are particularly sought after in architectural devices.

2. Plant movements as inspiration source for new elastic systems in architecture

Aiming for a radically different design approach, the authors suggest rethinking the primacy of rigid body mechanics and instead learning from the soft mechanics that can be observed in plants. They argue that the flexible motion principles in plant movements can be successfully transferred, scaled-up, and integrated in lighter and less complex bio-inspired mechanical devices. To test this hypothesis, the authors teamed up for a trans-disciplinary collaboration of architects, engineers, and biologists. This combination enables a seamless knowledge transfer between basic biological research (biology) and man-made technology (architecture and construction). Although both research fields investigate a wide range of highly sophisticated movable devices, these mechanical systems are neither akin nor cover the same performance spectrum. In mechanical engineering, for instance, motion is mainly obtained by linking rigid elements with technical hinges, whereas mobility in nature is often gained by the targeted deflection of structural members [1]. This constructional design approach, which is based on flexibility rather than on movable joints, is diametrically opposed to the still persistent paradigm in mechanical engineering. While so-called compliant mechanisms, for example, are rampant in nature, they are largely unknown in engineering or only implemented in very few special-purpose applications [2]. Consequently, it is not surprising that the use of compliant mechanisms for large-scale architectural applications is almost non-existent in the building industry.

With their countless fascinating motion principles, however, plants can well be a promising inspiration source. In particular, the bending and folding mechanisms of leaves and petals demonstrate, impressively, how to reduce the number of susceptible mechanical parts by making use of flexible and elastic material properties. Many examples show, that when it comes to the topic of movement, plants blur the boundary between structure, material, and mechanism [3–10]. Since plants have little diversity in building materials (e.g. cellulose, hemi-cellulose, pectin, lignin), mechanical adaptation is mostly based on variations in form and structure on different hierarchical levels [1]. Compared to technical systems, which typically align rigid bodies of various materials, these pliable structures in nature integrate diverging characteristics in all-in-one multifunctional components. Global flexibility is often achieved through the versatile behavior of locally differentiated regions with special morphological features that act as living hinges and allow for large elastic deformations. While civil engineers perceive a structure's instability mostly as undesirable failure, plants systematically exploit structural malfunctions to their advantage. In fact, some plant movements are composed of a series of individual buckling failures that together form a cascading sequence, in which the deformation of one element will subsequently trigger the deflection of an adjacent member and finally result in the movement of the entire organ. In these plants, structural members are often linked together in the form of a biological compliant mechanism that is capable of transmitting forces, torque, and motion. Plant-specific geometrical and material relationships often contribute to this linkage and increase its efficiency. The prospect of learning how to gear the flexibility of a kinetic structure by either fine-tuning its geometrical constituents or tailoring its material characteristics is the motivation for the next step in this research. It is devoted to the questions of exactly how it is possible to model plant movements and how to transfer the underlying motion principles to technical devices.

3. Mapping repeating themes and emerging trends of a possible transfer process

In the following, the authors aim to address the question of modeling and transferring the plants’ underlying motion principles by proposing a methodological framework with procedural themes and categories. According to their experience, however, the working process therein is not always one distinct, linear progression that follows a chronological sequence. Instead, it seems to operate like a vibrant composite, in which biomimetics acts as a connecting theme in the process that brings individual key aspects together. Since it is very difficult to identify possible intermediate steps, previous definitions have focused mainly on the motivations for entering biomimetics. According to Speck et al. [11], for instance, an initial approach to biomimetic research can either follow a biology push (bottom-up process) or a technology pull (top-down process). While the biology push describes a development which is initiated from basic knowledge in biology, the technology pull is motivated by the desire to solve a technical problem in order to improve an already existing product or process. In respect to the dynamics of architectural developments, however, this clear linear development is often difficult to maintain and, instead, asks for an expanded definition of the biomimetic working process. To facilitate a better navigation, therefore, the authors mapped the themes that repeatedly informed their research, as shown in Fig. 1.

3.1. Analyzing biological role models and their functional morphology

In most cases, the process starts with finding a suitable role model and describing its motion, as well as the composition of the moving organ as accurately as possible. The next step is to identify and locate all elements that play a key role during the deformation and to define their functional–morphological relationship. An important point is the elucidation of the principle(s) of actuation: plant movements can be actuated hydraulically by a displacement of water in the respective tissue, or by implementing elastic instabilities (pre-stressed organs, snap-buckling, explosive bursts) to speed-up the motions, or function completely passively by an application of an external mechanical force [9,10,12]. Once examinations have revealed the general characteristics of the
movement, it may be useful to expand the screening. Generally, the mechanism observed may show a “natural variability” in the same species (or among closely related species) due to heterogeneous expressions in organ structure. Such variations may indicate a potential resilience of the mechanism to distortions. On the other hand, it may also represent an acquisition of the same trait (evolutionary answer) in distinctly related lineages (“convergence”). In such a case, the respective mechanism has evolved several times independently as a result of the same boundary conditions (evolutionary pressure). The possible similarities and differences between plants with the same motion principles may indicate the conditions under which scaling and distortion of the mechanisms may be possible. A perfect example for this is demonstrated by the two closely related carnivorous snap-trap plants Dionaea muscipula (the Venus’ flytrap) (see Ref. [13] for a figure) and Aldrovanda vesiculosa (the waterwheel plant) (Fig. 8). The latter will be discussed in detail as a case study in Section 4.2. Although Darwin already regarded Aldrovanda as an aquatic miniature version of the terrestrial Dionaea, it was recently shown that both plants, which are sisters and share a common ancestor, shut their traps in very different mechanical manners, which is most presumably due to the different life-forms and physical constraints in their respective colonized habitats (air/water) [12, 14].

3.2. Disclosing motion principle

When the plants essential components and functional–morphological relationships are unveiled, the next step is to abstract them to the simplest mechanism, best capable of demonstrating the underlying “Wirkprinzip” (elementary principle of functioning). Following the idea that initial simplification may lead to greater diversity in the long run, this step aims to reduce the complexity in order to find the basic principle of the mechanism. A subsequent reconfiguration of the identified building blocks may open up a larger design space of simple, compound, or even complex solutions. Therefore, this approach may render it possible for a systematic and far-reaching design exploration, beyond the direct copy of the biological role model.

3.3. Modeling bio-inspired mechanisms

The term mechanism is mainly used in mechanical engineering for a technical device that is capable of transferring motion, force, or energy [15, 16]. However, when reduced to the basics, this explanation seems also suitable for describing the motion principles in biological structures, in particular, when including the extended definition of so-called compliant mechanisms. These devices can also transfer or transform motion, force, and energy, but instead of joining rigid links with hinges, their mobility is based on the deflection of flexible members [2]. Hence, in their purposeful exploitation of flexibility and elasticity, compliant mechanisms and plant movements are very similar due to their sole reliance on deformation principles. In detail and in scope, however, some biological structures may be partially ahead of their technical counterparts because they have not originated from a design process of well-established types and categories. On the contrary, their typology-free approach to flexible mechanics makes them an appropriate starting point for the development of novel compliant mechanisms. For the computational design of a bio-inspired mechanism, however, it seems important to recognize its hierarchical composition, in which three aspects build up on one another and form a positive feedback loop. This can be represented with a geometric, kinematical, and kinetic model, as shown in Fig. 1. These digital models offer the possibility for target-oriented computational analysis.

A geometric model drawn in a conventional CAD environment is usually a good starting point because it provides a precise yet immovable representation of the structure’s shape. It can be based on previous investigations of plant geometry, for instance, using 2D or 3D scans. When the functional–morphological dependencies are known, it is also possible to build a parametric model of the mechanism. Here, topological relationships between elements stay fixed while the parameters that define the shape become variable. With this kind of model it is possible to quickly generate a series of similar mechanisms that differ slightly in size and proportion. Based on this, an abstracted kinematical model can be built in the CAD environment. This model enables a focused examination of the mechanism’s motion, considering only the geometrical aspects without reference to either masses or forces that actuate the movement. Here, the flexible elements in the mechanism are replaced by a series of rigid links and connecting hinges. Once the system is specified by assigning degrees of constraint (DOC) and degrees of freedom (DOF), it becomes possible to determine the structure’s kinematics. This form of representation can describe the mechanism in relation to its position, displacement, path, and rotation. For simple constellations, a kinematical model also has limited suitability to determine the interplay of forces and geometries in a compliant mechanism. This is achieved by applying torsional springs for an analytical analysis of forces and motion based on the calculation of virtual work in the system. This so-called pseudo-rigid-body model replaces in-depth nonlinear analysis with a closed form analytical description based on the theories from classical mechanics [2]. This closed form solution of the mechanism enables a fast calculation of the forces and motion in the system and thereby offers an excellent basis for in-depth parametric studies and optimization of the basic mechanical system.

The kinematical approximation compares to the more precise representation of a kinetic model, which studies the movement in a system under consideration of external forces and internal
material stresses. At this point, it should be emphasized that the traditional distinction between kinematics and kinetics as separate entities is based on the assumption of dealing with rigid bodies. In order to describe the mechanics of flexible bodies, however, the study of forces and motion has to take place simultaneously since their geometry and motion depends on the forces exerted on them. This fact increases the complexity of analysis significantly. Fortunately, today’s advanced FEM (Finite Element Modeling) simulations make it possible to calculate the forms and forces of structures under large elastic deformation and in complex equilibrium states. In comparison to previous models, the special feature of FEM is that it displays the nonlinear behavior of the system and enables a look inside the mechanism’s elements during the deformation and therefore can offer a more complete mechanical description of the system. Since FE-simulations are based on the exact physical properties of a system, they cannot only accurately represent the complex geometrical changes that occur during the deformation process but also provide an extensive overview of all stresses and forces therein.

Each of these models has its strengths and weaknesses. The great opportunity for the design of bio-inspired mechanisms lies, consequently, in the combination of all three models. Therefore, one has to overcome the individual drawbacks and simplify the information exchange between them. FEM, for instance, may be very precise in its results but is currently less suitable as a design environment. Both setting a model up and simulating the deformation often takes too long to provide the immediate feedback needed for a creative design process. In addition, while it is relatively easy to change material properties or support conditions in FEM, modifying a model’s input geometry requires a switch back to the pre-processing environment (text or CAD based). In order to accelerate this process, it would be best to couple all models in such a way that changes in one automatically re-compute information in the others without the necessity for manual adjustments. In such a synchronized design environment it would be possible to immediately study how geometrical, structural, and material changes affect the kinetics of the elastic mechanical system. The resulting information can then be used to systematically evaluate various models according to their mechanical performance or to fine-tune a compliant mechanism to the most effective setup for a given task.

3.4. Conceptualizing flexible component

The next step after modeling a bio-inspired mechanism is to consider its practical use and possible implementation. A kinetic structure that takes internal as well as external factors into account is referred to as a flexible component. Depending on the application, this flexible component has to meet specific functional demands, material requirements, and load profiles. Furthermore, the application of flexible components may require special orientation for the functioning. In this case, the tessellation and panelization of a targeted structures or surface plays an important role and defines the shapes of the components. This spatial arrangement also affects the possible locations for sensors, actuators, and control systems. The transfer process usually ends with a proof of concept, a materialized prototype or mock-up, for example.

4. Exemplary case studies

To illustrate the proposed methodology more clearly, it was applied to three exemplary plant movements. Each of the plants features a compliant mechanism, which is particularly promising for mechanical abstraction and further transfer. The authors have selected these case studies because they represent three basic actuation principles that are typical for kinetic structures in plant kingdom yet very unusual for kinetic structures in mechanical engineering. These mechanisms can be distinguished from one another by their characteristic actuation and the structural response in the respective plant organ: While the mechanism in Strelitzia reginae is driven by a punctually applied load, the mechanism of Aldrovanda is based on bidirectional changing surfaces, and the one in Lilium casablanca can be traced back to unidirectional expanding edge curves.

4.1. Case study 1: Strelitzia reginae

4.1.1. Biological role model

The first case study is a compliant mechanism found in the Bird-Of-Paradise flower (Strelitzia reginae, Strelitziaceae). This plant was chosen because it features a point-actuated, passive, and non-autonomous movement. The motion is part of an elastic and reversible valvular pollination mechanism, which is driven by the direct application of an external force. The latter, in particular, is of great significance, because it means that one can artificially trigger the mechanism over and over again and study the resulting elastic deformation closely. In previous publications, the authors reported already about the plant’s fascinating pollination mechanism and demonstrated its transfer to a novel technical product called FlectoFlor® [3,4,17–19]. In the context of this paper, the previous findings will be summarized and updated in order to generate a common basis for comparison with the following two case studies.

As an adjustment to its relatively large and heavy pollinators (mainly birds), Strelitzia reginae has developed a protruding perch of two adnate petals that act as a landing platform. When a bird lands on this structure to reach for rewarding nectar, its weight causes the perch to bend downwards, as shown in Fig. 2. This initial deformation triggers a secondary sideways flapping of two thick petal wings. As a result, the previously enclosed stamens are exposed and pollen is transferred to the bird’s feet. When the bird flies away, the open perch resets to a protective closed state again and the bird may transport the pollen to another Strelitzia flower where pollination takes place.

4.1.2. Functional morphology

The analysis of the functional morphology of this plant started with the identification of all the decisive members in the mechanism. Therefore, multiple specimens were dissected. A closer look at the cross-section of the perch showed its monosymmetric build-up [17]. Three loosely connected lateral ribs are located on each side, of which the uppermost features a thick petal wing that covers the sheath cavity of the perch. By gradually trimming the flower and cutting away all unrelated parts, the precise location of the compliant mechanism was revealed. Its essential members were traced back to a distinct mechanical interaction between the highest lateral rib and its adjacent wing
As seen in Fig. 3. These two elements are linked together in such a way that whenever a point-actuation causes bending in the rib, this initial deformation inevitably triggers a flapping motion of the wing. Here, the stored elastic energy in the deformed elements is enough to reset the system afterwards. It is particularly fascinating that this mechanism is not only reversible but also highly repetitive, even beyond its natural utility. While birds only visit the flower a few times during the flower’s lifespan, its mechanics are reliable enough to perform over 3000 cycles with only small signs of fatigue [19].

4.1.3. Disclosed principle

The underlying mechanical effect responsible for the deformation of this coupled system is called “lateral torsional buckling” and can easily be depicted with a physical model, as shown in Fig. 4. This physical model is a quick way to test the mechanism’s functionality in a different material composition. Here, the plant’s mechanical elements are abstracted as an elastic fin, which is attached perpendicularly to a stiff beam element. Uniaxial bending of the beam causes tension in the upper edge of the fin, which forces a subsequent out-of-plane bending of the fin when a critical point is reached. By deflecting to one side or the other, the fin dodges peak tension forces and deviates into a less strained equilibrium position. This special form of lateral–torsional buckling is not unfamiliar to engineers and is a common problem in structural analysis when loading thin-wall beams [20]. However, this mechanical effect is mainly perceived as a dreaded failure mode that needs to be avoided. For the plant though, this phenomenon does not have a negative connotation; it takes “advantage” of it in order to perform a specific movement. The idea to strategically functionalize this failure mode and embed it in a mechanism capable of amplifying the occurring effects is called Flectofin® [17].

4.1.4. Bio-inspired mechanism

Next to the physical model, it is also possible to simulate the mechanical behavior of the Flectofin® in a computational kinetic model by using FEM. The advantage of this digital form of representation is that one can test the system under several geometrical and structural configurations, including those that differ from the biological role model. Therefore, the adaptability of the mechanism to changes in the setup can be tested. Fig. 5, for example, shows the mechanism after several iterations. However, contrary to its biological counterpart and previous physical model, this version has two fins attached to the beam, each of them with the dimensions 2000 × 250 × 2 mm. The material properties for both beam and fins are standard values for hand laminated glass fiber-reinforced plastic (GFRP) with a Young’s Modulus of $E = 16,000$ N/mm². An externally induced support displacement causes bending of the eccentric beam and triggers the Flectofin® mechanism. In Fig. 6, the mechanism was additionally fine-tuned by changing the thickness and stiffness ratio between beam and fins. As a result, the two fins flip in opposite directions. Furthermore, their bending radii become much larger and the stress condition is more evenly distributed over the entire structure. This enables uniform material utilization. Additional reduction of stress concentrations was achieved by changing the fiber orientation and contour geometry of the fins, particularly at the location of surface transition to the beam. All these changes to the setup improved not only the system’s structural performance but also positively affected its mechanical efficiency, entailing an impressive optimization of the leverage. A small, slow, and powerful displacement of one support by 25 mm is needed to activate this 2 m long Flectofin® and to entail a large, fast, and spacious deflection of both fins [21–24]. (See Fig. 7.)
4.1.5. Special focus: scaling

Scaling the Flectofin®-principle was validated by small laser-sintered polyamide models of about 0.2 m length up to larger GFRP fins ranging in height between 2 and 14 m. Exploring the limitations of scaling flexible kinetic structures like the Flectofin® and therefore its applicability to large-scale constructions, gave rise to an in-depth analysis [25]. By comparing multiple slender structures in varying dimensions, this study revealed that scaling of elastic systems is highly dependent on the influence of dead load and stability. In fact, for the structural integrity, stability in respect to snap through buckling plays the decisive role. Compared to other structural systems, stability in bending-active structures cannot simply be achieved by increasing elastic stiffness, since element thickness is limited by material strength and bending curvature. However, there are ways to influence the stability of a structure: While residual compression stresses act destabilizing, tension stresses can generate a self-stiffening effect that increases a structure’s stability. Since the Flectofin® lamella in its deflected state exhibits predominantly tension stresses, one can observe an increase in stability. In addition, it is interesting that the up-scaling of a fin in length does not require a proportional scaling in thickness [17]. So while a 2 m long fin requires a thickness of 2 mm, a significantly larger 14 m long fin can be built with a thickness of only 8 mm. At some point the dead load becomes the predominant factor and thus gives the scaling an upper limit. Even though these findings may differ slightly between various systems, they clearly demonstrate the beneficial scalability of these types of systems for macro-applications.

4.2. Case study 2: Aldrovanda vesiculosa

4.2.1. Biological role model

The second case study is a compliant mechanism that can be observed in Aldrovanda vesiculosa (Droseraceae). This aquatic carnivorous plant is commonly known as waterwheel plant. It was chosen as a role model because of its quick and reversible snapping motion. Here, the movement is hydraulically driven by a central surface with a midrib, which both cause a bidirectional change in the plant mechanism. This compliant mechanism is particularly interesting since it is capable of transferring a small initial movement to a large subsequent motion of the entire plant organ. More precisely, it converts the bending of a central surface to an amplified motion of two adjacent lamellas. The resulting flapping motion is comparable to the Flectofin® yet inverse in its moving direction. Among biologists, the plant’s fascinating snap-trapping movement has already been the subject of multiple publications, which focused mainly on the physiological response to prey stimuli [26–28]. Only very few research groups, however, have investigated the trap’s post-stimulating mechanical aspects [14,18]. Therefore, the authors started their analysis by studying the plant’s functional morphology in order to disclose its motion principle.

4.2.2. Functional morphology and disclosed principle

The special features of Aldrovanda are its leaves that terminate in little clam-like traps of approximately 5 mm length, as shown in Fig. 8. Each of the traps consists of two sickle-shaped lobes that are connected to a lens-shaped central portion by a curved living hinge. In the symmetry axis of the trap and in the middle of the central portion is another distinct element—a midrib. Together the midrib and the central portion act as “driver” for the closing movement. When prey (e.g. small crustaceans like water fleas) stimulates the trap by touching its sensory hairs, it closes instantly. From a mechanical perspective, this rapid motion results from a controlled sequence of multiple interconnected deformations. At first, hydraulically actuated motor cells cause a bending in the midrib and in the central portion. This initial movement triggers a subsequent out-of-plane bending of the adjacent lobes due to their mechanical coupling to the central portion along the curved living hinge. It is astounding that this rapid underwater closure only takes ∼100 ms, and it is assumed that the trapping mechanics at work are an evolutionary answer to cope with water as a surrounding medium.
4.2.3. Bio-inspired mechanism

The trapping mechanism was abstracted as a cascading motion sequence with simplified origami patterns, which could be folded digitally using the Rigid Origami Simulator [29]. The mechanical behavior of these kinematical models is strongly influenced by the curved-line hinge geometry that provides a significant mechanical amplification [18]. Fig. 9 shows the flexible component with the corners A, B, C, D and two circular arcs along the diagonal. These arcs divide the square into two distinct portions, a lens-shaped center and two symmetrical lobes. After all the creases in this initially flat quad mesh are assigned to a folding direction, they either act as mountain or valley folds. Similar to the Flectofin®, the mechanism is actuated by a support displacement of D to D’. This translation movement causes bending in the center surface and triggers the flapping motion of the lobes (lifting point A and C). Typically, for curved-line folding, this principle couples convex and concave bending reactions, which increase in curvature as the folding proceeds. Due to the orientation of the curved-line fold, however, the lobes rotate in the opposite direction to the Flectofin® and thus, can be understood as its inverse mechanism. Using kinematical models is not only a quick method to retrace the displacement needed for opening/closing, but also creates an opportunity to determine a mechanism’s sensitivity in respect to its geometrical characteristics. One experiment, for instance, compared the displacement factors and transmission ratios of several models, which differed either in fold curvature or lobe proportions [18]. It was observed that the fold geometry has a strong influence on the mechanism. In the most cases, a less curved fold has a stronger amplification effect on the transmission.

After the kinematical models shed light on the mechanism’s geometrical interdependencies, they were turned into kinetic models by assigning different material properties. In FEM, they were remodeled as GFRP squares with a diagonal length of 1500 mm, a thickness of 10 mm (Young’s Modulus of \( E = 16,000 \text{ N/mm}^2 \)) in the central portion and 5 mm (Young’s Modulus of \( E = 12,000 \text{ N/mm}^2 \)) in the lobes. The curved-line fold was constructed as a 50 mm wide living hinge with reduced thickness of 1 mm (\( E = 12,000 \text{ N/mm}^2 \)). In Fig. 10, it can be seen that the bending of the central portion not only initiates a lifting motion of the lobes, but also causes increasing stresses in the bent surfaces. To stay within given material limitations and to meet a desired safety factor, the simulations were therefore checked carefully and the kinetic model was constrained in its geometrical adaptability to a specific feasible configuration.

4.2.4. Special focus: distortion

The most interesting finding in these experiments, however, was that the mechanism stays operative even when being scaled in size or distorted in shape. This positive behavior towards distortion opens up completely new possibilities. This can be illustrated effectively by applying the flexible component to synclastic and anticlastic surfaces, as seen in Fig. 11. While previous models were mapped on regular four-sided polygons, it is also possible to use any distorted polygon as a base as long as it stays convex, which means that all line segments between two vertices remain inside or on the boundary of the polygon. Therefore, modular arrangements beyond the orthogonal grid are possible. Lobe contours with corner angles of 60°, for example, enable hexagonal configurations. One has to consider, however, that the location-dependent distortion of the component affects its mechanical sensitivity. In order to guarantee that a group of components shows a similar response, despite the different position on the curved surface, one has to fine-tune their leverage individually, for example by adapting their fold curvature.

Fig. 9. Kinematic model of the abstracted folding mechanism reveals the influence of geometrical parameters on the folding motion. Source: Adapted from Fig. 4 of Ref. [18].

Fig. 10. Kinetic model of Aldrovanda’s snap-trapping mechanism in FEM.
4.3. Case study 3: Lilium casablanca

4.3.1. Biological role model

The third case study is the compliant mechanism in the flower of *Lilium casablanca* (Liliaceae).

It features a completely new principle for actuation and mechanical transmission that has not yet been implemented in any technical kinetic structure. Here, the movement of the plant organ is based on unidirectional changes at the periphery caused by differential edge growth.

 Shortly before the lily flower bud opens, it is tightly packed and around 100 mm long and 25 mm wide. It consists of three outer and three inner tepals. Each convex double-curved tepal has a significantly greater curvature along the lateral axis than along its longitudinal axis, as seen in Fig. 12. This bud geometry provides enough space and protection to enclose the flower’s sexual organs. When the lily blossoms, a relatively fast opening movement takes place, in which the bud bursts open as growth-induced stresses unlock the bond between the tepals. Once set free, they undergo a curvature inversion and bend outwards, which opens the flower widely. In some flowers, this plant movement is accompanied by a distinctive wrinkling effect that occurs typically along the tepal lamina edges.

4.3.2. Functional morphology

The flower’s growth, geometry, and mechanics have been investigated in great detail by Liang and Mahadevan [30]. By mapping the flower’s deformation with photogrammetric time-lapse videos, they created the base for a mathematical model with which it was possible to numerically simulate the blooming of the flower. They tracked down the mechanism that drives the opening in the lily to the differential planar growth that appears along the edges of the tepals. An excessive growth of the margin relative to the center causes a strain gradient in the lamina, which forces the
The opening movement of a lily bud is driven by differential edge growth in the tepals. The stamen (male flower parts) and the stigma (female flower parts) are indicated. The right image shows the fully opened flower from another angle. Note the wrinkled tepal edges that occur due to the growth processes.

Kinetic model inspired by the opening in the lily uses temperature differences to enforce edge expansion.

4.3.3. Bio-inspired mechanism

In particular for the lily mechanism, a holistic approach combining kinematical with kinetic analyses is needed since the driver for the movement is no longer based on external forces or modified geometrical boundary conditions but on internal changes of the material state (growth not only includes cell elongation but also cell division). This raises the question of how the plant’s growth processes can be mimicked by technical means. A first set of experiments, therefore, aimed to find a suitable mechanical concept with which to prove the proper functioning of the mechanism in general. The chosen approach was to simulate a temperature-controlled actuator that enforces edge expansion when heat is applied. Therefore, the lily bud was rebuilt in 2000 mm high parametric model and imported to FEM. To simulate the edge expansion, two idealized materials were assigned to the tepal surface (thickness = 2 mm, Young’s Modulus of $E = 12,000 \text{ N/mm}^2$, $\alpha_T = 17 \times 10^{-6}/\text{K}$) and the tepal edges (diameter = 13 mm, Young’s Modulus of $E = 3200 \text{ N/mm}^2$, $\alpha_T = 85 \times 10^{-6}/\text{K}$). These materials differed, in particular, in their thermal expansion coefficient by a factor of 5. Fig. 13 shows that locally increasing the temperature in the edges by 70 °C corresponding to 0.6% strain, provokes a comparable strain gradient in the structure as in the lily mechanism, forcing the tepals to bend outwards. Depending on the application scenario, an actuator like this could be built, for instance, by combining materials with diverging thermal expansion coefficients like GFRP and PMMA (acrylic glass).

4.3.4. Special focus: comparative study

The parametric model allowed also for a comparative study of multiple models that were all equipped with the same bending actuator yet featured slightly different geometries. Therefore, the parameters of the edge curves stayed constant while the surface curvature became the variable. Two radii in the lateral axis determined the rotational surface that spans between the curves, as shown in Fig. 14. Radius ($r_1$) defined the cross-section at the center and radius ($r_2$) at both ends of the surface. Fig. 15 shows 25 slightly different models. Viewed from back to front, radius ($r_1$) increases gradually in this series, which results in less curvature at the center of the surface. Whereas, viewed from left to right, the radius ($r_2$) decreases gradually, which results in greater curvature at the tepal tips.

All models were linked to the FE-program and assigned with the same idealized material properties. For actuation, the edge beams of all models were slowly expanded up to 1.1% of their individual length and their deformation individually calculated. For comparison purposes, various load cases were saved at different temperature increments and imported back into the CAD environment. A closer look at the models side-by-side revealed that their deformation behavior is all but uniform. Even though they are built from the same material and driven by the same actuators, some hardly deform at all whereas others deflect greatly. This is due to their structural stiffness that results from the geometrical shape of the tepal before deflection. In particular, the settings at the center cross-section influenced the model’s mechanical response the most. Fig. 16 (left) shows one extreme, in which, a smaller radius ($r_1$) creates a larger distance between the edges and the centroid of the cross-section and thus enables a more effective lever arm for the actuator; it also increases the global curvature of the surface significantly. Models with this geometrical...
Fig. 14. In this abstracted geometric model, variable parameters define the shape of the tepal.

Fig. 15. Combined parametric and kinetic modeling enables a comparative study between multiple structures with slightly different geometrical settings.

Fig. 16. FE-simulation of two models, which only differ in shape, shows how much the geometry affects the structures’ deformation behavior.

characteristic can offer more resistance and form a constriction at the center when being bent. This compares to all the models that have a larger radius ($r_1$). Here, less curvature in the tepal surface entails both little structural stiffness as well as an unfavorable lever arm. This leverage, however, is still enough to cause a curvature inversion in the surface and thus a large deflection of the structure,
as shown in Fig. 16 (right). Between these two extremes, the scope of possible reactions is wide. Depending on the balance between the model’s parameters, an initially homogeneous bending movement, for instance, may progressively dissipate energy by this edge wrinkling, which was previously described to occur during the lily opening. Another setting may cause the formation of smaller buckles and ripples in the surface that stall the movement or result in a cascading breakdown of the tepal.

5. Conceptualizing a flexible facade shading system

The case studies introduced above hypothesize that motion principles found in plant movements can be transferred to large-scale compliant mechanisms in architecture. One application that could greatly benefit from their use is the task of protecting modern building facades from the sun. Here, kinetic structures like blinds and louvers are used to reduce radiation loads and regulate the amount of daylight entering the building. By adaptively mediating between external environmental factors and internal user demands, shading devices are largely responsible for the quality and energy efficiency of our living spaces.

The problem with a shading device is though, that the performance greatly depends on its position inside or outside the facade. If it is external, the efficiency is 3–5 times higher [31]. This means, however, that the device is exposed to harsh weather influences (e.g. rain, wind, water, heat, cold, and pollution), which pose a major challenge to its complex and susceptible mechanics. Placing the sun protection behind the facade is not a good alternative either. Its lower performance increases the building's energy consumption and constantly requires artificial cooling of the heated spaces.

The authors believe that external facade shading systems, which are more resilient to weather influences due to their less prone flexible mechanics, may be a possible remedy and eco-friendly alternative. In addition, using flexible designs may widen the application range for shading systems to areas that are hardly attainable for traditional devices. The new design freedom becomes particularly evident in the task of shading fully glazed facades with double curved geometries. In most cases, traditional shading devices with their standardized mechanics cannot easily be adapted to the individually shaped facade panels. Customizing each and every device, however, would only increase the planning and material costs unreasonably. As a consequence, developers often plan curved facades simply without any sun protection, which is of course the most inefficient and user-unfriendly solution.

The following will demonstrate that flexible shading devices can tackle the geometrical and mechanical challenges of double curved facades. Therefore, the previously presented bio-inspired mechanisms were installed externally on a complex test surface, in this case an ellipsoid. For the panelization of the surface, a conformal mapping method was used, which results in a subdivision into planar elements of different sizes, but similar in shape and angles. In Fig. 17, for example, the ellipsoid was clad with the kinetic structure inspired by *Aldrovanda*. Each component was generated according to the individual information of the panels, as well as intrinsic mechanical interdependencies. Depending on the tessellation symmetry, the flexible components can be arranged in various ways. Some patterns may be more suitable than others for preventing interference or ensuring desired contact. In fact, the tiling enables another level of design freedom, in which a smart formations and clusters can create further synergy effects. In the chosen pattern, four neighboring components were oriented in such a way that the position of their actuators was concentrated to one point only. This allows a single actuator to drive a group of four components. A similar procedure can also be used for the lily-inspired flexible component, shown in Fig. 18. Here, the plant’s tepal shape was morphed to a square shingle. Similar to the role model, two adjacent edges perform as actuators and drive the deformation of a shingle as they expand. To prevent cascading buckling effects and to enhance the leverage in the mechanism, the shingle surface is slightly preformed. The undulated shell-like geometry provides an additional advantage by being more rigid against wind pressure. Furthermore, it can transfer compression loads to a sub-structure better, which would most likely align with the quad edges. Since the movement of the lily-inspired component differs from the previous example, the panelization and tessellation needed to be adjusted so that the component can perform best as a sunshade. Finally, similar strategies can also be implemented with the Flectofin® component, which stays operative even when being mapped to complex facade geometries as seen in Fig. 19.

6. Outlook

The here presented work demonstrates in general that new concepts for flexible kinetic structures can be derived from highly specialized plant movements. It also illustrates, however, how much natural systems differ from common engineering solutions in their approach to solve issues related to kinetic structures. Therefore, learning from these biological role models can greatly encourage innovative means beyond traditional preconceptions.
However, an exact working method to attain this objective has still to be developed. Aimed to make a contribution, the authors proposed a possible working process of abstracting, analyzing, and transferring biological motion principles into bio-inspired compliant mechanisms which are applicable to technical constructions. This was tested right away using three case studies. In this process, the outlined methodology has proven to be an extremely helpful guidance by mapping main themes, procedural stages, and the relationships therein.

Even though the finally proposed application concepts are still at an early design stage and should rather be considered as prototypical proof-of-concept, they already render the potential for innovative product alternatives and new market niches. Thus, their further development (e.g. in respect to materialization and technological integration) will certainly be subject of future research. Next to these project specific developments, however, the authors also recognize the unique opportunity to generally explore the bandwidth and range of elastic systems in architecture. Hence, the authors will further investigate these and other flexible kinetic structures in order to establish a widely-applicable design library for elastic systems.

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