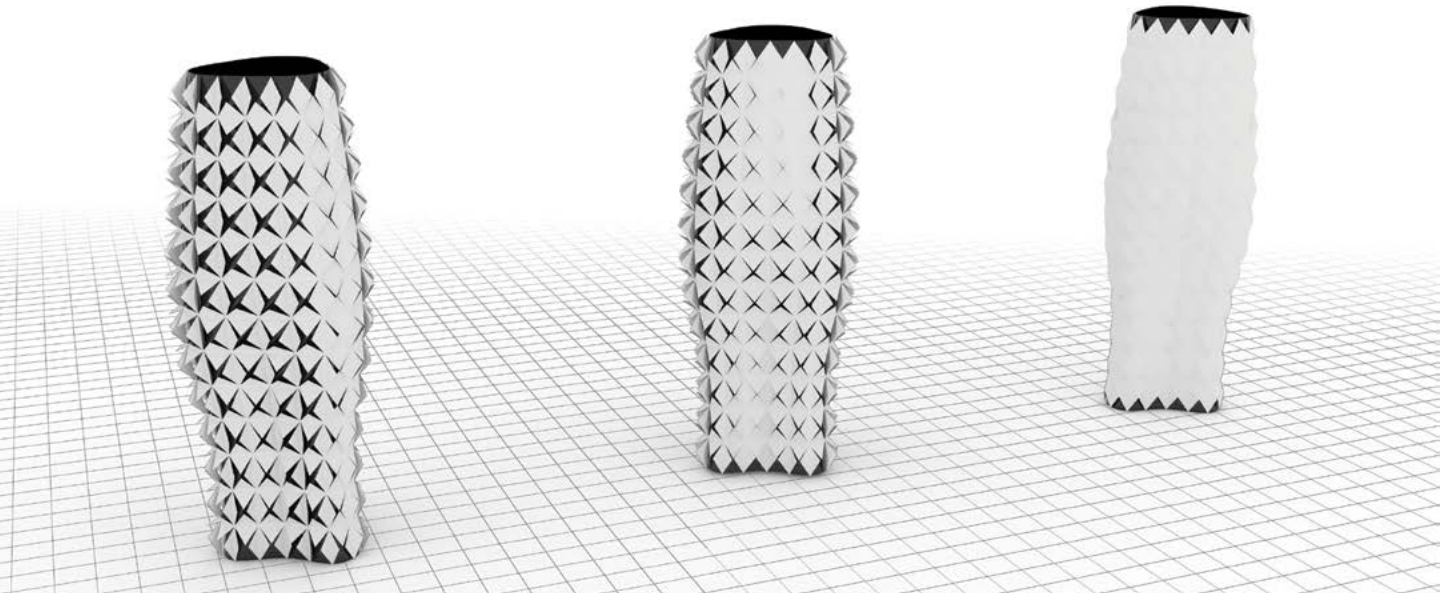
Bio-Inspired Kinetic Curved-Line Folding for Architectural Applications

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ABSTRACT

This paper discusses the development of a bio-inspired compliant mechanism for architectural applications and explains the methodology of investigating movements found in nature. This includes the investigation of biological compliant mechanisms, abstraction, and technical applications using computational tools such as finite element analysis (FEA). To demonstrate the possibilities for building envelopes of complex geometries, procedures are presented to translate and alter the disclosed principles to be applicable to complex architectural geometries.

The development of the kinetic façade shading device *flectofold*, based on the biological role-model *Aldrovanda vesiculosa*, is used to demonstrate the process. The following paper shows results of FEA simulations of kinetic curved-line folding mechanisms with pneumatic actuation and provides information about the relationship between varying geometric properties (e.g. curved-line fold radii) and multiple performance metrics, such as required actuation force and structural stability.

1 Application on geometry of synclastic and anticlastic double curvature.

INTRODUCTION

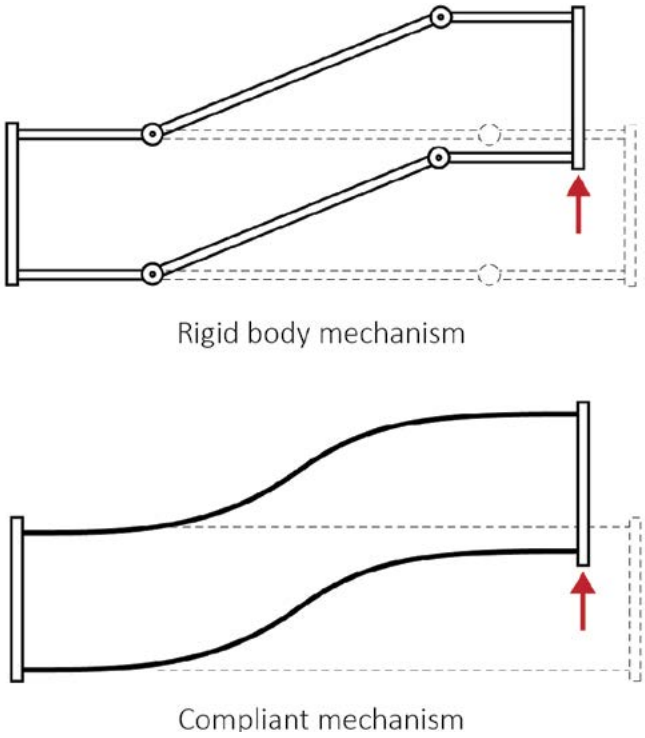
Buildings account for nearly 40% of the global energy consumption, and the importance of the development of energy-conscious design and construction strategies is known and well established. Building facades are the most intense energy-exchange zones and kinetic building envelopes have a high potential to improve the energy efficiency of the overall design and to perform multi-objective tasks in an integrative fashion. Solar-shading and daylight-control can be improved by controlling movement configurations, and energy-collection and lighting-integration can be integrated by embedding PV elements and light fittings into their material structure.

Past examples of kinetic facades have heavily relied on rigid body mechanics to achieve movement. These complex mechanical systems are mostly guided along straight translation or rotation axes – resulting in geometrical constraints. They are expensive to manufacture, prone to failure, hard to maintain and therefore not feasible in terms of operation economy. However, recent biomimetic research has identified strategies to achieve mobility by utilizing elastic deformation of fibrous materials to drive transformation. These kinetic elastic systems (compliant mechanisms) have the potential to dramatically reduce the mechanical complexity of kinetic elements while providing a wide range of complex yet efficient movements that are arguably more suitable for the design of freeform architectural envelopes of the near future.

BACKGROUND

Kinetic Structures

Recent research has defined a terminology for Kinetic Facades, classified them into various categories based on their system properties, and defined a methodology for their performance evaluation. Most notably, Wang defined the term Acclimated Kinetic Envelopes (AKE) as "an envelope with the aptitude to adapt itself in reversible, incremental and mobile ways" (Wang et al. 2012) and Loonen has defined Climate Adaptive Building Shells (CABS) as "a system that has the ability to repeatedly and reversibly change its features, functions or behaviour over time in response to changing performance requirements and variable boundary conditions with the aim of improving overall building performance" (Loonen et al. 2013). Furthermore CABS have been classified into multiple categories based on their (i) source of inspiration for their design (phototropism and heliotropism of plants) (ii) relevant physics of their interface with the environment (blocking, filtering, converting, collecting or storing energy), (iii) time-scales of their operation (seconds, minutes, hours, diurnal and seasons), (iv) scales of adaptation to external stimuli (micro-scale and macro-scale), and (v) control types in charge of their operation (extrinsic and intrinsic).



2 Comparison between rigid body and compliant mechanism.

Adhering to the above mentioned classification, the specific Kinetic Facade Element *flectofold* discussed in this paper can be identified as a system that is bio-inspired, capable of blocking, converting and possibly storing energy, has the potential to operate on multiple time-scales, adapts on a macro-scale, and is controlled extrinsically through pneumatic actuation.

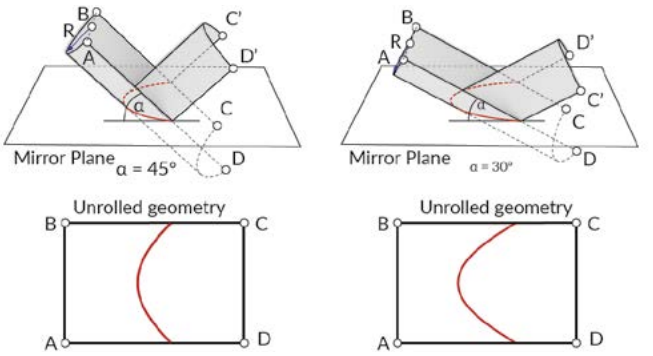
Compliant Kinetic Mechanisms

Compliant mechanisms achieve their flexibility by controlled elastic deformation of flexible members. In contrast to conventional rigid body mechanisms, they consist of only one part with locally defined stiffness. These mechanisms can transfer motion, force or energy upon deformation of the flexible parts. The main advantage of compliant mechanisms is the reduction of parts, resulting in potential economy due to simplified manufacturing and assembly. Furthermore, wear can be reduced, and unlike classical joints, there is no need for lubrication and maintenance.

Some early man-made machines, like bows, are compliant. Nowadays, compliant mechanisms known as living hinges can mainly be found on a smaller scale in medical devices or in the packaging industry, as in book covers or lids of shampoo bottles, but not on a larger scale as in architecture or building construction. (Howell et al. 2013) (figure 2)



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To create movements in kinetic structures, actuators are necessary to transform an energy input into motion. The input can occur as thermal, electrical or mechanical energy, allowing for a passive reaction to environmental conditions such as heat and humidity, or may demand an active trigger. Examples for passive actuation can be bimetals or anisotropic swelling. For active actuation, so called smart materials, such as shape memory materials or electrorestrictive and magnetorestrictive materials can be integrated into kinetic structures (Ham et al. 2009). Due to their high power-to-weight ratio and low material and fabrication cost, pneumatic and hydraulic systems are promising actuators for kinetic structures (Polygerinos et al. 2015).

Biomimetic Kinetic Structures

Adaptability to various geometric conditions and robustness during service is of primary importance when it comes to architectural applications. High requirements with respect to accuracy, velocity and weight can be seen in most cases compared to many other fields of kinetic technology. Many movements in biological organisms fulfill these criteria and are utilized by compliant mechanisms, triggered for example by hydraulic pressure, hygroscopic swelling and the release of stored elastic energy. This makes it valid to investigate biological compliant mechanisms as alternative solutions of adaptive building systems. Research in this field can be differentiated in two directions: Top-down and bottom-up. Biomimetic research for kinetic architectural applications has been studied intensively at the ITKE, most noteworthy in the doctoral theses of Mohammad-Reza Matini and Simon Schleicher.

Matini developed a systematic approach for the investigation of movements based on compliant mechanisms as found in biology. He abstracts the basic movement principles, transfers them into geometric models, and categorizes them into types of movements (2D or 3D, change of curvature, change of curvature direction, etc.), leading to a catalogue of compliant movements. He proposes a series of potential architectural applications using abstracted and combined principles. His work is mainly guided by technological questions, and can be seen as a top down approach. (Matini 2007).

In collaboration with biologists, Schleicher developed a methodology for abstraction and simulation of plant movements by the means of computational tools in his dissertation. His methodology includes the simulation of the actual plant movements, the disclosure of underlying geometrical principles and their variations, and analysis of the involved forces and energy. More focused on the biological role-models, it can be seen as a bottom up approach (Schleicher 2016).

METHODS

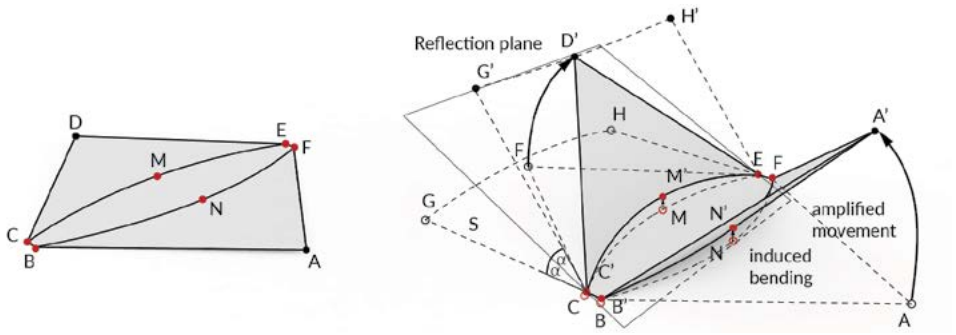
The aim of the described process is to investigate and identify basic principles of biological compliant mechanisms and the transfer into applicable technical solutions by exploring the geometrical variations.

The sequential methodology of analysis, abstraction and technical translation of biological movements builds upon the work by Simon Schleicher (Schleicher 2016), (Schleicher et al. 2015). He divided the process of modeling and simulating the bio-inspired kinetic mechanisms into three main categories: geometric, kinematic and kinetic models.

The geometrical model can be seen as a static representation of the underlying geometrical features responsible for movements. Once identified, the geometric principles can be parameterized and a catalogue of variations of topologically identical specimens can be generated.

The kinematic model investigates the actual movement. The geometrical variations can be qualitatively evaluated in terms of their influence on the movement without taking forces and needed energy into account.

The kinetic model uses non-linear finite element analysis to simulate large elastic deformations and to evaluate the involved forces. Based on exact physical material properties, it enables a sophisticated comparison of the actuation force and resultant movement for the geometrical variations and different gradients



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3 Biological role-model *Aldrovanda vesiculosa*.

4 Method of reflection, adapted from Mitani and Iagarashi (Mitani, Iagarshi 2011).

5 Kinematic model based on method of reflection.

in material and stiffness distributions.

For the abstraction of bio-inspired compliant systems, the integration of the described modeling and simulation methods and their specific application during the design process is crucial. The trade-off between speed and accuracy associated with those methods and the information exchange between them has to be taken into consideration during the design process. In particular, the simulation and evaluation of aggregations of kinetic components on an architectural scale require computational economy to gain real time feedback on the feasibility and performance of the design. Once certain mechanical and geometrical constraints and structural behaviors are determined and evaluated with the use of kinetic models, this information can be integrated into the kinematic model in a numerical manner. Thus, necessary adjustments to the underlying global geometries can be made and information of needed energy, efficiency and appearance can be extracted.

DEVELOPMENT OF KINETIC CURVED-LINE FOLDING ELEMENT

The following section will illustrate the development of the bio-inspired shading device *flectofold* starting from the investigation of the biological role-model to a functional prototype and the possibility of geometrical variations.

Biological Role-Model

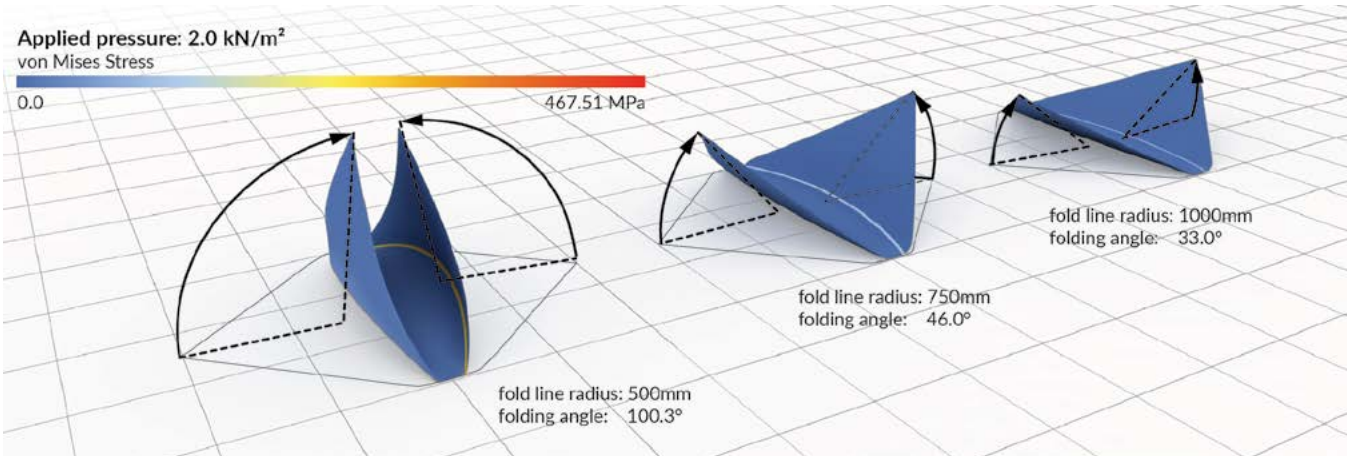
The trap movement of the underwater carnivorous plant *Aldrovanda vesiculosa* served as biological role-model. The trap consists of two lobes connected with hinge zones to a mid rib. While the lobes and the central area are of higher stiffness, the hinge-zone is more flexible and describes a curved fold line (figure. 3). After being triggered by prey, a change of turgor pressure leads to a small change in the bending curvature of the mid rib which is amplified by a curved line folding mechanism and leads to a complete closure of the trap (Poppinga et al. 2016)

Abstraction and Simulation

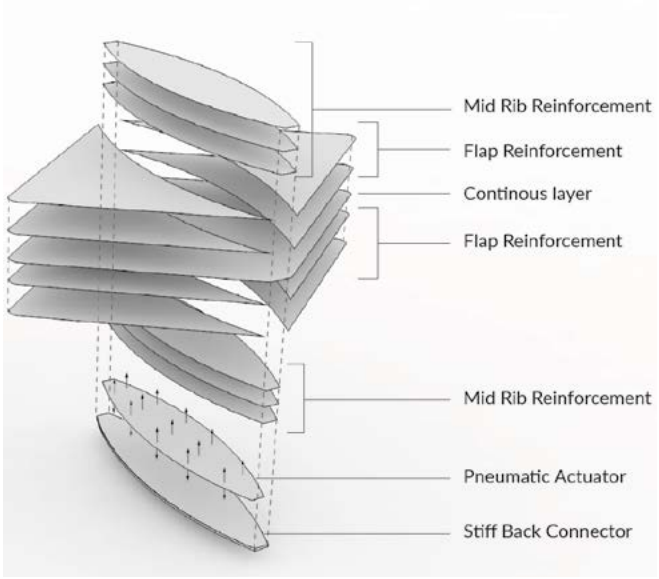
For the translation into a technical application we based our work on the preliminary studies done by Simon Schleicher (Schleicher 2016) which focused on the translation of the trap mechanism into a kinetic curved-line folding model where two flaps are connected to the stiffer middle part by areas of reduced bending stiffness (Figure 4). The most intriguing aspect for technical use is the extensive amplification of a small bending deformation on the central part into a large closing movement of the adjacent flaps. Geometrically, the relation between bending and opening is determined by the radius of the curved-line fold. To evaluate this correlation, Schleicher et al. developed a kinematic model using the “Rigid Origami Simulator” (Tachi 2009) which allows one to simulate a discretized simplification of the curved-line fold where the bending elements are represented by a finite number of rigid components.

To achieve a seamless integration into the design process and to reduce the computational effort, especially for the visualization of a high number of elements, we developed a geometric kinematic model based on the method of reflection (Mitani, Iagarshi 2011), applicable where the curved-line fold remains on one plane, to approximate of the geometry of curved-line folding. The plane which contains the fold line can be used to mirror the two adjacent surfaces to one fold-line. By varying the angle of this plane or by adjusting the curvature of the surface it is possible to control the folding angle (figure 4). To simulate the folding movement controlled by the induced bending, we created the bent mid-rib geometry based on the elastic-curve in relation to the displacement of the translation of the control points. The reflection plane, given by the points C’, E and M’, is used to mirror the lens-shaped rib surface and the initial outline of the flap surface (figure 5). With the curvature and deformed outline information, it is possible to rebuild the folded geometry. A minor displacement of C to C’ and B to B’ leads to an amplified deformation of A to A’ and D to D’.

This method allows not only for parametric manipulation in real-time, but also provides immediate information about the relation between displacement of support points and folding angle.



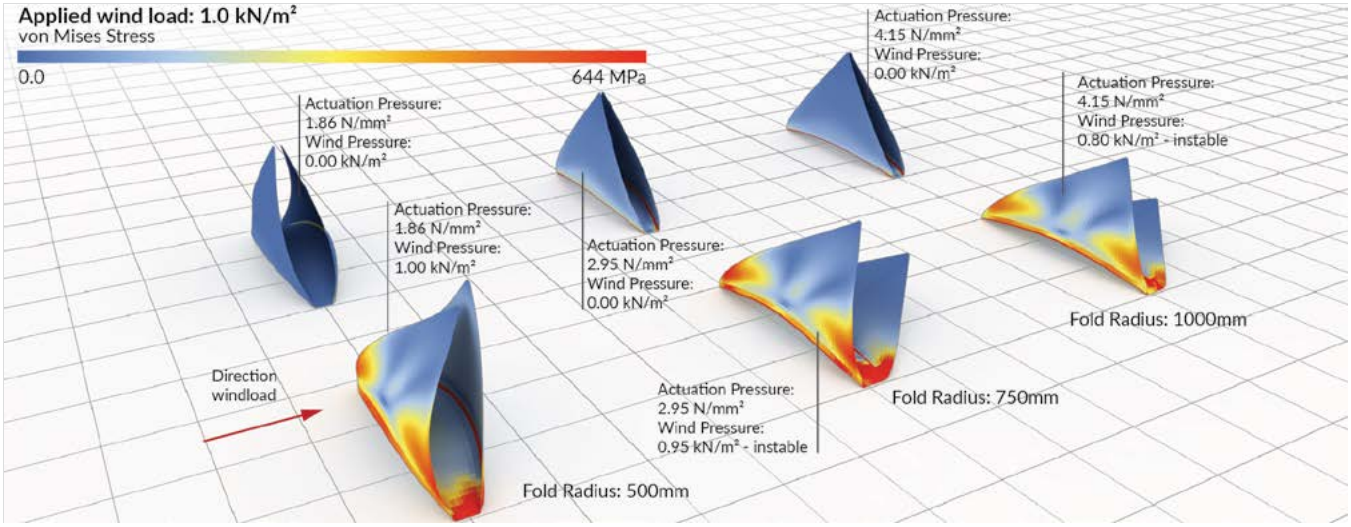
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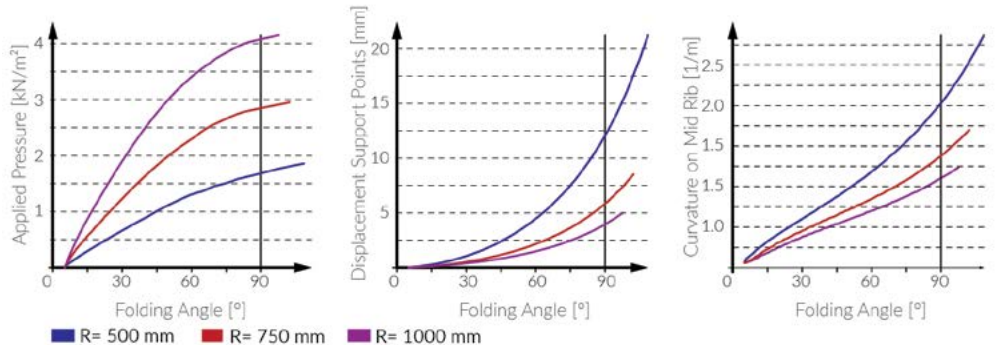
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The so-established geometric relationships were transferred into a kinetic model using the FEM software SOFiSTiK (SOFiSTiK AG, Oberschleißheim, Germany), taking actual material properties of glass fiber reinforced polymers (GFRP), actuation forces and resulting stresses into account. Several variations regarding the hinge zones in terms of width and stiffness gradient between hinge, flaps and mid-rib have been simulated and evaluated to establish an appropriate material gradient between the specific zones, leading to the desired closing movement. A pneumatic actuator was simulated in this study by uniformly distributed pressure onto the mid-rib (figure 7). With this method, a series of different curved-line hinges (radii of 500mm, 750mm and 1000mm) were simulated and evaluated in terms of needed pressure, resultant stresses, corresponding displacement of support points and sensitivity to the actuator (figure 6 and figure 9).

To analyze the stiffening effect of curved-line folding, we applied



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6 Comparison of fold line radii variations.

7 Material and actuation set up for FEA simulation – stiffness gradient through differentiated number and orientation of glass fiber fabric layers.

8 Comparison of fold line radii variations under wind load.

9 Comparison of fold line radii variations.

10 Physical prototype *flectofold*.

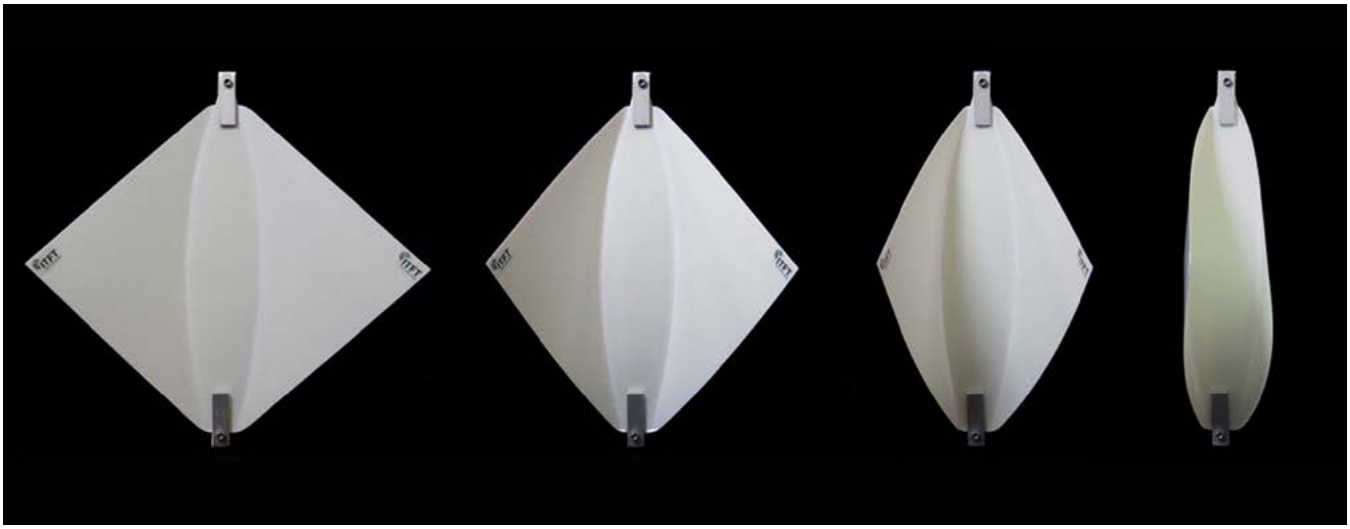
wind load of 1.00 kN/m² to all models once they were fully closed. As expected, the smaller radius leads to higher curvature within the mid-rib which is transferred into the lobes, resulting in higher geometrical stiffness and therefore more stability subject to external loads (figure 8). Also a smaller radius needs less actuation energy to fold, but a higher displacement of the connection points to the substructure. A larger radius will lead to a narrower mid-rib, which would make the mechanism as a shading device more efficient since the central portion around the mid-rib will always remain closed.

Flectofold - Physical Prototype

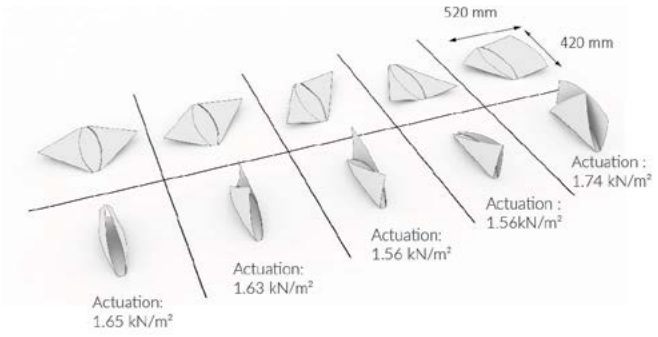
A first physical prototype was constructed with glass fiber reinforced polymers (GFRP). The curved folding mechanism corresponds precisely to a defined stiffness gradient between the different zones—mid-rib as well as lobes must exhibit a certain stiffness while remaining flexible enough to allow for the induced bending. The hinge-zones need to be flexible and have to compensate for the bending forces in small area. The use of GFRP allows for the precise articulation of mechanical properties in certain areas according to local demands. By adjusting the fiber orientation and varying the layer build-up, it is possible to achieve a stiffness gradient within the component that enables the curved folding mechanism (Poppinga et al. 2016).

The component is fixed to a stiff back-part. Movable connections allow sliding along the substructure to compensate the displacement induced by bending. Bending deformation of the mid-rib is generated by a pneumatic cushion which is located between the component and the stiffer back-part. The pneumatic cushion is lens shaped and fits the dimensions of the stiffer mid-rib to allow for a distributed surface actuation avoiding stress concentrations in the mid-rib as well as the hinge zone. It is fabricated from a special airbag fabric able to withstand high pressures and is laminated airtight.

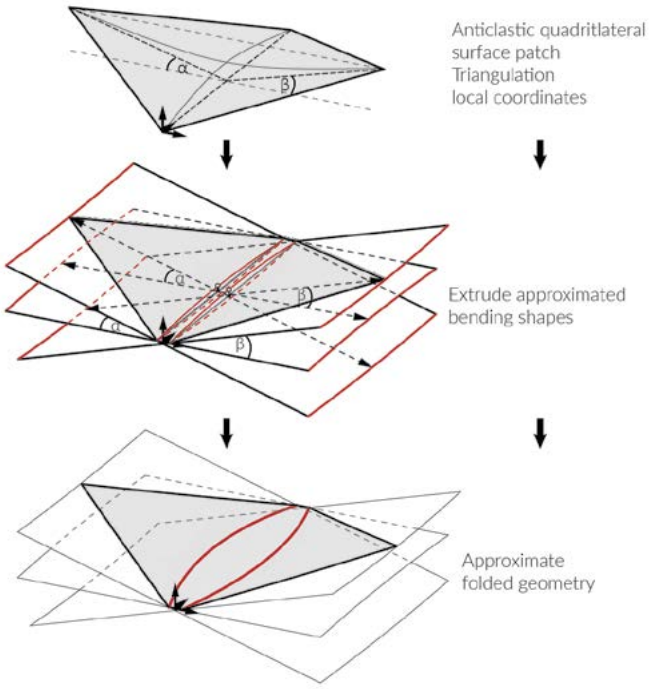
By regulating the pressure according to input criteria, such as light conditions or user preferences, the folding movement can be precisely controlled (figure 10).



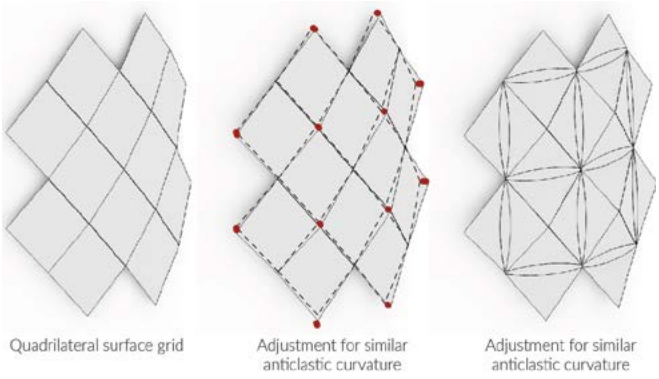
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11 FEM simulations of asymmetric *flectofold* configurations.

12 Translation of folding mechanism into quadrilateral patches.

13 Tessellation and adjustment of global geometry.

Geometrical Adaptability

While the described simulations and the physical prototype assume an axial symmetry of the component, further investigations were carried out on the geometrical adaptability and non-symmetrical configurations. Distortions of the basic rectangular configuration have only minor influence on the folding movement and actuation energy (figure 11).

The adaptability into different boundary geometries is especially of interest for applications on double curved geometries. To translate the curved-line folding model onto geometries of positive and negative Gaussian curvature, we developed an algorithm which subdivides a given surface into quadrilateral patches of similar anticlastic curvature. A certain degree of anticlastic curvature is necessary to ensure a pre-fold in each panel while in an entirely closed configuration to give each panel the correct folding direction during actuation.

Based on the Reflection Plane Method (Mitani, Iagarshi 2011), it is possible to translate each of the quadrilateral surface patches into a curved-line folded geometry (figure 12).

The first step divides the patch into two triangles and generates the width of the mid-rib. In the next step, bending curvature is induced in the two directions of the extended mid-rib surface. By mirroring this surface and rotating it by the angle α and β respectively, the bend geometry of the flaps can be generated. The intersection of the two flap surfaces with the extended mid-rib surface gives the curved-line fold. By adjusting the bending curvature in the first step, it is possible to control the radius of the fold. Knowing the radius of each curved fold line and the degree of pre-fold, it is possible to evaluate the needed actuation force for each patch (figure 13 and figure 1).

Geometrical variations

The tessellation procedure as described in the previous section is based on a UV grid applied to the input geometry. This leads to certain geometrical constraints and limitations regarding component size variations and connections between different surface patches. Variations of the proposed mechanism using three fold-lines have been studied extensively by Aline Vargauwen (Vergauwen et al. 2014) and could be used for polygonal tessellation patterns, suitable for translating surfaces into curved-line folding elements and allowing for more design freedom (Chandra et al. 2015). To adapt the curved folding mechanism to a polygonal, preferably hexagonal, boundary condition, we imposed a triangle inside the polygon, where per definition all three vertices lie on one plane. The edges of the inner triangles can be seen as straight line representations of the curved fold lines. These straight lines can be translated into NURBs curves by using

the end points of two adjacent edges and center point of the inner triangle, and interpolation points between end points and center point as control points (figure 14). By adding an additional control point along the axis from vertices to center point the curvature of fold-lines can be adjusted.

For the geometric-kinematic model, the center point is moved in the normal direction of the plane spanned by the inner triangle. The corresponding displacement of the endpoints of each curved-line fold can be calculated by Pythagorean theorem and therefore the bend shape of actuation portion of the component can be approximated. Using the mentioned variation of the Reflection Plane Method, it is possible to approximate the folded geometry of the opening flaps. FEA simulations of GFRP panels with varying curvature in their fold lines provide first confirmation about the feasibility of the mechanism and the relation between actuation force and folding behaviour (figure 15).

RESULTS AND DISCUSSION

The process from investigation of a curved-line folding mechanism abstracted by Adlrovanda and the abstraction to a first working prototype lead to the following results:

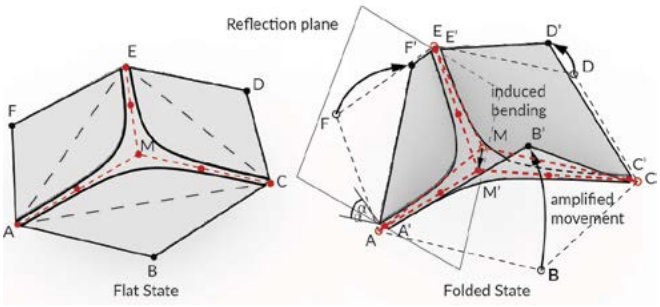
Methodology

The development of a new approach for kinematic models for curved-line folding mechanisms using the method of reflection to simulate the movement of *flectofold* as well as the geometrical variations introduced by Vergauwen (Vargauwen et al. 2014) enables the direct integration within the design environment without external software such as rigid origami simulator or Kangaroo for Grasshopper. The established geometric rules enable the translation of surface tessellations into curved-line folding components. The geometric kinematic model reduces the computational effort compared to rigid origami simulations, which is of high advantage for the simulation of the behavior of large aggregations.

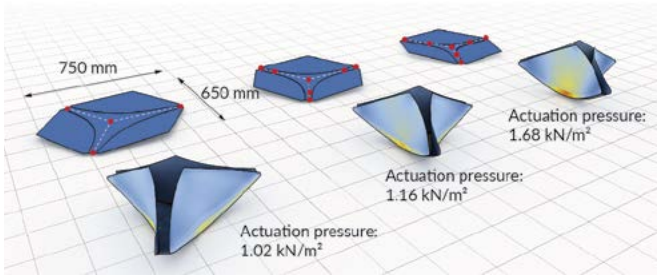
The proposed kinetic simulations are highly directed to the development of physical prototypes made of GFRP and implemented pneumatic actuators. One major aspect for the simulations was to investigate the influence of curvature of the fold line on the actuation energy required, displacement of support points and stability to external loads such as wind loads in different geometrical variations.

Geometrical Potentials and Constraints

The proposed compliant curved-line folding mechanisms are adaptable to a variety of boundary geometries. It is possible to apply the devices on double curved surfaces. Nevertheless, a central aspect of curved-line folding mechanisms is the need



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14 Geometric and kinematic model for curved-line folding element with polygonal boundary condition.

15 FEM simulation of geometrical variations – polygonal boundary condition.

of a certain pre-fold in the closed configuration to ensure the folding during actuation. Thus the proposed tessellation methods for freeform geometries include an adjustment of each patch to ensure the necessary pre-fold. This can require geometrical adjustments of the initial design, and can lead to an altered appearance. Also the folding components remain in this anticlastic configuration throughout the folding movement – a change of direction of curvature is not possible without complex actuation and control mechanisms. Therefore, future research will investigate biological role-models which are capable of changing from convex to concave configurations (e.g. *Adiantum peruvianum* or *Pterostylis curta*).

Material Composition and Scaling constraints

The movement of the components is triggered by bending deformation in one part of the component which is transferred to the adjacent areas. To facilitate this bending actuation, it is essential that the material is flexible enough to allow for the bending within an acceptable range of actuation force while remaining stiff enough to withstand external forces. Although the curvature induced by bending acts advantageously for the gain of geometrical stiffness, the inherent need for flexibility leads to scale limitations which need exploration in more detail.

Curved-Line Fold Radius and Efficiency

The radius of the curved-line fold influences the actuation force, and the sensitivity as well as bending deformation within the component. In addition to those mechanical parameters, it also has an impact on the width of the middle part, which will be always closed in the proposed application. A wider mid-rib will not only reduce the efficiency as shading device, but also disturb the view of users, thus it has physical and psychological impact on the performance. Trade-offs between all involved criteria must be defined from case to case.

Fabrication Advantages

One of the key advantages is the simplicity of fabrication of flat elements. The curved folded elements can be unrolled into planar elements, produced in a flat state and folded according the tessellation boundaries. Therefore, no special formwork is needed for the fabrication process.

Integrated functionality

While flexible enough to allow for the bending associated with curved-line folding, the flap surfaces provide enough stiffness and area to serve as a substrate for additional functional components such as PV cells, LED lighting, sensors, light guiding mirrors etc. This differentiates the proposed compliant systems not only from textile devices but also from roller blades or similar mechanisms, which only provide substrates with low stiffness.

CONCLUSION

This case study reveals the potential and limitations of the discussed curved-line folding principles and the use of GFRP materials for fabrication of a bio-inspired kinetic compliant mechanism to inform the design and construction of kinetic façade systems independent from linear or rotational translation movements. The curved-line folding mechanism is used to translate a one dimensional actuation force into a three dimensional deformation of the element. The study provides insight into the involved forces, actuation energy and structural behavior during the folding process.

Design and subsequent evaluation of kinetic envelopes is mainly informed and driven by quantifiable performance criteria such as energy efficiency, fabrication feasibility and operation ease, which result in strategies to optimize movement, reduce mechanical complexity and utilize compliant mechanisms. Nevertheless, there exist a number of not readily quantifiable, yet equally important factors that need to be taken into account at the concept stage of design. These include psychological and physiological effects of such systems on building occupants and methods of user control and levels of interaction as summarized by Francesco Fiorito (Fiorito et al. 2016).

In addition to technical performance aspects and user-interaction, kinetic envelopes bring forward a novel palette of time related properties that have vast design potential in composition of architectural facades and closely relate to human perception of movement. This has been well elaborated and presented by Schumacher (Schumacher et al. 2010) and includes aspects such as movement-speed, acceleration, serial repetition, complexity, weight, mystery, balance and more.

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REFERENCES

Chandra, Suryansh, Axel Körner, Antiopi Koronaki, Rachelle Spiteri, Radhika Amin, Samidha Kowli, and Michael Weinstock. 2015. "Computing Curved-Folded Tessellations through Straight-Folding Approximation." In *Symposium on Simulation for Architecture & Urban Design (SimAUD)* 2015. edited by H. Samuelson, S. Bhooshan, and R. Goldstein. Washington: SIMAUD. 221–228

Fiorito, Francesco, Michele Sauchelli, Diego Arroyo, Marco Pesenti, Marco Imperadori, Gabriele Masera, and Gianluca Ranzi. 2016. "Shape morphing solar shadings: A review." In *Renewable and Sustainable Energy Reviews 55*. 863–884.

Ham, Ronald van, Thomas G. Sugar, Bram Vanderborght, Kevin W. Hollander, and Dirk Lefeber. 2009. Compliant actuator designs. *In Robotics & Automation Magazine, IEEE* 16 (3): 81–94

Howell, Larry L., Spencer P. Magleby and Brian M Olsen. 2013. *Handbook of compliant mechanisms*. Chichester, West Sussex, United Kingdom: John Wiley & Sons.

Loonen, Roel C. G. M., Marija Trčka, Daniel Cóstola and Jan Hensen. 2013. "Climate adaptive building shells: State-of-the-art and future challenges." In *Renewable and Sustainable Energy Reviews 25*. 483–493.

Matini, Mohammad-Reza. 2007. *Biegsame Konstruktionen in der Architektur auf der Basis bionischer Prinzipien*. Dissertation thesis. Stuttgart: ITKE (Forschungsberichte aus dem Institut für Tragkonstruktionen und Konstruktives Entwerfen, Universität Stuttgart, 29).

Mitani, Jun, and T Iagarshi. 2011. “Interactive design of Planar Curved Folding by Reflection.” In *Pacific conference on computer graphics and applications*. Edited by B. Chen, J. Kautz, T. Lee, and M.C. Lin. Kaohsiung: 77–81.

Polygerinos, Panagiotis, Zheng Wang, Johannes T. B. Overvelde, Kevin C. Galloway,, Robert J. Wood, Katia Bertoldi, and Conor J. Walsh. 2015. “Modeling of Soft Fiber-Reinforced Bending Actuators.” In *IEEE Transactions on Robotics 31* (3). 778–789

Poppinga, Simon, Axel Körner, Renate Sachse, Larissa Born, Anna Westermeier, Jan Knippers, Mandred Bischoff, Götz Greser, and Thomas Speck. 2016. “Compliant Mechanisms in Plants and Architecture.” In *Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures*, edited by J. Knippers, K. Nickel and T. Speck. Dordrecht: Springer Science + Business Media B.V. (accepted)

Schleicher, Simon. 2016. *Bio-inspired Compliant Mechanisms for Architectural Design. Transferring Bending and Folding Principles of Plant Leaves to Flexible Kinetic Structures*. Dissertation thesis. Stuttgart: ITKE (Forschungsberichte aus dem Institut für Tragkonstruktionen und Konstruktives Entwerfen, Universität Stuttgart, 40).

Schleicher, Simon, Julian Lienhard, Simon Poppinga, Thomas Speck, and Jan Knippers. 2015. “A methodology for transferring principles of plant movements to elastic systems in architecture.” In *Computer-Aided Design 60*. 105–117

Schumacher, Michael, Oliver Schaeffer, Michael-Marcus Vogt. 2010. *Move - Architecture in Motion - Dynamic components and elements*. Basel, Switzerland: Birkhäuser.

Tachi, Tomohiro. 2009. “Simulation of rigid origami.” In: *Origami 4: the fourth international conference on origami in science, mathematics, and education*. edited by R. Lang and AK Peters. Natick: 175–187

Vergauwen, Aline, Niels De Temmerman, Lars De Laet. 2014. “Digital modelling of deployable structures based on curved-line folding.” In: *Proceedings of the IASS-SLTE 2014 Symposium “Shells, Membranes and Spatial Structures: Footprints”*. edited by Brasil, R. & Pauletti, R. Brasilia.

Wang, Jialiang, Liliana O. Beltrán, and Jonghoon Kim. 2012. “From Static to Kinetic: A Review of Acclimated Kinetic Building Envelopes.” In *Proceedings for American Solar Energy Society, vol. 2012*. 1–8.

IMAGE CREDITS

Figure 3: Aldrovanda vesiculosa (www.sarracenia.com)
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