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Herausgeber: Professor Dr.-Ing. Jan Knippers

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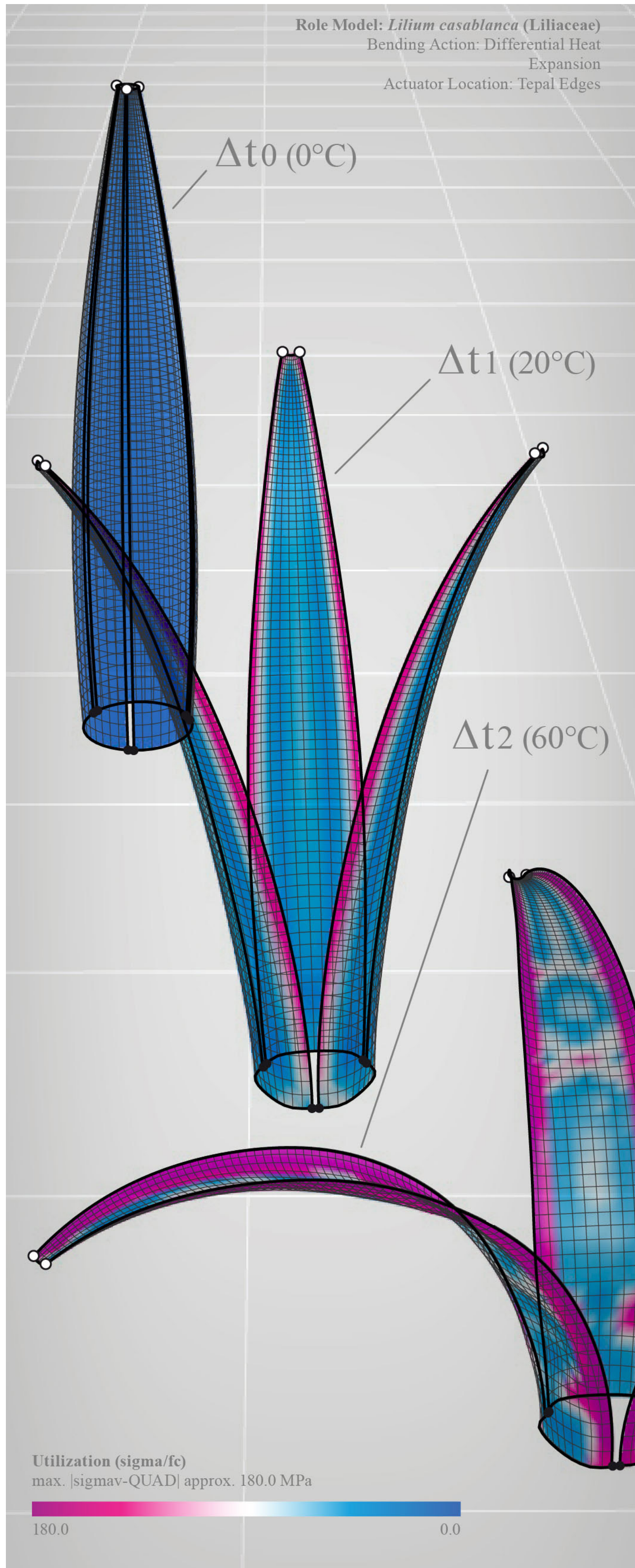
Simon Schleicher

Bio-inspired Compliant Mechanisms for Architectural Design

Transferring Bending and Folding Principles of Plant Leaves to Flexible Kinetic Structures



Forschungsberichte

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aus dem Institut für Tragkonstruktionen
und Konstruktives Entwerfen,
Universität Stuttgart

Herausgeber:
Professor Dr.-Ing. Jan Knippers

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Simon Schleicher:
Bio-inspired Compliant Mechanisms for Architectural Design:
Transferring Bending and Folding Principles of Plant Leaves
to Flexible Kinetic Structures

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BIO-INSPIRED COMPLIANT MECHANISMS FOR ARCHITECTURAL DESIGN

Transferring Bending and Folding Principles of Plant Leaves to Flexible Kinetic Structures

Von der Fakultät Architektur und Stadtplanung der Universität Stuttgart
zur Erlangung der Würde eines Doktor-Ingenieurs
(Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von
Simon Schleicher
aus München

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'I'm not trying to imitate nature, I'm trying to find the principles she's using.'

- Buckminster Fuller

ACKNOWLEDGEMENTS

My desire to study Architecture and dive deeper into Biomimetics arose early in life. After visiting two path-breaking exhibitions in Munich, I saw the fusion of these two fields as a vital source of inspiration and emerging scientific discipline. The first exhibition, "Gestalt finden", featured the work of Frei Otto and Bodo Rasch (1995). The second was "Bionik: Biologie und Technik" (1999). I am thankful for young exposure to their work as it left a deep impression on my future path.

I began my study at the University of Stuttgart and end it here with my dissertation. I thank all those who helped me most along that path, especially my two doctoral supervisors Prof. Dr.-Ing. Jan Knippers from the ITKE and Prof. Thomas Speck from the Plant Biomechanics Group in Freiburg. During my time as a doctoral candidate, I was very fortunate to have two colleagues at my side who not only conducted similar research but also became close friends: Julian Lienhard and Simon Poppinga.

I would also like to thank Prof. Neri Oxman, who since our mutual studies at MIT has always provided me with very good consultation and support.

It is these two universities and those who accompanied me there - my professors, colleagues, and friendly staff - that provided me such stimulation, enthusiasm, professional competence, and pedagogical engagement, for which I am very grateful.

From San Francisco, my current living and working environment, I look back in gratitude on the interesting years of apprenticeship and am thankful for the financial support by various funding programs like the Studienstiftung des deutschen Volkes, DAAD, and BMBF.

Finally, of course, my special thanks go to my family, my parents and all those who have made my adventurous path into work life possible. Sincere Thanks!

ZUSAMMENFASSUNG

Dieser Forschungsbericht liegt im Grenzbereich zwischen Architektur, Ingenieurwissenschaften und der Biologie. Inspiriert von flexiblen und widerstandsfähigen Strukturen in der Natur, werden kreative Ideen untersucht, die das übliche Konstruktionsverständnis, nämlich starre Bauteile mit Hilfe von Gelenken miteinander zu verbinden, durch neue Ansätze ergänzen und ablösen könnten. Im Mittelpunkt steht dabei die Untersuchung der Bewegungsmechanismen flexibler Pflanzen am Beispiel von Blüten und Blättern und deren möglicher Abstraktion und Nutzbarmachung für neue technikrelevante Design- und Fabrikationsprozesse. Hierzu werden Vorschläge entwickelt die gelenkfreie Biegung als Bewegungsmechanismus einzusetzen. Während das Prinzip der elastischen Verformung in der Technik noch kaum Beachtung findet oder sich nur als Versagensfall erwiesen hat, findet hier der Versuch statt, flexible Strukturen in der Architektur zu integrieren und beispielsweise als innovative Verschattungssysteme einzusetzen.

ABSTRACT

This thesis lies at the intersection of architectural design, engineering, and biology. Inspired by flexible and robust structures found in nature, the research explores creative ideas that challenge our present understanding of mechanical constructions and offers an alternative to the prevailing paradigm of rigid-body mechanics. By exploring how the motion principles in flexible plant movements can be understood, abstracted, and transferred into novel design and fabrication processes; this thesis proposes innovative concepts that integrate hitherto neglected structural behaviors, such as bending and buckling. These behaviors are considered potential design drivers in the development of new kinetic structures.

The first section offers a comparison between *Kinetic Structures in Design* and *Kinetic Structures in Biology*. While at first glance these two areas may seem entirely unrelated, they share much in common. A particularly interesting connection is provided by compliant mechanisms where technical devices obtain their motion by the flexibility of their members and functionalize large elastic deformations. With these characteristics they are not that dissimilar to the motion principles found in plant leaves.

The second section on *Methodology* is devoted to the transfer of knowledge between technology and biology. This section introduces the emerging science of biomimetics and generally discusses its working methods while also outlining its practical use for this research.

In the third section of this thesis, a transdisciplinary framework is employed for a series of *Case Studies*. Here, seven exemplary plant movements are closely investigated and their underlying motion principles are recreated by means of modern computational simulation techniques. Based on these insights various bio-inspired compliant mechanisms are developed and transferred into adaptive facades shading systems. In the following section on *Implementations*, this technology is utilized for providing sun protection to double-curved building facades and showcased on three conceptual projects.

The thesis concludes with a reflection on the *Research Contributions and Future Outlook* of this work and thereby invites the next generation of researchers and designers to build up on this work, keeping these newly created bonds between the disciplines alive.

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1. INTRODUCTION

'While in appearance a machine differs greatly from any of the force- or motion-distributors of nature, yet for the theoretical or pure mechanician no such difference exists, - or rather it completely disappears on analysis, so that for him the problems of machinery fall into the same class as those of the mechanical phenomena in nature. He sees in both forces and motion existing, and subject to the same great laws which, developed in their most general form, govern and must govern every single case.'

- Franz Reuleaux (Kinematics of Machinery, p. 17)

1.1. Bio-inspired Compliant Mechanisms

Background - The ability to perform a motion is for most systems - whether biological organisms or technical artifacts - the key characteristic that enables them to specifically react and adequately respond to a given stimulus. In these movable systems, which from now on will be referred to as kinetic structures, motion is often functionalized and attributed to fulfill a specific task. By moving partially or in full, a kinetic structure can adapt itself to either conform to its environment or to deviate from it. When doing so, the behavior related to movement and the resulting functioning can be versatile, which often enables a seamless transition between diverse or even contradictory performances. The appearing motions of kinetic structures in nature and technology cover a wide spectrum ranging from changes in form, position, orientation, configuration, and multiple other functional states. In addition to movement as means to propel an object, sometimes the change to a kinetic system itself is already the desired goal.

Kinetic structures, which are typically used in areas like automotive industry, aircraft industry, or architecture gain their agility most often by the use of mechanisms that are inherent in their construction. These mechanisms usually consist of moving components that are arranged and linked together in such a way that they compel mechanical forces to do work accompanied by a determinate motion. With the help of these mechanisms, a kinetic structure can transform input forces/movements into a desired set of output forces/movements. Some kinetic mechanisms transfer thereby these input forces and movements almost directly to output forces and movements. Other mechanisms, however, can offer an additional amplification effect, providing a significant mechanical advantage, which renders potential applications to a wide range of uses in many industries.

What kinetic structures in biology and in technology often have in common is the fact that their inherent mechanisms can efficiently convert small, local, or directed input forces and movements to a global, amplified or redirected set of output forces and movements and vice versa. Moreover, the discrete motion of individual elements chains together to form an attuned set of interacting components that complement each other to a system of higher complexity - or what in technical terms is known as a machine. Since mechanisms are the basic building blocks in most kinetic systems they are of the very essence of what generally is described as Mechanical Engineering.

Problem Statement - Nature and man-made technology both feature a wide range of highly sophisticated kinetic structures and fascinating mechanisms. However, their designs do not share the same performance spectrum. In fact, most often they are based on a totally different mechanical understanding. In classical mechanics, for instance, technical mechanisms are typically designed as rigid-body systems that connect multiple rigid elements and obtain their mobility by distinctive hinges, bearings, and cylinders. In contrast to that, the movement in many biological kinetic structures is often based on compliant mechanisms that are integrated in larger flexible organs.

In the history of technology, the design of man-made mechanisms seems to have abstracted away and detached itself from the design principles found in nature. Furthermore, the current design paradigm in technology has developed its very own set of processes, methods, and objectives that are quite different to those active in biological systems. While man-made mechanisms in the past were responsible for many technical achievements, they also entail some limitations and begin to create a hindering inertia for future developments. In fact, many industries that follow the traditional approach to the design of kinetic structures have difficulties coping with new challenges that are emerging due to the increasing availability of new materials, new computational design methods, and new functional demands. This circumstance calls not only the present procedure into question but also asks for a new and maybe unconventional approach to the design of kinetic structures. One starts to wonder if some of the design principles found in biological kinetic structures might eventually be better suited for these tasks or at least could inspire a new pattern of thought on how to respond to these changing conditions.

Research Question - This thesis on “Bio-inspired Compliant Mechanisms for Architectural Design” explores the unconventional hypothesis that biological principles, such as mechanisms with elastic behavior and flexible movements, can inform a wide range of technical applications in design and engineering. By associating the soft and elastic systems in nature with kinetic structures in technology, this thesis challenges our basic understanding of mechanical constructions. In order to push this hypothesis beyond the level of just a general overview, this thesis also explores the practical applications that this idea might possibly have on concrete examples at the intersection of architectural design, engineering, and biology.

The question then becomes whether the motion principles found in flexible plant movements can be abstracted and understood to such a degree that they can be successfully transferred to specific technical applications for the building industry. With this objective in mind, the thesis will examine bending and folding mechanisms in plant leaves and petals and will integrate their flexible motion principles into the development of flexible facade shading systems.

Research Significance - The special significance of this thesis lies in its willingness to address and rethink key aspects of mechanical design that are deeply rooted in nearly every moveable construction today. It challenges the modus operandi by demonstrating with a number of case studies how bio-inspired kinetic structure could be developed and manufactured. Furthermore, based on the gained experience of these examples, this research also outlines a systematical approach for a multidisciplinary knowledge transfer, which can certainly be applied to other research projects as well.

Motivation - This research topic clearly does not relate to one profession only but requires a completely new approach that is not yet defined by a single discipline. Instead, it calls for the work of someone, who is equally a designer as well as inventor, scientist, and scholar. In the authors opinion, it is exactly this extended profile that offers entirely new possibilities for creative work beyond traditional boundaries. Therefore, the key motivation for this thesis is to tap into the full potential of many areas of knowledge and to be at the forefront of a new professional direction. A path that is not self-centered nor stays within long-established partnerships (e.g. architecture and engineering), but also explores unknown intersections with other sciences. Outside its own comfort zone, this work seeks inspiration from biology and material science in order to open up a new perspective and explore a seldom visited terrain. Driven by personal curiosity, this thesis aims to initiate cross-disciplinary connections and to lay the foundation for a mutual beneficial relationship. In return, this experimental approach creates unexpected and far-reaching research questions for all the participating fields. These points of friction could easily act as catalysts for further projects and collaborations in the future.

Theoretical Framework - The meta-level of this thesis addresses the question whether an transdisciplinary working process can successfully span over academic, institutional, and professional boundaries. Thereby, it explores how this creative approach may challenge common preconceptions and thus spark pioneering innovations. Unlike a traditional scientific thesis, which would focus on one specific problem and solve it by means of in-depth analysis and empirical data from a set of well-proven experiments, this thesis aims for a more holistic approach. It combines the methodological steps from different disciplines to one shared vision. So rather than following the classical vertical direction of research, one needs to understand that this thesis is conceptualized horizontally. This means that the work therein aims to establish a network of connections between multiple disciplines and thus to create a mutually beneficial conceptual framework.

Framework Limitations - Since the scope of this thesis spans, quite deliberatly, across multiple disciplines, a single individual soon encounters natural limitations. What is necessary instead is the synergistic effort of a broadly-based team. Fortunately, this thesis is embedded in exactly this kind of fertile soil. It can build up, for instance, on a predecessor thesis called “Biegsame Konstruktionen in der Architektur auf der Basis bionischer Prinzipien” by Mohammad-Reza Matini (Matini, 2007). His work at the University of Stuttgart was the first to identify nature’s flexible structures as potential inspiration for pliable constructions in architecture. His trend-setting work at the Institute of Building Structures and Structural Design (ITKE) brought biomimetics into focus and initiated a collaboration with the Plant Biomechanics Group (PBG) at the Albert-Ludwigs-Universität Freiburg.

In contrast to this prior work, however, the investigation proposed here is integrated in a broader-scale effort and is conducted in coordination with two other researchers - a biologist and a structural engineer. While the main goal in this thesis is to build a conceptual bridge between the disciplines, the work of the other teammates focuses on individual aspects that are particularly relevant for their fields. The biologist Simon Poppinga, for example, analyses the functional relationships between the form and structure of plants in his thesis on “Quantitative und qualitative Analyse des Form-Struktur-Funktionszusammenhangs biologischer Verformungs- und Versteifungssysteme und deren bionische Umsetzungspotentiale” (Poppinga, 2013). Whereas the structural engineer Julian Lienhard looks into “Bending-active Structures - Form-defining strategies using elastic deformation in static and kinetic systems and the structural potentials therein“ (Lienhard, 2014). Together with this thesis, all three contribute to a grant project called “Biegsame Flächentragwerke auf Grundlage

Bionischer Prinzipien," which is supported within the funding directive BIONA by the German Federal Ministry of Education and Research (BMBF).

Thesis Objectives - At first glance, the constituent parts of this thesis on "Bio-inspired Compliant Mechanisms for Architectural Design" may not only seem unrelated to each other but, as mentioned before, also belong to very different disciplines. Since each of these fields has its very own mind-sets and grown working methodologies, it is very difficult to put them on the same level or relate one to another. Recent changes in their self-conception, however, may have brought these disciplines closer together than ever before. It therefore appears reasonable that pioneering projects like this could foster their coalescence by establishing a common language and mutual understanding. Therefore, the main objective of this thesis is to envision, initiate, and curate a knowledge transfer between the participating disciplines of architecture, engineering, and biology. A special emphasis is put on a project-oriented and interest-driven learning process, in which the rules of the game are not known beforehand but have to be developed on the fly while the team is working together over a longer period of time. With this creative and playful approach, the thesis envisions a novel transdisciplinary working routine that generates innovation by breaking existing preconceptions of the partial disciplines and synthesizing their individual know-how to a shared canon of values and knowledge.

Limitations and Expectations - Of course, with this strong orientation towards pioneering, this thesis makes no claim of completeness. Instead, it should be read as an overview that points out promising research directions for future work. The summaries at the end of each chapter, thereby, play a special role and will help for successive contributors to provide multiple access points. Additionally, the author makes no secret about the fact that this work attempts to perform a balancing act: On the one hand, the work wants to live up to the expectations that are placed on the scientific rigor of a doctoral thesis, by discussing a specific inner-professional research topic that may probably only be interesting for a small body of experts. On the other hand, the thesis aims to set these discussions in a much larger context, by re-thinking the methods of resolution, exploring new sources for inspiration, and actively entering a dialogue with other disciplines, which might give this work additional value for other professional areas.

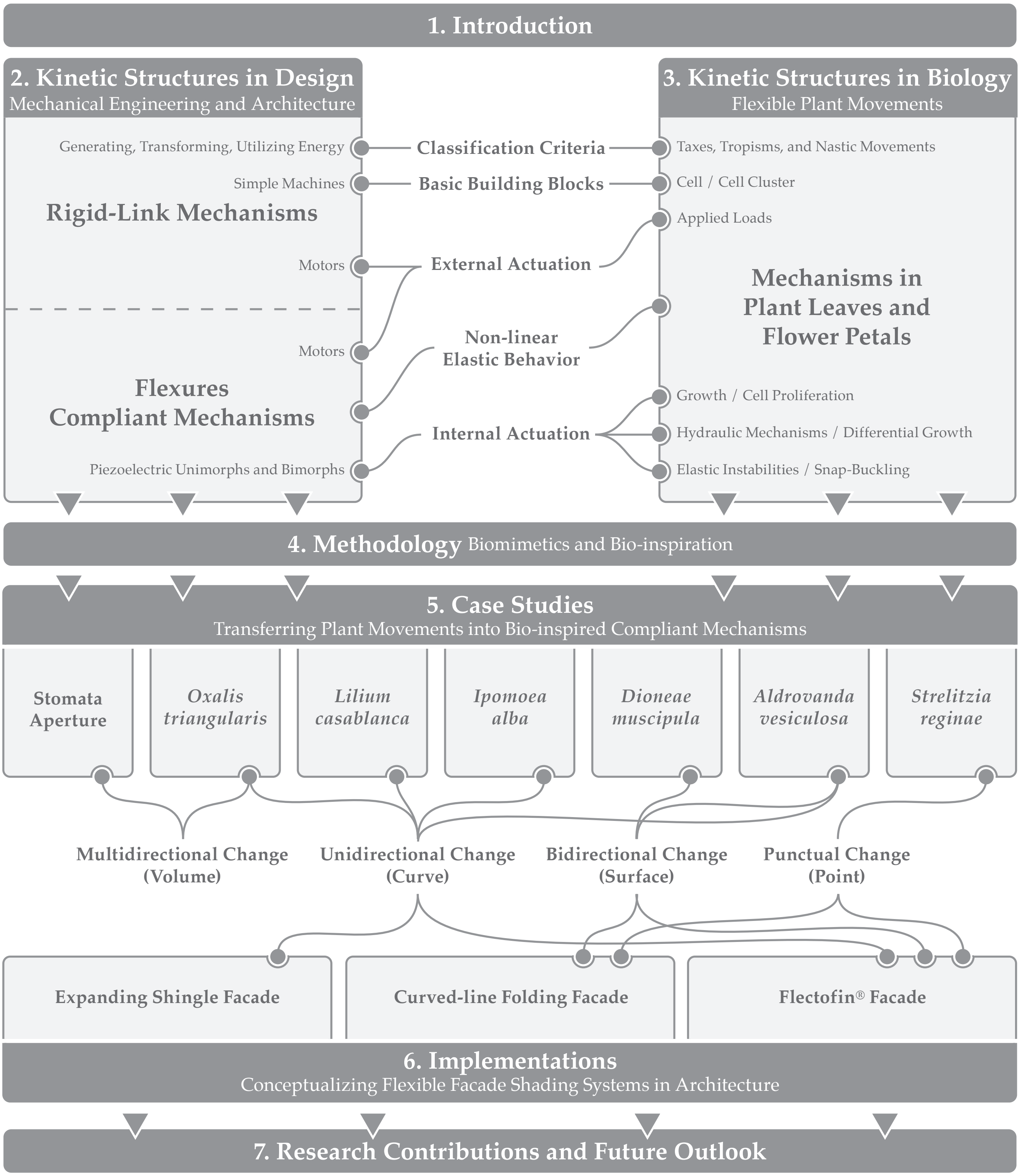


Figure 1.1: Diagram showing the structure of the thesis.

1.1.1. Organization and structure of the thesis

The transdisciplinary approach of this thesis covers a wide range of topics from different research areas. For a better orientation, the illustration in Figure 1.1 is mapping the organization and structure of this work. It shows a division into seven chapters that naturally form three parts.

Part 1 - Chapter 2 and 3 offer a theoretical foundation for this thesis and provide insights to the fields of design and biology. And even though both chapters look at the topic from different directions, they face one another as equally inspiring partners. While Chapter 2 (entitled: *Kinetic Structures in Design*) presents the historical and contemporary concepts for movable structures in mechanical engineering, Chapter 3 (entitled: *Kinetic Structures in Biology*) looks at the topic from a different angle and discusses the motion principles in flexible plant movements. By this comparison, it becomes obvious that the ability to perform a movement is provided very differently in technical devices and biological structures. In respect to some conceptual ideas, however, kinetic structures from both fields can be well referenced in the same breath and be studied for inspirational commonalities and differences.

Part 2 - Chapter 4 (entitled: *Methodology*) makes a leap forward and serves as a necessary bridge head for the further course of the thesis. This chapter provides guidance on the question as to how knowledge can be systematically transferred from one area to another. Therefore, this section introduces the creative method of biomimetics (also called bio-inspiration) and discusses its specific relevance for this work. With its special emphasis on the practical use of biomimetics, Chapter 4 equips the reader with a set of instructions how a plant movement may exactly be able to inspire architectural applications.

Part 3 - Chapter 5 and 6 are the core chapters of this thesis and aim to demonstrate a technical implementation of the proposed biomimetic approach. Therefore, Chapter 5 (entitled: *Case Studies*) presents seven exemplary plant movements and reveals their underlying motion principles. By using various steps of abstraction and digital simulations, this chapter illustrates how these motion principles can be understood and transferred into bio-inspired compliant mechanisms. What innovative applications for design and engineering may arise from using these bio-inspired compliant mechanisms is then presented in Chapter 6 (entitled: *Implementations*).

Finally, this thesis ends with Chapter 7 (entitled: *Research Contributions and Future Outlook*) that reviews the theoretical, methodological, and technological contributions of this work.

1.1.2. Organization and structure of the chapters

The following sections represent the structure of this thesis. Each of the seven paragraphs carries the title of the respective chapter and contains a brief summary of the content.

1.2. Kinetic Structures in Design

Aiming to provide a theoretical foundation to this work, Chapter 2 takes a closer look at kinetic structures in design, particularly in the area of mechanical engineering and architecture. The chapter begins with a summary of the cultural and technological achievements of the Industrial Revolution and argues that particularly this era shaped a dominant paradigm of machine design that is still lasting until today. Using the example of the steam engine, this chapter shows how the mind-set of the Industrial Revolution has affected its designs and initiated a systematical exploration of what is now called classical mechanics. At this time, a new science of mechanics emerged that created its very own terms and theories but most importantly was centered around the assumption of dealing with rigid bodies when designing kinetic structures. Thanks to this conceptual simplification it became possible to calculate and predict the behavior of materials and structures and invent an impressive range of mechanisms and machines. By referencing the work of early pioneers like Franz Reuleaux, this chapter pays tribute to his contributions to a reductionist approach in machine design. This concept primarily refers to the idea that a complex machine is nothing more than a composition of essential building blocks, which by recombination and gradual improvement can lead to new designs. In most kinetic structures, these essential building blocks consist of so-called simple machines like commonly used rigid-link mechanisms and joints that are capable of transferring or transforming motion, force, or energy in an advantageous way. While this knowledge of a machine's inner build-up made today's mechanical achievements possible in the first place, it also restricts the possible design space to everything that is already inherent in the basic design vocabulary.

The limitations of this traditional approach to machine design become particularly obvious in the second part of this chapter, which introduces the topic of flexures and compliant mechanisms as fascinating alternative. Compliant mechanisms also transfer motions, forces, and energy but in contrast to rigid-link mechanisms they don't rely on movable joints but gain at least some of their mobility from the deflection of flexible members. With a look back at the history of compliant mechanisms, the chapter describes that this construction principle may be well known to mankind ever since the invention of the bow, but has hardly been implemented in technical constructions so far. Due to recent advancements in material science and computational analysis, however, the application of compliant mechanisms is becoming more and more feasible, which brings along multiple challenges and advantages. In the context of this thesis, however, compliant mechanisms play an additional role. With their clever use of elastic material properties, large deformations, and structural instabilities, they may be highly unusual for mechanical engineering but closely related to the design principles in nature. Therefore, compliant mechanisms are perfectly suited as transfer topic into the next chapter.

1.3. Kinetic Structures in Biology

The third chapter supplements the theoretical background of this thesis and adds another perspective on the topic of kinetic structures by looking into nature as source for inspiration. With its particular focus on flexible plant movements, this chapter shows that many biological systems obtain the ability to perform a movement in completely different and even opposite ways than the previously described rigid-body systems. Despite the lack of muscles and articulated hinges, plants are capable of performing an astonishing range of motions. Plant organs such as roots, tendrils, leaves, and petals respond to their surrounding very sensitively and can react, for instance, with adaptive growth and specific shape changes. In order to gain a deeper insight into this matter, this chapter introduces the most common approach to plant movements that subdivides them into taxes, tropisms, and nastic movements. In this classification system, an affiliation to one or the other category is influenced by selection criteria such as stimuli that trigger a plant reaction and signals that regulate and control the movement. In addition to that, the chapter also describes another way to distinguish between plant movements by having a closer look at the motors and mechanisms involved. Depending on the observed plant, these can be, for instance, external loads, growth and hydraulic mechanisms as well as elastic instabilities and snap-bucking. Based on this knowledge, the chapter goes on and makes the case that plant movements may become promising role models for technical structures for several reasons. With their targeted exploitation of structural flexibility and elastic material properties, plants represent, for instance, an innovative approach to kinetic structures that integrates multiple and sometimes contradictory characteristics into one coherent and highly differentiated design. In addition, plant movements may also render a high innovation potential for the development of new mechanisms with embedded actuators. This is due to the fact that the mechanical advantages in many plant movements is gained by a clever transformation of small, local changes, which happen in specific cell groups, into amplified deflections of an entire plant organ. In both aspects, plant movements remind strongly of the earlier described compliant mechanisms. Their relation becomes even more obvious at the end of the chapter, where a diagram compares rigid-body mechanisms, compliant mechanisms, and flexible plant movements with each other. A simplified juxtaposition of their key features reveals the bridging role that compliant mechanisms can play for the transfer of knowledge between biology and design.

1.4. Methodology

Chapter 4 looks at the topic from greater distance and is devoted to the small but incredibly difficult question of how knowledge can actually be transferred between the disciplines in a systematical and sustainable manner. Therefore, this chapter refers to the creative method of biomimetics and reflects on its central relevance for this work. Biomimetics (also called bio-inspiration) is a new line of interdisciplinary research that enjoys increasing popularity not only among a few specialists but also a broad public. Despite its high acceptance and widespread media coverage, not everyone is aware that biomimetics is still on the verge of becoming a fully recognized science mainly because its precise methodology is all but clear. While this chapter provides further definitions of terms, objectives, and challenges, it is the way how it speaks about biomimetics that makes it special. Besides a general consideration of biomimetics as a trend, this chapter also inspects its practical use and aims to develop a set of precise working instructions for this thesis. This chapter focuses on how exactly to disclose inspirational mechanisms from flexible plant movements and transfer these findings to the development of architectural kinetic structures in particular. To offer further guidance, the chapter suggest a possible transfer process that is based on repeating themes and emerging trends, which were identified during the course of this thesis. By mapping this process and discussing its work packages, this chapter ends with a useful framework for the following two chapters.

1.5. Case Studies

Based on the previously described methodological framework, Chapter 5 now goes into detail and tests the feasibility of the envisioned biomimetic working routine in practise. For this reason, the chapter presents seven exemplary plant movements and analyzes their motion principles in a sequential process. These seven case studies are certainly not the only suitable role models in plant kingdom but were selected because they illustrate a good range of basic motion principles in different size scales. Furthermore, some of these plant movements were picked because they are rather similar, which allows for interesting comparisons as well as in-depth studies of the same mechanism in slightly different shapes and forms. The examination of all plant movements follows the same sequence, starting with a short presentation of the biological role model, its functional morphology, and the specific movement that can be observed. In the next step, the chapter discloses the underlying principle of the plant movement and simplifies it into an abstracted bio-inspired mechanism. Last but not least, the mechanical variability and consistency of each revealed mechanism gets tested with the primary focus to find useful insights regarding its functional-morphological relationships.

The fist case study to be analyzed this way is the opening and closing of leaf stomata. This reversible movement is particularly interesting because it is based on multidirectional changes of two interacting cells. The volumetric swelling and shrinking of these cells due to changes in turgor pressure in combination with the cells' structural setup forms an effective mechanism, which allows for different aperture sizes. The second case study looks into the leaflet movement of *Oxalis* (Oxalidaceae). This plant features a similar turgor-depended mechanism and also shows multidirectional changes of cells but in this case it is the volumetric swelling and shrinking of an entire cell cluster that drives a reversible motion. The third case study examines the flower opening of *Lilium* (Liliaceae). The movement of this plant has different characteristics than the previous ones and is driven by local expansions along the edges of the flower tepals. The here-appearing unidirectional changes at the perimeter result in a differential growth that forces a bending deformation of the tepals and thereby opens the flower bud. Comparable to this, the fourth case study investigates the flower opening of *Ipomoea* (Convolvulaceae). While this plant has a similar mechanism, which is also driven by the differential effects of expanding edge curves, its precise functioning shows a slightly different configuration. The fifth case study presents yet another mechanism by looking into the trapping movement of *Dionaea* (Droseraceae). This carnivorous plant moves due to bidirectional changes in the cellular tissue of its trap lobes. Particularly fascinating in this plant movement, however, is the fact that this initial movement gets significantly amplified by the use of a clever snap-buckling effect that results from the shell-shaped geometry of the trap lobes. In this respect also the sixth case study of the underwater trap *Aldrovanda* (Droseraceae) demonstrates an interesting concept to accelerate a movement. This plant couples the unidirectional changes of a bending rib with bidirectional changes of its lobe surfaces by using a curved-folding mechanism. Finally, the seventh and last case study explores the pollination mechanisms found in *Strelitzia* (Strelitziaceae). This plant movements is driven by a punctual change, which is triggered by a locally applied load at a specific point. The resulting deformation can be described as lateral torsional buckling and can be used for a broad range of purposes.

1.6. Implementations

Chapter 6 continues to investigate if the biomimetic approach can be used practically and wants to know whether it can actually help improve already existing kinetic structures or inspire the development of completely new technical solutions. In turn, this chapter confronts the ideas developed so far with a specific problem from the field of architecture, in this case providing sun protection for complexly formed building facades by means of mechanical adjustable shading devices. While this very challenging application scenario represents just one among many possibilities, it is well suited to demonstrate what impact bio-inspired compliant mechanisms may have because it sets them in context with specific requirements and expectations.

In its aim to address this task, the chapter begins by emphasizing the significance that facade shading systems play for modern architecture. Many building facades today heavily rely on the presence of mechanical systems to mediate between external environmental factors and internal user demands. With the help of kinetic structures such as blinds, shutters, and louvers it is possible to react to changing light and weather conditions, reduce radiation loads, and regulate the amount of daylight that enters the building. Due to these important functions, shading devices are essential elements for the living quality and energy efficiency of our buildings. And because of their key role, the building industry has developed a wide range of well-proven and effective products. For the particular problem of shading double-curved facades, however, are the previously found solutions not fully satisfactory. By looking into the geometrical and mechanical challenges related to this task, the chapter finds a reason for this and explains that conventional shading devices were designed for regular and planar geometries and thus cannot easily be applied to freeform designs. The implementation of flexible shading devices, however, may provide a real remedy to this problem and the chapter tests this hypothesis with a more detailed breakdown. It explains that the panelization of double-curved facades usually results in thousands of irregular and thus costly panels. By using an ellipsoid as an challenging test-surface, the chapter shows that the panelizing complex geometries can nowadays be rationalized and optimized so that a cladding with flexible components becomes more feasible. A verification for this idea is provided by the conceptualization of three bio-inspired facades shading systems. The first is a curved-line folding facade that was inspired by *Aldrovanda.* The second is a shingle facade that uses the compliant mechanism derived from *Lilium*. And the third is the patented Flectofin® facade, which integrates the motion principles of the *Strelitzia* flower.

After having illustrated a practical application of bio-inspired mechanisms by these examples, the chapter moves on and considers their materialization and prototyping. It begins by screening for suitable materials. Based on a defined performance profile, the chapter then identifies thermoplastics and 3-D printing technology as well as fiber-reinforced polymers and composites as particularly suitable materials for the construction of flexible kinetic structures. How that may look in detail is then exemplified on the Flectofin® and its prototyping in different materials and size scales. This chapter ends with an outlook on how compliant mechanisms and flexible materials can already be used for larger scale architectural projects today and refers to the exciting development of the thematic pavilion "Ocean One" at the EXPO 2012 in Yeosu, South Korea.

1.7. Research Contributions and Future Outlook

Finally, this thesis ends with a review of the theoretical, methodological, and technological contributions of this work. Chapter 7 summarizes this thesis and is structured according to its chapters. This final chapter aims to provide not only a brief recap of the individual focus areas and the most important findings obtained in this thesis but also uses the opportunity to point out the issues that remained unresolved or could be investigated further. In doing so, this chapter does not attempt to be a concluding summary but should rather be understood as starting point and invitation for future scholars to contribute to the topic in their own way.

2. KINETIC STRUCTURES IN DESIGN

Mechanical Engineering and Architecture

'A machine is a combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motions.'

- Franz Reuleaux (Kinematics of Machinery, p. 35)

2.1. Overview - Why looking into architecture and engineering?

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 built environment has a considerable amount of moving parts and helpful devices that serve a large number of different tasks. Typically, these kinetics structures are mechanical systems that are implemented whenever there is a need for adaptation to internal or external factors by means of spatial adjustment. Once an actuating force is provided, they transform this energy into structural movements in order to open, close, release, stop, direct, regulate, accommodate, counteract, control, or fulfill a variety of 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.

Despite their difference in scale, kinetic structures in architecture are often very similar in appearance and function to those in other areas of engineering such as the automotive or aviation industry. This has to do with the fact that they draw from the same engineering knowledge of "Rigid-body Mechanics" with its profound repertoire of methods, scientific theories, and wealth of experience. In comparison to their counterparts, however, these architectural machines are usually produced in much smaller quantities or are designed for every application scenario anew. In fact, most kinetic structures in architecture that go beyond simple doors and windows are not mass-produced products but custom-made special constructions. Another difference is that they usually are not intensively tested like products, for example in the automotive industry. This means that they cannot be easily evolved or refined over multiple cycles of product development. Contrarily, architectural machines often are both prototype and final product at the same time. In many cases they have to function already in the first attempt of production. Certainly, this is one of the key reasons for their high planning and acquisition costs. Another is related to the traditionally grown approach to machine design, which prioritizes aspects like uniformity, regularity, and interchangeability.

Many of our mechanical devices today are conceptualized as mono-functional modules with mechanics that conform to a grid of orthogonal axes and normal proportions. A mechanical system based on standardized forms, however, entails many limitations and is difficult to apply to geometries other than planar and parallel configurations. For these systems, adaptation can only be achieved at the expense of additional mechanical complexity. Unfortunately, this often results in heavy and maintenance-intensive structures that are extremely prone to failure. Therefore, the traditional approach of designing kinetic structures may have 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. In addition, with the rise of CAD/CAM technologies and the availability of modern high-performance materials, the general framework for designing technical constructions has changed dramatically and requires different patterns of thought and new sources of inspiration.

2.2. The Legacy of the Industrial Revolution

Anyone who doesn't know the past can't understand the present and is unable to create the future (Kohl, 1995). This freely translated thought by the former Chancellor of Germany, Helmut Kohl, seems to have a general validity and may also be applicable in the context of this thesis. By understanding the traditional roots that defined the craft and science of mechanical engineering, one might better understand the current paradigm of machine design and will therefore be able to envision a new approach, which may have the power to affect all the areas that use kinetic structures in the future.

In the history of machine and mechanism design, the most profound technological changes arguably appeared during the years 1760-1820/40, in a period known as the Industrial Revolution. This revolution was a technological and social turning point in human history. Industrialization swept the countries, which experienced the most significant transformation in their history. It began in Britain and within a few generations quickly spread to Europe, the United States, and the rest of the world. In the United Kingdom, rural communities lost precedence to factory towns as the population tripled. The focus of the economy moved from farming to textiles and iron with the aid of key technological developments.

Inventions such as the machine loom and the steam engine changed the face of manufacturing. At this time, cheap iron and steel became widely available and vast new cities grew up around manufacturing centers. But this revolution went much deeper than the development of new economic centers and the invention of new machines. From today's perspective, one can say that it had profound effects on humanity and changed the society and living environment forever.

In the context of this research, however, the technological changes that happened during the Industrial Revolution are of particular interest and will be discussed further. During the Industrial Revolution a new energy resource was made accessible by extracting coal from the ground on a large scale. Burning this energy-rich fossil fuel enabled energy-intensive processes, such as the industrial refining of metals. Iron and steel quickly improved in quality and became the new primary construction materials, which easily outperformed the commonly used wood and stone in many applications. The accessibility of these advanced materials also changed the fabrication and further processing of goods. The transition included going from hand production methods to machines as well as new chemical manufacturing and iron production processes. The use of coal and steel also made the development of new engines (e.g. steam engine) possible, which, in turn, powered new machines (e.g. looms). These new machines were tied together with conveyor belts and line shafts forming coordinated assembly lines and larger-scale production facilities. The workers in these manufacturing centers used complex machines to build even more complex products. The locomotive and automobile industries, for example, perfectly exhibit approaches to design and fabrication rooted in the Industrial Revolution. The most important of these methods, the assemblage of goods from mass-produced, mono-functional, rigid, and interchangeable parts, is still common practice today.

2.2.1. The design of the steam engine

When relating kinetic structures in design and potential to the legacy of the Industrial Revolution, one must remember the importance of the steam engine and its affect on machine design. Its invention and gradual improvement illustrates perfectly how a novel technology paved the way for modern mass-production and simultaneously shaped the engineering knowledge of its era.

The first steam engines were invented in Britain around 1712 and were used to pump water out of the deep coal mines. The basic concept implemented in these devices was the idea of transferring thermodynamic energy (vapor pressure) from steam generators into mechanical work. In this case, the work of lifting water with a clever interaction of specific machine components and devices.

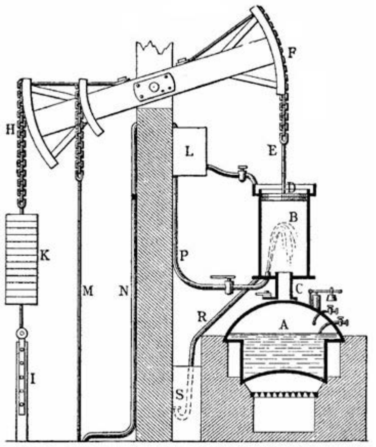


Figure 2.1: Newcomen steam engine serves as water pump.

One of the very first of these systems is the Newcomen steam engine. It has a typical set-up of mechanical parts that together form the machine (Fig. 2.1): First, heating up water in a boiler (A) produces steam. The steam presses into an iron cast cylinder (B) through a pipe (C). The pressure that is built up by the steam in the cylinder forces a piston (D) to move upwards. This motion is assisted by a counterweight (K). The moving piston is coupled to a beam element (F), sometimes referred to as a balancer beam, by a rod and a chain (E). On the other side of the beam element hangs the counterweight (K) on a chain (H). A pump rod (I) is rigidly coupled to the counterweight, such that both their movements correspond to the up and down motion of the piston. The illustration shows a moment in the cycle, in which the closing of pipe (C) stops the flow of steam. The following injection of water from a reservoir (L) into the cylinder speeds up the condensation of the steam and thus causes a vacuum. As a result the piston is pushed downward again, which lifts the counterweight (K) and the pump rod (I) upwards. This sets the machine back to its initial state and the process starts anew. Usually, steam engines can change these states very quickly and perform multiple cycles per minute.

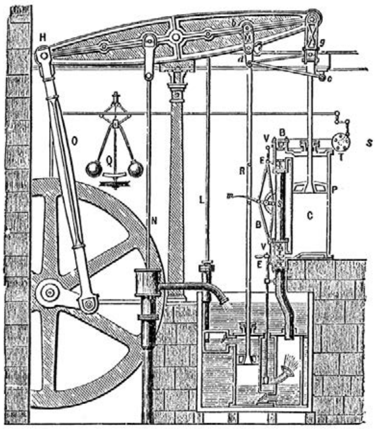


Figure 2.2: Rotative steam engine as invented by Boulton and Watt.

The next great step in the development of the steam engine came with the introduction of the crank and the flywheel, which were added to the balancer beam. Here, the scientist James Watt (1736-1819) made four key contributions to the set-up of the steam engine, which highly increased its efficiency (Fig. 2.2). While one of these improvements was based on thermodynamics, the others were interestingly only pure mechanical changes to the underlying mechanisms. The first invention was a separate condenser for the steam that obviated the need to reheat the piston and increased the efficiency of the steam engine by a factor of five. The second invention was a kinematic mechanism that allowed the rocker arm of the beam element to produce an approximate straight-line motion (H). The third invention was a planetary gear that was able to convert the oscillating linear motion of the piston inside the reciprocating engine into the rotating motion of a flywheel (O). This change was especially significant since the rotating motion of the flywheel is much better suited to accommodate applications like conveyer belts or ship propellers that demand a driver with a constant, uniform motion. Finally, Watt's fourth intervention was perhaps of the greatest significance. He created the speed governor (Q) to regulate the speed of the flywheel even when the load varies. This little device was one of the most important milestones in machine design at that time because it gave the user full control over the machine's operating speed, allowing a steamship for instance to travel faster or slower. Only through these further developments to the initial design of the steam engine was it possible to integrate this engine to other downstream machinery for a large breath of applications.

In the context of this research, the design development of the steam engine is an interesting precedent because it brings attention to an important fact: Once the basic principle of the steam engine was discovered, it was mainly the fine-tuning of parts and their mechanical interaction that drastically increased the machine's performance. This was well understood by theoreticians such as Willis, Reuleaux, or Ampere who pushed the design of these machines to the next level. They applied their knowledge in physics, engineering, and mathematics in order to enhance the machine's energy efficiency, increase the precision of the mechanical parts, reduce wear and friction losses, and extend the variation of design alternatives opening up an even wider field of applications (Ferguson, 1962). With their work, these pioneering experts laid the foundation to the design of mechanisms and machines based on "Applied Sciences" and opened the "Science of Mechanics" as a new field of research.

2.3. The Science of Mechanics

Over the last centuries, many engineers have applied their knowledge to the design and construction of incredibly complex machines that are ingenious masterpieces of manufacturing and precision. Their motivation to thoroughly investigate the science of mechanics was driven by the desire to understand the fundamental principles with which to describe a machine's behavior and to refine its performance. They systematically developed a pool of mathematical theories and formulas with which to predict not only the transmission of forces but also the resulting displacements and the subsequent effects of moving bodies on their environment.

A scientific treatment of mechanics became possible by combining the disciplines of physics, engineering, and mathematics. Together, they can provide an explanation of the acting principles in mechanical devices on the basis of physical laws. In particular, the sub-discipline of classical mechanics is concerned with the accurate description of the motion of bodies due to acting forces and under consideration of time (Uicker, 2011).

The study of the motion of macroscopic objects, from projectiles to parts of machinery, as well as astronomical objects, such as planets, stars and galaxies, is an ancient one, making classical mechanics one of the oldest and largest subjects in science. However, it was only a few centuries ago in the early modern period when the foundation for this discipline was laid. At this time, the knowledge was organized by defining the most relevant terms and forming scientific theories, with which it became possible to produce testable explanations and predictions of the physical systems.

2.3.1. Definition of terms

When looking in technical literature for the terms “mechanics” and “classical mechanics”, one will find a preliminary definition and most certainly a differentiation into various sub-branches and sub-disciplines. The term classical mechanics was coined in the early 20th century to describe the system of physics, which centered on the work of Sir Isaac Newton and other natural philosophers in the 17th century. However, the inspirational roots for classical mechanics can be traced back to even earlier theories of Johannes Kepler and Galileo Galilei. The further subdivision of classical mechanics into various branches and disciplines mainly differentiates based on the choice of mathematical formalism or the followed school of thought.

The initial stage in the development of classical mechanics, for example, is often referred to as Newtonian mechanics, and is associated with the physical concepts employed by the mathematical methods invented by Newton himself, in parallel with Leibniz, and others. Later, more general methods were developed, leading to reformulations of classical mechanics known as Lagrangian mechanics and Hamiltonian mechanics. These advances were largely made in the 18th and 19th centuries, and they extend substantially beyond Newton’s work.

Another approach to define mechanics is based on the subdivision into fields of study. Dependent on the region, these disciplines can differ in their hierarchical order. In Europe, for example, is the commonly used classification slightly different to the one in the US. Even within the engineering disciplines does the interpretation vary. However, what they all have in common is the identification of the sub-categories: kinematics, statics, dynamics, and kinetics. The term kinematics was coined by André-Marie Ampère (1775-1836). Kinematics describes the geometry and motion of points, bodies, and systems without considering the causes for the motion. Based on mathematical functions, kinematics can be used to analyze a system regarding positions, displacements, rotations, speeds, velocities, and accelerations (Uicker, 2011). In contrast to kinematics, dynamics does consider the loads in a physical system and looks into the development of a system over time. Dynamics studies the equilibrium conditions in a system and analyzes the relationship between motion of bodies and its causes, namely forces and torques acting on the bodies and their properties (particularly mass and moment of inertia). A sub-category dynamics or in some way a special case is the field of statics. Statics deals with physical systems in the specific state of static equilibrium in which the relative positions of its components do not vary over time. This applies, for example, to systems that are either moving at constant velocity or are stationary. Especially the later is well known to structural engineers and architects since it is of crucial importance for the planning and construction of buildings. Finally, the branch of kinetics is often used in English-speaking countries and is in the wider sense equivalent to dynamics. Kinetics is also concerned with the relationship between the motion of bodies and its cause. It combines kinematical variables with the consideration of internal and external forces. It should be mentioned at this point that a clear distinction between these categories, however, is anything but easy and has also changed more than once over time. Traditionally, the three main branches of classical mechanics were statics, kinetics, and kinematics (Wright, 1896, Whittaker, 1988), which have been connected to dynamics in several ways. Currently the most common approach in recent engineering books separates statics and combines kinetics and kinematics under the rubric dynamics (Timoshenko & Young, 1956, Lakshmana et al., 2004).

2.3.2. Construction principles based on the assumption of rigidity

"The investigation of the motion of a rigid body may be conveniently separated into two parts, the one geometrical, the other mechanical. In the first part, the transference of the body from a given position to any other position must be investigated without respect to the causes of the motion, and must be represented by analytical formulae, which will define the position of each point of the body. This investigation will therefore be referable solely to geometry, or rather to stereotomy. It is clear that by the separation of this part of the question from the other, which belongs properly to Mechanics, the determination of the motion from dynamical principles will be made much easier than if the two parts were undertaken conjointly."

- **Leonhard Euler (qtn. in http://goo.gl/fSNaZ6)**

By recognizing that dynamics could be divided into kinematics and kinetics, Leonhard Euler simplified the task of designing machines significantly. This breakdown allowed for a focused view either on geometrical constraints or on mechanical strains. It should be carefully noted, however, that Euler's assumption was based on dealing with rigid bodies. This is a very important restriction because for flexible bodies, the shapes of the bodies themselves, and therefore their motions, depend on the forces exerted on them. This means that the study of forces and motion in flexible bodies has to take place simultaneously and cannot easily be simplified. This circumstance makes the design of flexible machines even more complicated. Fortunately, although all real machine parts are flexible to some degree, it has been previously mentioned that machines are traditionally designed from rigid materials, keeping part deflections to a minimum. Therefore, it is common practice to assume that deflections are negligible. This assumption that machine design can be reduced down to rigid body systems in which deflections within the parts are negligible had some far-reaching consequences.

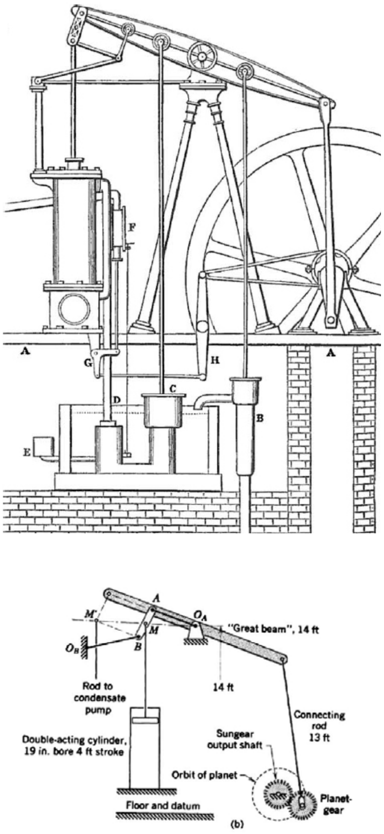


Figure 2.3: Illustration of a steam engine and its abstracted representation in form of a schematic diagram that shows all the key kinematic relationships.

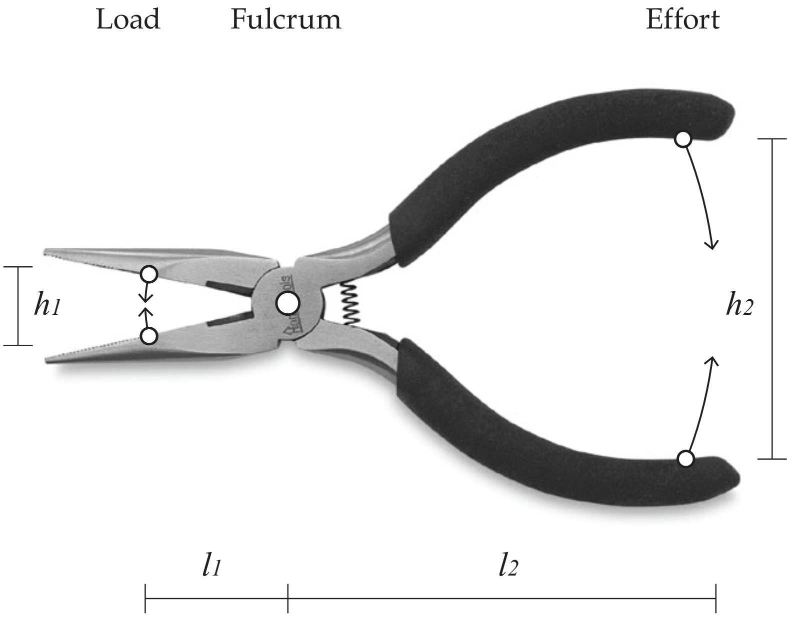
The most direct consequence of this simplification is the fact that it allowed for a very convenient, linear planning process that placed the design of the machine's kinematical performance before its dynamic analysis. Only after the geometrical properties were defined was it possible to determine the expected loads and to adjust the dimensions of the parts so that they can handle the stresses. This successive process is still evident in typical collaborations between designers and engineers.

The second consequence was that it allowed using an abstracted form of representation - the schematic diagram - to illustrate the information that is necessary for the conceptualization of machines or structures (Uicker, 2011). When studying the kinematics, many of the intricate details of the actual parts in the system are insignificant. Therefore, even complex formed machine elements or structures can be communicated with an abstracted diagrammatic representation, which eliminates confusing factors that do not affect the analysis. As a result, it is common practice today to draw highly simplified schematic diagrams, which only contain the important features of the shape of each link, such as the relative locations of pair elements, but that completely subdue the real geometry of the manufactured parts. The slider-crank mechanism of the previously mentioned steam engine, for example, can be simplified for the purpose of analysis to the schematic diagram as illustrated in Fig. 2.3. The huge potential that lies in this simplified approach becomes even more visible when examining the concept of machine mechanisms and so-called Simple Machines.

2.4. Mechanisms and Machines

In mechanical engineering, a mechanism describes a device that is capable of transferring or transforming motion, force, and energy from an input to an output only by means of connecting mechanical elements to each other (Erdman et al., 1997, Shigley et al., 1995). While a mechanism conserves the total energy and only passes it over from input to output (neglecting friction losses at this point), it can be used to change or balance the proportional interrelation between an input and output motion in respect to an input and output force. For example, a large input motion with little force can be turned to a small output motion with relatively high force. We take advantage of this effect, for instance, when using pliers to cut a wire (Fig. 2.4).

Compared to this, a machine is very similar to a mechanism and differs only in its purpose. A machine transmits power and force in order to fulfill a specific task or to perform a defined work, whereas the predominant idea behind a mechanism is to achieve a desired motion or to redirect an input to a specific output. Therefore, a machine can consist of multiple mechanisms acting together. In modern technology, mechanisms are largely hidden and virtually absent from general mechanical engineering education, especially in Europe and North America (Moon, 2003). Yet mechanisms remain important components and are ubiquitous in many technologies across all scales including aircraft flaps, automobile suspensions, robotic manipulations, satellites, consumer electronics, and biomechanic prostheses. Central to the design of these devices is the previously described field of kinematics. While half a century ago, this subject had its own identity, it is taught today only as a prelude to dynamics. Very few universities still offer advanced courses in mechanism design but for most students the previously mentioned slider crank and the four-bar linkage are all the sole topics covered. Likewise the study of machines as complete entities has become a victim of a reductionism in engineering sciences and nowadays the focus rather shifted to topics like fluid dynamics and heat transfer for instance. (Moon, 2003). Yet the pioneers of the engineering sciences in the 19th century had a different vision for their revolution in engineering. Franz Reuleaux in Berlin, for example, was in the first generation of engineering scientists who advocated a mathematical treatment of mechanical engineering by systematically investigating the power of kinematical mechanisms and Simple Machines.



Mechanical Advantage:

$$MA = \frac{l_2}{l_1} = \frac{3}{1} = 3$$

Figure 2.4: Long nose pliers takes advantage of a lever (class one). This lever has the fulcrum between the load and the effort. If the two arms of the lever are of equal length, the effort must be equal to the load. If the effort arm is longer than the load arm, as in this example, the effort travels farther than the load and is less than the load.

2.4.1. Simple machines

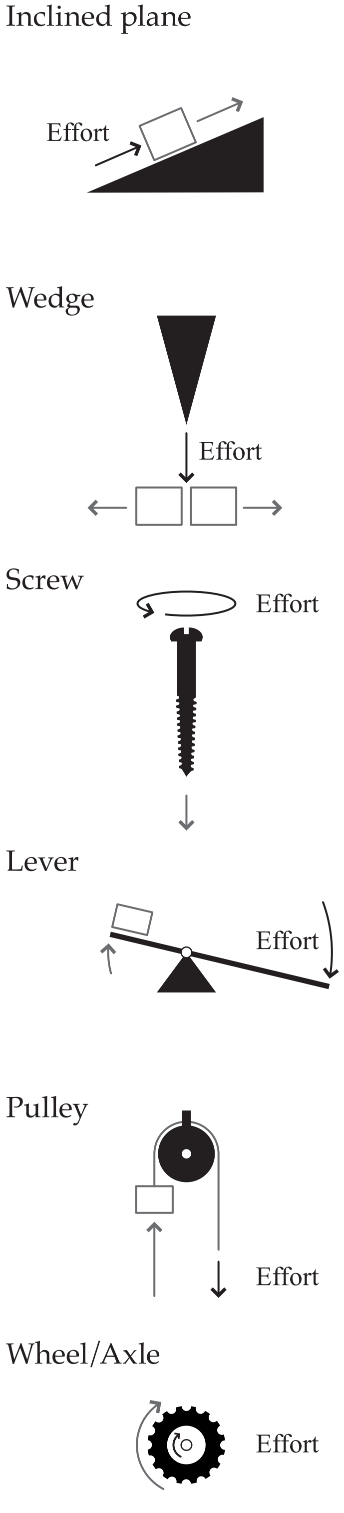


Figure 2.5: Six simple machines.

A simple machine is a mechanical device that changes the direction or magnitude of a force (Paul et al., 2004). In general they can be defined as the simplest mechanisms that may provide a mechanical advantage (Assimov, 1988). A simple machine has an applied force that works against a load force. If there are no friction losses, as it would be the case for a so-called "ideal machine", the work done on the load is equal to the work done by the applied force. This allows an increase in the output force at the cost of a proportional decrease in the distance moved by the load. The ratio of the output force to the input force is the mechanical advantage of the machine. If the simple machine does not dissipate or absorb energy, then its mechanical advantage can be calculated purely from the machine's geometrical characteristics and is equal to the ratio of its lever arms. In the case of the pliers shown in Fig. 2.6, for example, the mechanical advantage has a factor of 3.

The concept of simple machines reaches far back into the past. Already in the 3rd century BC, Archimedes has introduced the idea that any machine of higher complexity can be broken down into few essential units, which he coined the "Archimedean" simple machines: lever, pulley, and screw (Assimov, 1988). He discovered that simple machines like the lever could provide an extremely useful leverage, for instance when lifting a weight (Ostdiek, 2005). Later Greek philosophers like Heron of Alexandria (ca. 10-75AD) defined five simple machines that can set a load in motion (lever, windlass, pulley, wedge, and screw) and were able to roughly calculate their mechanical advantage (Usher, 1988, Chiu, 2010). However the Greeks' understanding was limited to statics and did neither include dynamics nor the concept of work. In the Renaissance, the study of simple machines or Mechanical Powers as they were called, was driven by the interest in finding out how much useful work they could perform. This eventually led to the new concept of mechanical work. In 1586, Flemish engineer Simon Stevin determined that the inclined plane can also provide a mechanical advantage, which expanded the total number of simple machines up to six (Anderson, 1914). The complete mathematical theory of classical six simple machines was worked out by Galileo Galilei and presented in his book on mechanics (Galilei, 1665). He was the first to understand that simple machines do not create energy but behave like mechanisms and only transform energy (Krebs, 2004). Simple machines fall into two classes: The inclined plane, the wedge, and the screw are characterized by the vector resolution of forces and movement along a line, while the lever, the pulley, and the wheel/axle are characterized by the equilibrium of torques and movement around a pivot (Fig. 2.5).

Simple machines are the elementary device in a mechanism that can provide a specific movement and force transmission. Both characteristics can be combined with other devices to form not only simple but also compound and even complex machinery. A compound or complex machine consists of a set of simple machines that are connected in series, such that the output force and motion of one is providing the input force and motion of the next. Over time, simple machines became the essential "building blocks" of machine design (Fig. 2.6).

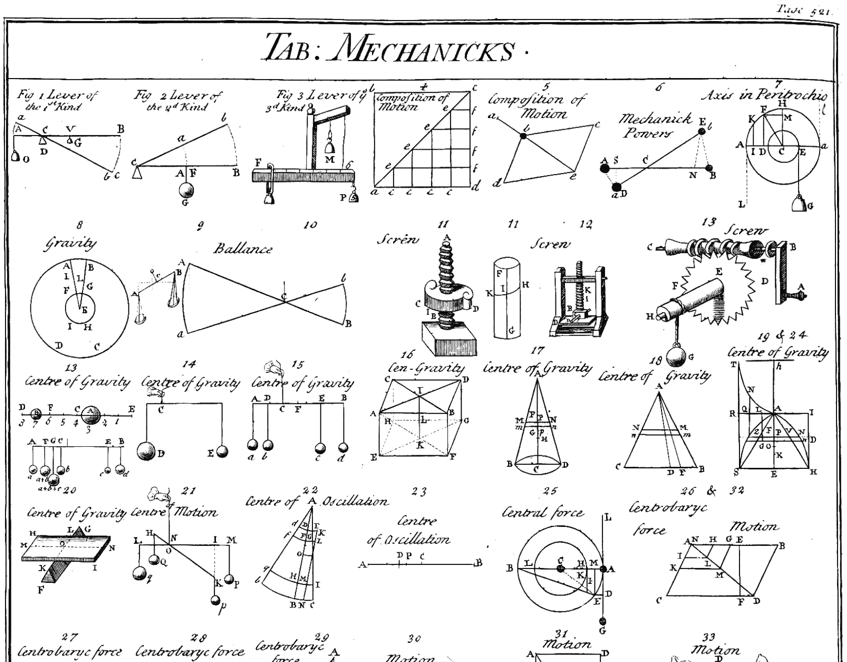


Figure 2.6: Table of Mechanicks. This overview panel lists a series of simple machines in order to provide a vocabulary for the understanding of more complex machines.

2.4.2. Reductionist approach

It was mentioned before that during the Industrial Revolution one of the biggest challenges was to mediate between steady circular motions and non-steady linear or curvilinear motions within the steam engine itself as well as when coupling it to various downstream machine applications. Practical inventors and mathematicians took up the challenge and created thousands of mechanisms that could successfully convert the different forms of motions and thus nurtured the widespread use and the triumphal march of the steam-based machines.

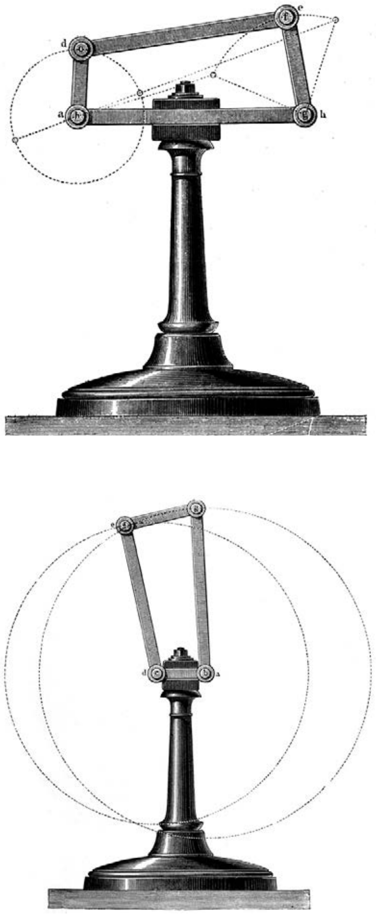


Figure 2.7: Four-bar linkage.

One of the most interesting pioneers at that time was the scientist Franz Reuleaux (1829-1905), who is often called the "father of modern kinematics". Reuleaux was in the first generation of engineering scientists who advocated a mathematical treatment of mechanical engineering with the context of machine design. Many of today's ideas about kinematics of mechanisms and multi-body systems originate in this period and stem from Reuleaux's two major books, *The Kinematics of Machinery* (1875/76) and *The Constructor* (1861-1893), a machine design book which went through four editions in four languages. In these influential books, he applied the ideas of kinematics to the evolution, invention, and development of machines in a new way. It was his belief that design diversity can arise from the knowledge about the essential design components. For that reason, he argued for a scientific approach to machine design, in which topological concepts, classification systems, and symbolic notations were brought together to a comprehensive design theory. His aim was to create a language of invention, which generates a systematic evolution in machine design through mathematical and scientific principles.

Reuleaux's intention was to codify, analyze, and synthesize kinematical mechanisms as mechanical building blocks, such that other engineers could design machines in a more rational and less intuitive way. Building up on the concept of the previously described simple machines, he defined six basic machine elements and described the essential kinematical characteristics of the lever, the wheel and axle, the pulley, the inclined plane, the wedge, and the screw. In addition, Reuleaux's ideas included kinematic pairs and constraints, open and closed kinematic chains, centrodes and instant centers, and the use of physical models of mechanisms to capture theoretical concepts and to prove their functionality. Equipped with this information, inventing a new machine or customizing an existing set-up could easily be done just by scaling and reshaping the geometrical parameters of these basic machine elements. In over 800 elementary machines he demonstrated how small modifications of these mechanical building blocks could generate a wide bandwidth of possible design solutions (Fig. 2.7). Furthermore, by illustrating how these elements could be connected to each other in series or in parallel, Reuleaux opened the door to the formation of complex networks of kinematic chains and compound machines, in which the motion of each part is attuned to its neighbors in the chain. Furthermore, he realized that a lever, pulley as well as wheel and axle are in essence the same device, a body rotating about a hinge, and that an inclined plane, wedge, and screw are similarly a block sliding on a flat surface. This finding confirms that it is the type of hinged connection that provides movement and which defines the primary elements of a machine. Starting with four types of joints, the rotary- , sliding-, cam-, and gear joint, as well as related connections such as cables and belts, it is possible to understand a machine as an assembly of solid interconnected parts (Uicker, 2011). For instance, the bearings that form the fulcrum of a lever and allow the wheel, axel, or pulley to rotate are examples of a kinematic pair called a hinged joint. Similarly, the flat surface of an inclined plane and wedge are examples of the kinematic pair called sliding joint. The screw is usually identified as its own kinematic pair called a helical joint. Two levers, or cranks, are combined into a planar four-bar linkage by attaching a link that connects the output of one crank to the input of another.

Figure 2.8: Four-bar linkage is implemented in a jaw vise-grip.

With his scientific and mathematical approach, Reuleaux provided more than just a useful classification system. By gathering the basic mechanical vocabulary and specifying the grammar needed for the recombination of rigid elements, his seminal example opened the door to an almost endless pool of design solutions, be they movable kinetic structures or static structural systems (Fig. 2.8-2.11). The rigorous methodology of the reductionist approach laid the foundation for new construction typologies and was quickly transferred into related technical fields such as structural engineering. The design of wide-spanning halls like the “Galerie des machine” in Paris 1889, for example, followed in principle the same approach, which reduced a structure to a predictable system of rigid elements with distinct linkages. Here, it was the innovative use of a new structural system - the three-hinged arch - that made it possible to span over 115 m with no internal supports (Fig.2.11). This dimension exceeded everything previously known and created a spatial impression that left the usual viewing habits. The length and width of the room dominate over its height and between the sidewalls and the ceiling was no longer a separation, but both gradually grew together into an insoluble unit. However, the most unusual was the design of the two iron half-arches, which were not only hinged together but also hinged to the ground. This construction detail allowed for previously unseen filigree base points which imbued the building with a real sense of lightness, causing the impression that the enormous structure is hovering above the ground.

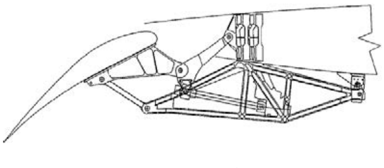


Figure 2.9 - 2.10: Airplane wing with four-bar linkage system for the movement of the flaps.

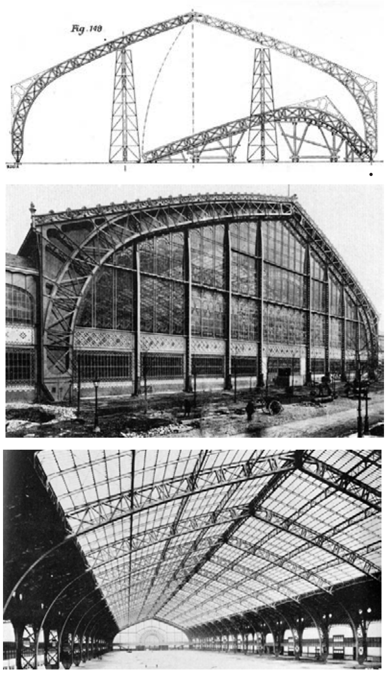


Figure 2.11: Galerie des machines during the World's Fair on the Champ de Mars in Paris in 1889. The structural system of a three-hinged arch made this building the largest single-span structure of its time.

2.4.3. Critique on the reductionist approach

While an appreciation for Reuleaux's approach is certainly necessary, from today's perspective it also seems appropriate to review it critically. Even though he defined the number of basic machine elements and showed that these mechanisms could mutate in their relative sizes and linkages to each other, the basic pool of design modules has not significantly expanded since then. In fact, his initially developed set of mechanisms was taken for granted and the degree of innovation stayed within a core area. Instead, engineers conveniently redirected their attention to the question of creating new classes of more and more complex machine configurations rather than to question the basic building blocks (Fig. 2.12). In a way the paradigm that was created by classical mechanics slowly became a design bottleneck.

In the past centuries since, we have seen a decrease in the variety of machine topology, while at the same time witnessed an increase in the number of parts, well into the hundreds and thousands (Fig. 2.13). In fact, some transformations and movements in current machines can only be achieved by a multitude of interacting elements, which increases the machine complexity disproportionally and raises the planning and manufacturing expenses unnecessarily. With this pattern of thought, it has become very difficult to rise to new challenges, such as integrating new materials, applying new design methods, or addressing new functional demands. In addition, other emerging sciences like fluid mechanics, thermal engineering, or electromechanics caught the interest of successive generations of engineers. As a result, the body of knowledge in kinematics of machinery and Reuleaux's envisioned innovation methodology has atrophied into an unspoken language.

Furthermore, one can also express criticism on the theoretical framework of the reductionist approach in general. In this framework, the nature of complex systems is understood by reducing them to the interaction of individual parts, or simpler or more fundamental subunits. It is based on the belief that a complex system is nothing more than the sum of its parts. With a good understanding of the components of the system, one could predict all the important properties of the system as a whole. However, in some cases this leads to a fallacy of composition and fails to take in the bigger picture. In this framework, emergent properties of the system are almost impossible to predict from the knowledge of parts of the system. In recent years, the development of system thinking has provided methods for tackling issues in a more holistic rather than a reductionist way and many scientists approach their work in a holistic and integrative paradigm.

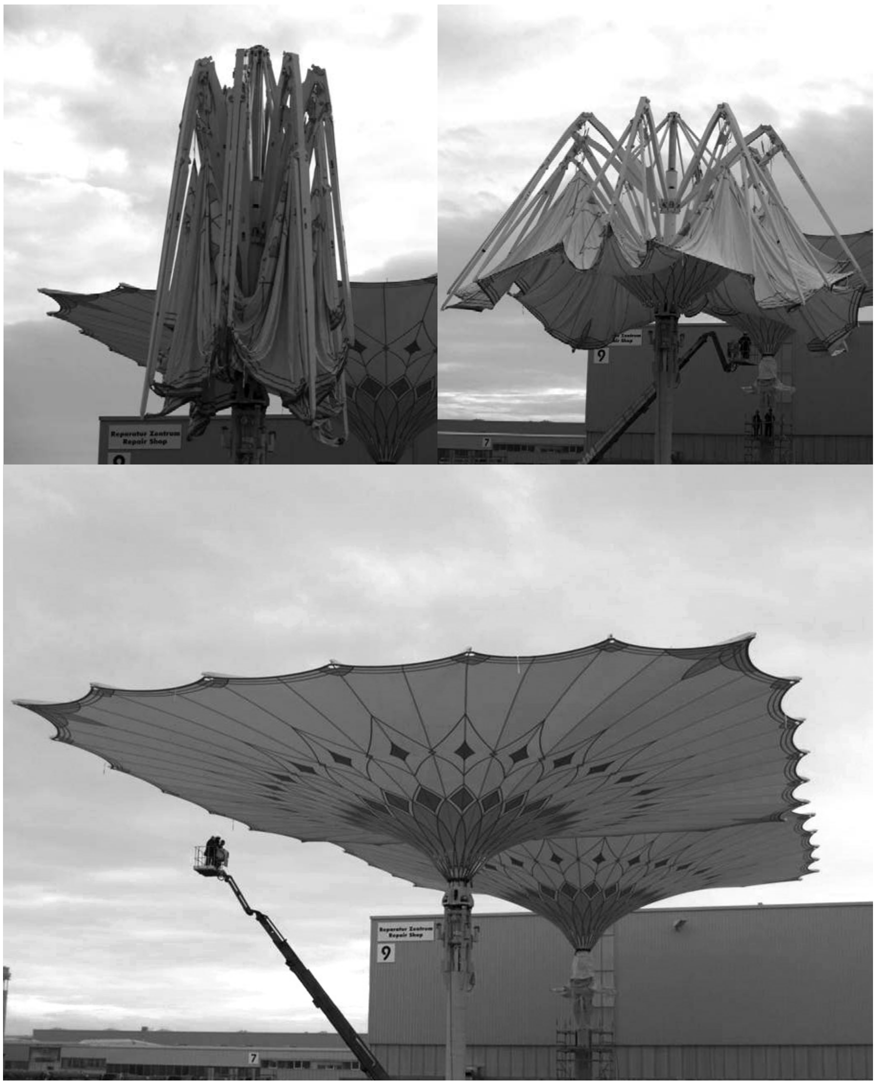


Figure 2.12: Construction of large convertible umbrellas. The retractable arms in this umbrella structure feature a parallelogram mechanism with a four-bar linkage.

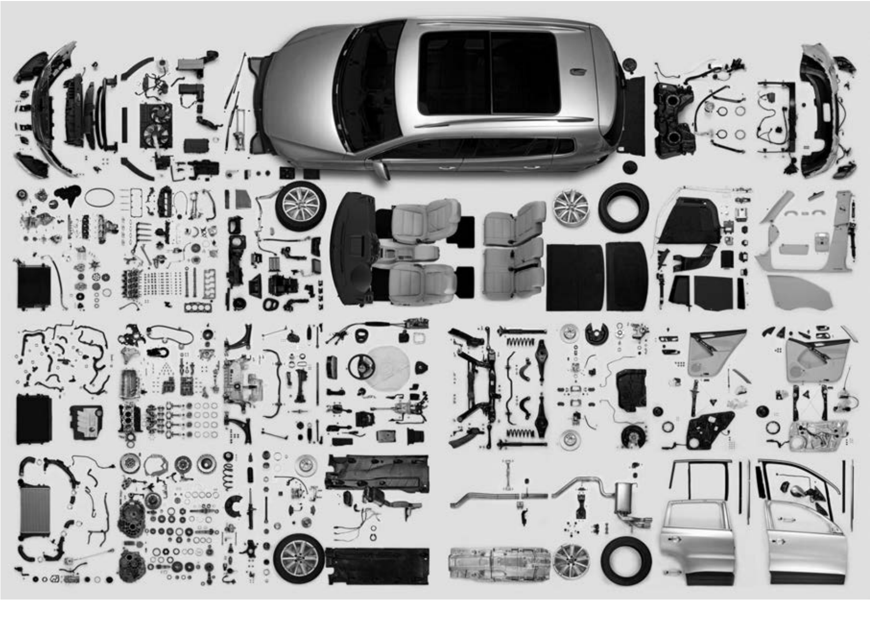


Figure 2.13: VW Tiguan in parts. A disassembled car like this exhibits more than 10.000 individual parts, which are build out of many different materials.

2.5. Flexures / Compliant Mechanisms

2.5.1. Construction principles based on the assumption of flexibility

Compliant mechanisms, or sometimes-called flexures, represent an interesting alternative to the traditional design approach used in classical mechanics. While conventionally engineered mechanisms are designed to be strong and stiff and can move only because their rigid bodies feature various joints, compliant mechanisms combine strength with elasticity and gain at least some of their mobility from the deflection of flexible members rather than only from movable joints (Howell, 2001). Similar to the previously discussed rigid-link mechanisms, compliant mechanisms can also transform motion, force, and energy, only now some of the energy is stored in form of strain energy in the deflected members. By exploiting elasticity of a material, compliant mechanisms produce a desired functionality, such as force motion transmission, motion guidance, shape morphing, or energy storage and release. A more comprehensive nomenclature of compliant mechanisms as well as their classification based on their functional design is given in (Midha et al., 1994; Howell, 2001; Lobontiu, 2010).


Figure 2.14: Archery bow.

2.5.2. Historic background of compliant mechanisms

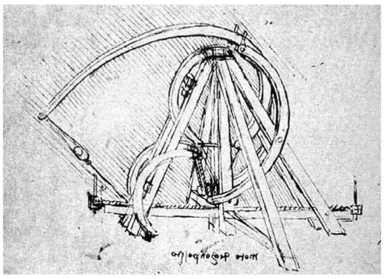


Figure 2.15: Spring catapult. Different types of catapult configurations were studied to improve the leverage and achieve greater propellant power.

Employing elastic strain to generate motions is not a new concept but a recurring idea in the history of technology. The fact that flexible members have spring-like qualities that can store and release energy was recognized early and was applied to various tools, products, and machines. Probably one of the very first application fields was the development of weapons. Bows, for example, have been in use since before 8000 B.C. and were the primary weapon and hunting tool in most cultures (McEwen et al., 1991). Traditionally, early bows were constructed of relatively flexible and elastic materials such as wood or combinations between wood and horn (Fig. 2.14). When shooting, the strain energy that is stored in the elastically deformed bow limps releases a reset force, which is transformed to the kinetic energy of the arrow. Another example for the early use of compliant mechanisms is the catapult. By the fourth century B.C. the early Greeks knew how to utilize the stored energy in the deflected wooden structure to efficiently propel a projectile over long distances (De Camp, 1974). Since then, this basic construction principle was continuously refined and subject of further improvements. Figure 2.15, for instance, shows a sketch of a complicated spring catapult by Leonardo da Vinci 1485-1490 (Gibbs-Smith & Rees, 1978). Moreover, compliant structures have long been used in everyday objects to simulate the motion of turning joints. The flexible hinges of book covers, for example, have been constructed by changing a material's thickness or composition at a specific point of flexure to obtain the desired motion (Fig. 2.16). With the availability of novel elastic materials like plastics, the use of so-called flexural or living hinges became more and more common and widely used in many different products (Paros & Weinbord, 1965; Chow, 1981). Typical examples are bistable closure lids of shampoo-bottles (Fig. 2.17) or handheld devices like the compliant grippers and pliers that are manufactured as a single piece (Fig. 2.18-2.19).

At present, the most sophisticated compliant mechanisms are used for special-purpose applications in the area of precision engineering and microsystems technology. Whenever there is a demand for highest accuracy and smallest dimensions, engineers are resorting to compliant mechanisms. High-end measurement instruments, for example, take advantage of the fact that the motion of compliant mechanisms is obtained from deflection rather than by adjoining parts rubbing against each other. Thus, mechanical noise and vibrations that may affect the measuring results can be reduced significantly. Currently the most common application for compliant mechanisms, however, is in the area of microelectromechanical systems (MEMS) as well as for laminar emergent mechanisms (LEMS) (Fig. 2.20-2.24). These extremely small devices can sometimes be in the micrometer scale and compliant mechanisms are often put here into action as movable structures, actuators, and sensors. Using compliant mechanisms for this scope is often the most straightforward solution because they can be miniaturized easily and fabricated with the same manufacturing technology (e.g. etching, photolithography) and materials (e.g. silicon, polymers, metals, and ceramics) as the circuits in which they are integrated (Derderian et al., 1996; Jensen et al., 1997; Larsen et al., 1996).

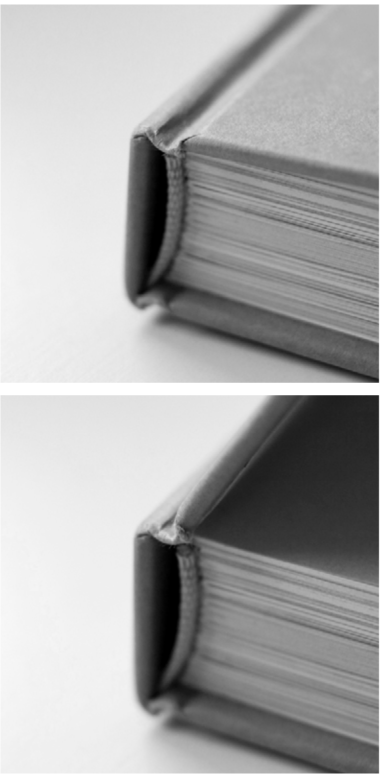


Figure 2.16: Living hinge in the cover of a book.

It can be summarized that over the last few decades, the number of products that rely on flexible members to perform their function has increased significantly. This is partially due to the availability of stronger and more reliable materials like high-performing thermoplastic polymers, fiber composites, and metals. With the rise of these novel materials as well as due to improved manufacturing technologies, engineers are rethinking how to conceptualize and build machines. In particular, when these machines are assigned to the task of motion- or force-transmission, conventional rigid-body systems get more often replaced or retrofitted by fully or partially compliant mechanisms (Zentner & Boehm, 2008). This process is intensified by the fast development cycles of these materials and the constant improvements of compliant mechanisms in general. In addition to the efforts done by the industry, now also the universities start to discover this emergent field of research and begin to play an important role in the development of a scientific theory for the design and analysis of compliant mechanisms (Ananthasuresh et al., 1994; Berglund et al., 2000; Boronkay & Mei, 1970).

Figure 2.17: Living hinge in the lid of a shampoo bottle.

2.5.3. Advantages of compliant mechanisms

The reason why compliant mechanisms are growing ever more popular in the professional world as well as in the scientific community is due to the various benefits that this construction principle possesses over conventional mechanics. A comprehensive evaluation of the advantages and disadvantages of compliant mechanisms can be found in (Howell, 2001) and is worthwhile to be described here in greater detail: By gaining motion through the flexibility of the construction, rather than linking multiple rigid parts together, one may cause a dramatic reduction in the total number of parts required to accomplish a specific task. Some mechanisms may be manufactured as one, fully functional piece by injection-molding technology or by using 3-D printing. Small part count may decrease assembly time and simplify manufacturing processes. This allows for a significant cost reduction.

Figure 2.18: One-piece plastic forceps with deltoid Q-joint.

Figure 2.19: This fish hook remover is an example for a one-piece compliant mechanism. It features a deltoid Q-joint with a passive joint where the handles get into contact.

Another important benefit is that compliant mechanisms often show an increased performance regarding reliability and precision. This is due to the fact that they have few or no conventional hinges, such as revolute or sliding joints. Thus, the wear in these structures and the need for lubrication is very low. These are valuable characteristics particularly for applications where the mechanism is either hardly accessible or operating in harsh environments, in which conventional joints would rust and require more maintenance. The lack of hinges is also an important benefit for the accuracy of measuring instruments. By using flexible and monolithic mechanisms, these devices can greatly reduce or even fully eliminate mechanical drawbacks like backlash, vibration, and noise that would normally be caused by the friction in the hinges (Motsinger, 1964; Tuttle, 1967).

As mentioned before, one of the main advantages of a compliant mechanism is the capability to store energy in its deflected flexible members. Similar to a deflected spring, a compliant mechanism can store strain energy over a longer time period, release it at wish in a later stage, or use it to reset again to an unbent state. But beyond that, it is also possible to fine-tune the force-deflection relationships in the flexible structure to correlate energy and motion and vice versa. The transmission ratio therein can be tailored to suit specific functional needs with targeted amplification effects. For a given energy input the mechanical response of compliant mechanisms can be customized, for instance, to achieve either a maximum displacement (displacement multiplication), or a maximum resulting force (force multiplication). This was used, for example, for the previously shown pliers (Fig. 2.18-2.19). Here, the sophisticated compliant mechanism converts the large yet rather weak actuation, which is caused by the user at the handle, into a small yet powerful gripping motion of the jaws.

Another benefit of compliant mechanisms in comparison to rigid-body systems is the possible reduction in weight. This is advantageous for nearly all industries, be it in the consumer or high-tech sector, because weight savings can help companies to greatly reduce shipping costs. In particular, however, the aerospace and automobile industry has a strong interest in compliant mechanisms. For their products, lightweight design has top priority and possible savings in weight directly affect the achievable payload range profile of an application. In these industries, compliant mechanisms are becoming more and more common. It is also here where one can find the largest applications such as deployable solar panels, antennas, and reflectors (Fig. 2.27) (Kwok & Pellegrino, 2010).

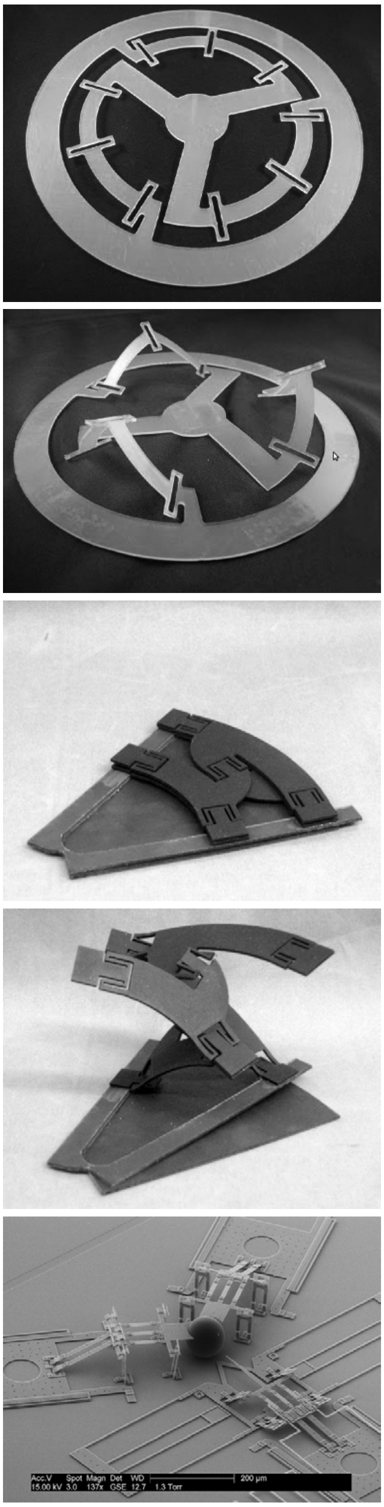


Figure 2.20-2.24: Laminar emergent mechanisms (LEMs).

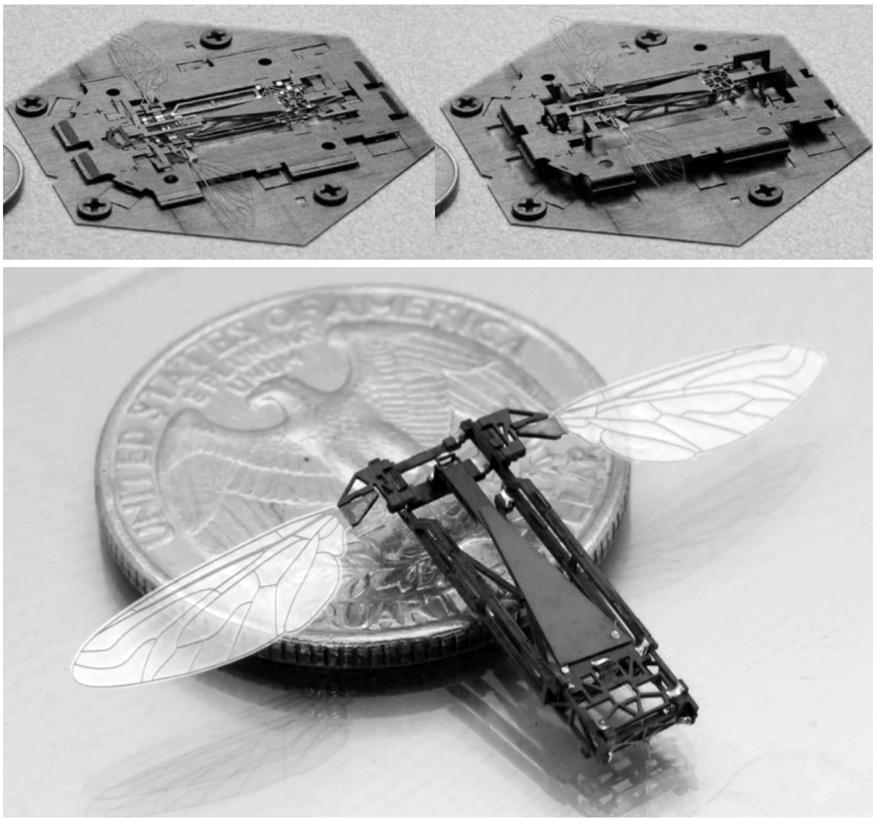


Figure 2.25-2.26: The monolithic bee pops up within an assembly scaffold, which uses compliant mechanisms to perform more than 20 origami assembly folds.

Figure 2.27: Spring-back reflector (MSAT) in deployed and packaged configuration.

2.5.4. Challenges of compliant mechanisms

Alongside the many advantages of using compliant mechanisms, however, there are also a number of disadvantages, which make their practical implementation rather difficult. The greatest challenge lies in the design and analysis of compliant mechanisms because their geometry is dependent on stress conditions and material properties, which are both very difficult to predict. Furthermore, since most members in a compliant mechanisms undergo large deflection, mathematical theories like the linear beam equations are no longer applicable. Thus, the structural deformations and mechanical interactions in a compliant mechanism cannot easily be simplified and abstracted with traditional methods known from classical mechanics. Instead, in order to cope with the geometric nonlinearities that are caused by large deflections, one has to use nonlinear equations. This mathematical theory, however, is highly complex and very difficult to handle. It is therefore no surprise, that many compliant mechanisms in the past weren't based on a scientific approach but rather from a trial an error design process. While this intuitive approach based on experience may be a helpful and quick method, it is also limited to very simple systems that can only perform relatively easy tasks and the right design needs to be worked out for every application anew.

Nowadays, however, a scientific approach to designing compliant mechanisms becomes gradually possible. This is due to the increasing processing power of modern computers, with which it is much easier to manage and solve nonlinear systems. Exemplary simulation technologies that enable this change will be discussed in more detail in chapter 4 and 6. Even though today's limitations may not be as great as they were in the past, designing and analyzing compliant mechanisms remains much more difficult than conceptualizing rigid-body systems.

Besides these methodological difficulties, compliant mechanisms also represent a huge mechanical and constructional challenge. One of the most vital issues, for instance, is to consider fatigue properties of the construction in the design process. Only if the used materials have sufficient fatigue life it can be guaranteed that the mechanisms can undergo high and cyclical loading. For the designer it is difficult to assess if the mechanism can perform according to the prescribed functions because the motion of its deflecting members is limited by their strength, which is a property that is not easily readable from the outside. Therefore, precise knowledge of the material properties and the desired motion range is required when shaping a compliant mechanism. In addition, it should also be remembered that the possible motion range of compliant mechanism is somewhat limited by its nature. A compliant link, for example, cannot produce a continuous rotational motion such as is possible with a pin joint. Furthermore, compliant links that remain under stress or are exposed to high temperature for long periods of time experience stress relaxation or creep, which both can highly affect the mechanisms behavior. Chapter 6 will present first attempts to address or overcome these challenges when it describes the manufacturing of the Flectofin®. In summary, it is important to always consider the inherent difficulties and limitations of compliant mechanisms in order to determine which application will benefit most by the use of compliant mechanisms technology.

2.6. Summary

In summary, kinetic structures in mechanical engineering are still based on the design traditions that were inherited from the industrial era. The predominance of rigid and strong materials like iron and steel during the Industrial Revolution conditioned the way machines were designed, analyzed, and manufactured. The thinking and actions were shaped by the rising scientific approach to engineering. Classical mechanics laid the foundation for a triad of achievements: mathematical theory, evolving engineering experience, and improving fabrication techniques.

Machine design is traditionally based on the agility of rigid-body mechanics. Motion is obtained by linking rigid elements together with highly strained hinges. Even today, most kinetic structures are made up on a multitude of modular parts. These components follow the logic of assembly lines and are usually mass-produced, mono-functional, and interchangeable. The maxim is that the more complicated the task, the more complex the machine needs to be. Rather than rethinking the basic building blocks in a compound machine, challenging requirements are usually addressed by interlinking numerous standard parts.

Previous attempts to widen the design vocabulary of kinetic structures by scientists like Reuleaux and others couldn’t withstand the high development pressures. In order to provide suitable solutions to as many technical problems as possible, it was easier to just recombine the well-established and well-proven rigid-link mechanisms. In doing so, design tasks were simplified in 2D representations and were understood in the logics of diagrams and section drawings. This created a pattern of thought in which motion was mainly considered to happen in planar or orthogonally connected systems. In this approach the predominant drivers for machine designs are kinematical relationships like axes and distinct points of connection. A notable exception to this long-lasting engineering tradition is the use of compliant mechanisms.

These flexible devices take advantage of their elastic material characteristics. And today, with the increasing computer-power it becomes even possible to solve the nonlinear calculations, which are needed to understand their complex deformation behavior and to predict the stresses within the elements. Furthermore, these techniques open the door to spatial mechanisms that use all three dimensions and are no longer restricted to planar or parallel movements.

However, this new development also shows that our knowledge of how to make best use of elasticity and how to integrate it in machine design is still at the very beginning. Designing with and not against flexibility would require to establish once again a new scientific approach to mechanics, to use novel materials that are more suitable for the task, to develop new design and fabrication principles, and finally to search for new role models to learn from.

3. KINETIC STRUCTURES IN BIOLOGY

Flexible Plant Movements

'In technology, shape is expensive, material is cheap. In biology, material is expensive, shape is cheap.'

- Julian Vincent (qtn in http://goo.gl/ZIKKFm, p. 8)

3.1. Overview - Why looking into nature?

Aiming for a radically different approach to the design of kinetic structures, this chapter turns to nature as a source of inspiration. By looking into kinetic structures in biology, this approach searches for promising alternatives to traditional rigid-body mechanics and the limiting design conventions and preconceptions that are associated with it. Compared to the previously described technical solutions in engineering, structures in nature are often simultaneously pliable and resilient. They seem to be governed by design principles that are very different to those that drive our mechanical designs. As it turns out, movements in nature are often based on flexibility and elasticity of structural members, whereas the mobility in mechanical engineering is mainly provided by the use of rigid elements that are connected with technical hinges (Knippers & Speck, 2012). The still persistent paradigm in engineering is, therefore, diametrically opposed to the construction principles in many biological structures. Moreover, while compliant structures are yet largely unknown in engineering or only used in very specialized industries, they are rampant in nature. Their diversity can very well be demonstrated by the example of flexible plant movements.

Before going into more detail, let's first address why plant movements can be suitable role models for kinetic structures in general. The thinking behind this may not be immediately apparent, since we know plants as sessile structures that are incapable of changing their location. Furthermore, it was a popular belief for a long time that since plants are tied down to one specific location, their motions are too small or insignificant to be studied any further. Yet portions of their body clearly exhibit detectable and often surprising movements. In fact, despite their lack of muscles, plants have evolved a remarkable range of motions principles that are highly sophisticated and well-attuned to their environment. However, what makes plant movements particularly suitable study objects is the fact that unlike the musculoskeletal system in animals, which usually has to be agile enough to allow for variety of different movements, plants often couple one type of actuation to a unique motion, with which to fulfill a specifically targeted function.

Figure 3.1: Snow buttercups follow the sun by using a motion principle based differential cell expansion in their stalks.

The spectrum of occurring movements ranges from very slow growth processes (ca. 1 mm/h) to exceedingly rapid discharge processes (ca. 10 m/s). The speed of these movements, whether it is the growing of shoots, leaves tracking the sun, or the rapid snapping of carnivorous plants, in fact spans over seven orders of magnitude (Dumais & Forterre, 2012; Forterre, 2013). Unfortunately, this also means that plant movements are often either too slow or too fast to be seen with the human eye. For this reason, we mistakenly perceive plants to be still while in fact they are always moving, seeking, changing position, avoiding danger, or are on the verge of capturing prey. However, thanks to today's time-lapse photography and videos that speed these movements up or slow them down, we begin to grasp the surprising behaviors of plants.

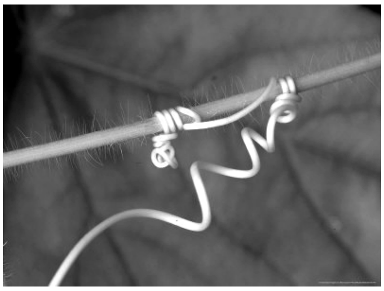


Figure 3.2: Tendril coiling is an example for thigmotropism and is contact sensitive movement based on differential growth and changes in turgor pressure.

3.2. Classification of Plant Movements

Ever since the pioneering work of the Darwin family (Darwin, 1865, 1875; Darwin & Darwin, 1880), generations of scientists became attracted to the question of how plants can move in the absence of muscles (Jost & Gibson, 1907; Ruhland, 1967; Hart, 1990). For biologists, the classification of plant movements and their physiology are of fundamental importance in order to understand how plants develop (morphogenesis) in general (Boudaoud, 2010; Mirabet et al., 2011), and in particular how they respond to environmental stimuli such as light and gravity (Braam, 2005; Gilroy & Masson, 2008; Moulia & Fournier, 2009). Therefore, it is no surprise that the work done on plant movements is extremely vast and still relevant today. Recent review articles provide a systematic overview on the status of research on the area (Scorza & Dornelas, 2011; Dumais & Forterre, 2012; Joyeux, 2012; Christie & Murphy, 2013; Forterre, 2013; Migliaccio et al., 2013; Toyota & Gilroy, 2013).

In general, one speaks of a plant movement when a plant responds to a perceived stimulus with a specific motion. When it comes to comparing plant movements to each other, the specialist literature mainly focuses on distinguishable key characteristics that are suitable for a classification. Typically, these criteria are either stimuli (e.g. physical and chemical impulses) that trigger a reaction or signals (e.g. hormones) that regulate and control the movement (Hart, 1990; Koller & van Volkenburgh, 2011). In this context, the most common classification of plant movements is a subdivision into taxes, tropisms, and nastic movements (Sonnewald, 2008). In addition to this, another common way to classify plant movements is based on motors and mechanisms that are responsible for the motion.

3.2.1. Taxes

One speaks of taxis, when a plant can independently perform free local movements because it is not tied to one location and thus not sessile. Due to its motility, the organisms can orient itself towards (positive taxis) or away (negative taxis) from the stimulus source (Sonnewald, 2008). In plant kingdom one can observe taxes, for example, in the movement of algae colonies like *Volvox* (Volvocaceae) with their flagellum-driven locomotion or other plants that are drifting on the water. Furthermore, taxes are also common in the propagation of seeds, fruits, or spores that are then transported by wind, water, and animals.

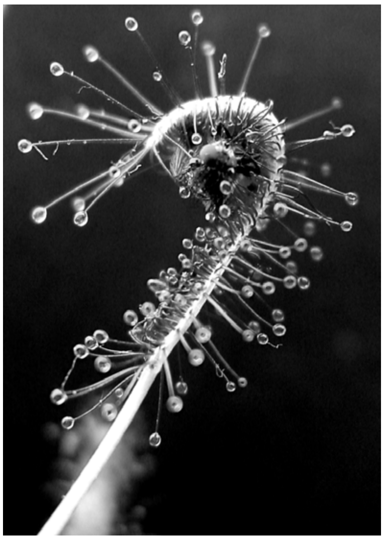


Figure 3.3: Drosera uses a thigmonastic movement to capture prey.

Figure 3.4: The touch sensitive mimosa pudica performs a thigmonastic movement as a defense and protection against natural enemies.

3.2.2. Tropisms

When a sessile plant can only move partially because it is tied to a location, one speaks of tropism. More precisely, tropisms are irreversible stimulus-dependent growth movements. The direction of the movement is usually tightly coupled to the direction of the signal as well as the physical location and orientation of sensory receptors (Koller, 2011). Similar to the previous category, there is a distinction between positive tropism and negative tropism, which describes whether a plant orients its organs towards or away from a given stimulus. In general, tropisms are very slow movements that bring about a long-lasting change to the plant since they are usually based on irreversible growth processes. Gravitropic movements of plant stems, for example, are guided by the perception of a gravity vector in specialized sensory cells. Phototropic movements of leaves and flowers are guided by differential interception of a light source. When this movement is meant to re-orientate the plant organ throughout the day in order to track the changing position of the sun, one speaks of Heliotropism. Stems and leaves of vines and other climbing plants can respond to friction when winding around a structural support or growing up a wall. This movement is called Thigmotropism (Fig. 3.2).

3.2.3. Nastic movements

Compared to the above-mentioned examples, one refers to nastic movements when the motion of a moving plant organ is a non-directional response to a stimulus and pre-determined by its construction (Fig. 3.3-3.4). In this case the origin of the stimulus is irrelevant and only acts as a triggering signal for a specific motion. Nastic movements are most often due to changes in turgor pressure but can also involve some more or less influential growing processes. Such movements are, as well as their direction, species specific and predetermined endogenously and exclusively by the fixed location and structural disposition of the driving motor or its parts.

Nastic movements are very common in plant kingdom and are characteristic for many dorsiventral organs like leaves, petals, and sepals. They are mostly controlled by both endogenous and exogenous signals. Endogenous signals originate from within an organism, tissue, or cell; while exogenous signals come from the outside. Often these nastic movements follow a circadian clock with a precise 24 h diurnal rhythm that corresponds to the daily cycle of light and darkness. This attuned motion is often crucial for plant function. In many flower species, for example, unfolding and refolding of leaves and petals synchronizes floral availability, with optimal periods for pollination determined by the activity of pollinating agents.

During blossom formation, flowers unfold sepals and petals (often referred to as calyx and corolla) and expose the stamens and ovary. Some species unfold their corolla only once before senescence. The ephemeral flowers of *Oenothera* (Onagraceae) and *Morning Glories* (Convolvulaceae), for instance, bloom in the early evening and then wither and die. Other species, such as the night-flowering cactus *Cereus grandiflorus* (Cactaceae), unfold and refold their flower repeatedly, employing epinasty as well as hyponasty. Other flowers perform folding movements around nightfall, which is called sleeping movement or nyctinastic movements. Diurnal movements that are synchronized to a dark/light transition are photonastic, whereas reverse movements that are synchronized to the opposite, light/dark transition are called skotonastic. Nastic plant movements that are an aftereffect of temperature fluctuations are called thermonastic movements. *Tulipa* (Liliaceae) and *Crocus* (Iridaceae) flowers, for instance, open in response to a small increase in ambient temperature and close in response to lowering temperature (by as little as 1°C to 3°C).

3.3. Motors and Mechanisms in Plant Movements

In addition to the classical categorization of plant movements, it is particularly interesting in the context of this thesis to consider the underlying motors and mechanisms that are responsible for the motion of plants. Here, a distinction is made between frequently encountered drivers like external loads, growth processes, hydraulic mechanisms, and elastic instabilities. A more detailed explanation can be found in the dissertation thesis of the biologist Simon Poppinga that accompanies this research (Poppinga, 2013).

3.3.1. External loads

The motion of plant organs can be a response to the application of an external mechanical load. In specialist literature, this is often not regarded as a real plant movement because the plant is not driving this movement itself but rather follows an external influencing factor passively. Quite different loads can act on a plant, such as flowing water, wind gusts, contact with pollinating insects, or attacks of natural predators (Fig 3.5). The resulting motion can be very versatile. Depending on the plant's structural setup, an external impulse can either cause an immediate deformation or be redirected to also trigger some secondary transformation processes (Fig. 3.6). An example that illustrates such a coupled mechanical sequence in more detail will be presented in Chapter 5.8.


Figure 3.5: Insect pollination.

3.3.2. Growth and hydraulic mechanisms


Figure 3.6: Calopogon.

Underlying most plant movements, whether they are generated in developing or mature plant parts, is a "motor" within the organism. In most cases, this can be traced back to highly specialized and smartly located motor tissue, whose structural changes drive and control the motion. The fundamental physical principles that are hidden behind their variability are either growth processes or hydraulic mechanisms. A clear distinction between the two is often very difficult since the term growth includes both cell-proliferation as well as cell-expansion. During proliferation a cell increases in size and then subdivides into smaller cells. The result is an irreversible local accumulation of additional material. Compared to this, cell-expansion means that a cell changes its shape, resulting in sometimes reversible swelling or shrinking (Tamiya et al., 1988; Forterre, 2013).


Figure 3.7: Pulvinus can deform based on differences in turgor pressure.

Some literature refers to plant movements also as "osmotic machines" (Hill & Findley, 1981, p. 173). Thanks to the hydraulic phenomenon of osmosis, individual cells and entire cell clusters can perform volumetric changes. Here, water flows from an area of low solute concentration to an area of high solute concentration until the two areas have reached a state of equilibrium. With its semi-permeable membrane, however, the cell is able to permit the diffusion of water in and out of the cell while at the same time restrict the flow of solute if necessary. Thereby, the cell can actively control its inner turgor pressure and thus manipulate its volume (Burgert & Fratzl, 2009). However, the resulting changes of the cell are not only dependent on the turgor pressure alone but also on the specific elasticity of the cell wall. In fact, for some hydraulic mechanisms, the structural setup, and in particular the anisotropic material characteristics of the cell wall, can have a significant effect on the resulting deformation behavior and cause predominant elongation directions, as will be shown in Chapter 5.2.

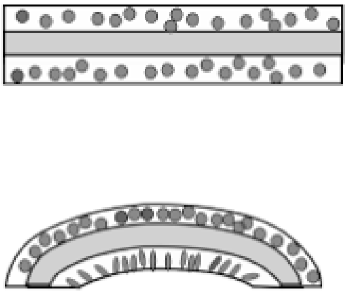


Figure 3.8: Differential growth.

Probably the most common mechanical principle in plant movements is based on the so-called differential growth (Fig.

3.8). Here, a plant organ has two opposite sides or zones in which motor cells grow or elongate unevenly, which leads to a bending deformation. Differential growth is one of the predominant drivers of flower opening and closure. For example, one speaks of an epinastic movement when a petal bends downwards, or of a hyponastic movement when the petal bends upwards. This simple mechanical setup of two unequally expanding or contracting sides can enable some surprising amplification effects on the motion. For example, the motor cells can generate a significant leverage if they are cleverly located by having some eccentricity to the organ's center of gravity. Furthermore, through the continuous cellular bonding between the opposite zones a good force transmission maybe obtained globally with little local energy dissipation. This mechanism can often be found in irreversible flower opening and closure or reversible sleeping movements of leaves that are driven by a pulvinus (Fig. 3.7). They will be explained in more detail in Chapter 5.3 - 5.6.

And finally, in hydraulic plant cells and structures, the osmotic pressure can also be increased and accumulated until it causes a sudden rupture or extremely fast explosion movements. Seedpods and capsules, for example, use this effect to cast their seeds out over wide distances.

3.3.3. Elastic instabilities and snap-buckling

There are also other mechanical principles in plant movements besides the previously described growth processes and hydraulic mechanisms. Elastic instabilities and snap-buckling effects are good examples. Strictly speaking, these are no motors but rather methods for translating small stimuli into large and amplified movements. Snap-buckling effects, for instance, can speed up movements beyond the limits imposed by simple hydraulic mechanisms. These elastic instabilities are special mechanical failure modes that are characterized by a sudden deformation of a structural element that withdraws from too high tensile or compressive stresses by deflecting into a less strained but geometrically deformed state. Generally, this dynamic process is very difficult to control because when a load is increased to a critical limit, it can come to a spontaneous buckling failure of the structure at any point. Nevertheless, plants and in particular carnivorous plants like the Venus Flytrap (*Dionaea muscipula*) seem to have mastered that technique quite impressively as will be described in more detail in Chapter 5.6.

3.4. Potential of Plant Movements as Role Model for Technical Kinetic Structures

The previous look into the most common plant movements and underlying motors revealed that plants use very effective mechanisms that enable fascinating motion principles of different types and for a multitude of purposes. These biological mechanisms may be ideal models for novel mechanical systems for several reasons:

First, plant actuation mechanics demonstrate how to make clever use of elastic material properties. With their flexibility and coherent structure, they represent a compliant mechanism that reduces the number of susceptible mechanical parts by an integrative design. It is astounding how the plant reaches that integrative design. Since plants have little diversity in building materials (e.g. cellulose, hemi-cellulose, pectin, lignin), mechanical adaptation is hardly based on material variations but mostly due to modifications in form and structure that often happen in different hierarchical levels (Vincent, 2002 ; Knippers & Speck, 2012). Moreover, plants seem to blur the boundary between traditionally distinct categories like structure, material, and mechanism. 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. Rather than inserting additional hinges, their global flexibility is often achieved through the versatile behavior of the entire organ. They often feature locally differentiated regions with special morphological characteristics such as living hinges or motor zones. Furthermore, 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.

Second, it may be interesting to examine plant mechanisms in respect to their kinetic efficiency by investigating how their structural setup enables a mechanical advantage. In most cases, these biological mechanisms effectively transform small geometric changes of local cell groups into an angular and global motion of an entire plant organ. Even though this is comparable to the muscle contraction and resulting skeletal movement known from the locomotion systems in humans and animals, there are some major differences. In both plant and animal movements, a small actuation is converted to a magnified motion of an entire organ - both types of systems operate as levers, sometimes with a significant mechanical advantage. While for animals, the components of the lever are quite obvious; the contracting muscle exerts a force on the short segment of the lever with the fulcrum being the joint between the bones to which the muscle is attached. In plants, the leverage is less obvious and depends on the complex interplay of the volumetrically changing motor cells that either transform relative to each other or in respect to neighboring fixed parts of the plant. A bending deformation of the entire plant organ is the result. This is all the more astonishing considering that unlike animal tissue which is soft and can easily deform; the vacuolated tissue in plants is usually very rigid and its deformation would require a strong force. This shows that plant mechanisms make clever use of their tiny yet powerful hydraulic actuators and integrate them in an efficient way, in which the actuators gain additional leverage through smart positioning.

3.5. Summary

The plant mechanisms presented here differ greatly from the technical constructions of the previous chapter in their form, structure, and material. In particular when examining them for their capability to perform motion, not only their differences but also their similarities become most visible (Fig. 3.10). These notable discrepancies, however, are also possibly new sources for inspiration. In particular, compliant mechanisms play an interesting role in this context because they share some characteristics of both technical constructions and biological constructions. Their study is definitely an interesting starting point for a knowledge transfer between these two areas. However, this kind of interdisciplinary collaboration requires a framework in which both fields of research start to merge together and seamlessly work on multiple levels of perspective.

The question arises whether the foundation upon which a framework for collaboration between the fields could be established has already been reached. Similarly to the previously discussed problem in which engineers seem to be trapped in traditional and slightly antiquated mindsets, biologists also have their historically rooted patterns of thought. From an outsider's point of view, for instance, it is conspicuous that when biologists discuss plant movements, they approach the subject typically in two ways. On the one hand, they target the larger scale by a peripheral view that sets plant movements in the context of external factors like environmental stimuli and signals. On the other, they quickly direct their attention to the smallest scale with a very focused view on the cellular structure of the plant and the changes happening therein. Of course, their gaze is focused on the local cell since it is traditionally perceived as the basic entity and the basic building block in the biological machine. This approach of looking at a single cell allows for an interesting reduction of plant movements to the influencing factors that initiate and control the changes in the motor cells. It is then possible to track the driving forces responsible for motion in cells that undergo irreversible growth, reversible swelling/shrinking, or differentials in water pressure. For this reason, most of the research conducted so far has examined these influencing factors. Typical studies in this area focus, for example, on the water potential inside and outside the motor cells, on the hydraulic conductance of the membranes, and the elastic properties of the cell wall. In addition, some research groups investigate the flow of water across the membrane, hydrostatic and osmotic pressure as well as fluxes driven by electrochemical potentials and differentials in ion concentration.

What seems lacking, however, are studies on plant movements that also address the larger scale mechanical aspects in plant organs. Broader studies on mechanisms and their motion should reunite the highly specialized investigations on elongating, expanding, and growing cells with large-scale movements of plant organs that spatially orient and conform themselves to fulfill a specific function.

Figure 3.9: The small bud of the Datura turns into a large trumpet-shaped flower, which can reach a length of 5–20 cm and a diameter of up to 4–12 cm.

Technical Constructions (Rigid-Body Mechanisms)	Technical Constructions (Compliant Mechanisms)	Biological Structures (Flexible Plant Movements)
Mostly 2-D Mechanisms	Mostly 2-D, few 3-D	Mostly 3-D, few 2-D
Micro-device to building scale	Micro-device scale	Cellular to organism scale
One component for one function	One component for one function	Each component is multifunctional
No or very limited redundancy	Little redundancy	High redundancy
Very different materials	Similar materials	Similar materials
Differentiated geometry	Differentiated geometry	Geometry and material are locally adapted and highly differentiated
Industrially fabricated	Industrially fabricated	Naturally grown
Constraint linkages	Elastic flexibility	Elastic flexibility
Majority of materials is isotropic	Majority of materials is isotropic	Properties are often anisotropic
Form is not defined by functional components	Functionality defines form	Functionality defines form
Either rigid or soft components, nearly no hybrid systems	Either soft components or local flexibility	Locally adapted stiffness
Rigid components joint by articulated hinges	Living hinges	No joints, no bearings Local zones of flexibility
External actuators	External actuators, Internal actuators	External actuators, Internal actuators

Figure 3.10: This table provides a general orientation over typical construction characteristics in technical constructions and in biological structures. In direct comparison it becomes apparent that technical constructions such as compliant mechanisms play an interesting intermediary role. However, it should also be noted that the categories in this table should not be regarded as unchangeable truth and that there are also many examples for technical and biological systems which cannot clearly be attributed to this simplified structures.

4. METHODOLOGY

Biomimetics and Bio-inspiration

'The same thoughts sometimes put forth quite differently in the mind of another than in that of their author: unfruitful in their natural soil, abundant when transplanted.'

- Blaise Pascal (Thoughts, p. 415)

4.1. Overview - How to turn inspiration into a working method?

By comparing kinetic structures in design with those in biology, it has become more obvious that nature can clearly have an inspirational role for future technological developments. However, this awareness alone is not resolving the remaining questions of how to tap into this source of inspiration, how to learn from it exactly, and how to transfer the gained knowledge in a practical and systematic way.

Gaining inspiration from nature isn't a novel concept in itself but a repeating theme in human history. However, for most of the preceding examples this inspiration remained mainly on a formalistic level. The floral décor of a Corinthian column or the filigree metalwork that is typical for the Jugendstil, for example, only mimic nature's appealing aesthetics and are not really informed by any functional or structural performance. The same applies to more recent architectural trends like Biomorphism, in which natural patterns and shapes are translated into a formal design language. Today's scientific method of biological investigation, technological methods of simulation and fabrication, availability of high-performing materials, all make a real knowledge transfer possible for the first time.

It should be clear that the intention of this thesis is not to only copy the aesthetics in nature but instead to establish a systematic knowledge transfer between biology and technology. It aims to learn from biological motion principles and integrate these insights into the development of bio-inspired kinetic structures. In order to attain this objective, this chapter will focus on an interesting new working method called biomimetics. The explicit goal is not only to discuss biomimetics in general but also to fathom out the relevance and impact, which it may have for this thesis in particular. The aim of this chapter is to envision a new methodological framework that could be used as an instructional guideline for the following chapters.

4.2. A Biomimetic Approach

Recently, a new line of interdisciplinary research has started to receive growing attention. This line of research is called biomimetics and enjoys a continuously increasing popularity not only among specialists but also in the general public. Judging from the broad media attention provoked over the last decade, one might think biomimetics is a well-established scientific discipline with a well-tested and proven research methodology. But unlike traditional fields of science that can build up on a long-grown framework of theories, methods, and working processes, biomimetics still is in its infancy and is just at the verge of becoming a recognized science. Precisely for this reason, it is interesting to engage with biomimetics. Now is the right time when every research project can enlarge the "toolbox" and contribute to a refined definition of the field and its associated workflow.

4.2.1. Definition of biomimetics

The English word "biomimetics" is comprised of the parts "biology" and "mimesis," which is the Greek term for imitation. This portmanteau word, however, is slightly misleading since biomimetics is not about the mere copy of a biological role model but instead emphasizes the innovative potential emerging from a creative process that transfers ideas and insights over several disciplines. To better capture this spirit, biomimetics is often used in combination with alternative words like "biologically inspired" or "bio-inspired." In other languages that often combine the word biology with technology, as for example the French "Bionique" or the German "Bionik", the interdisciplinary agenda of biomimetics becomes even clearer.

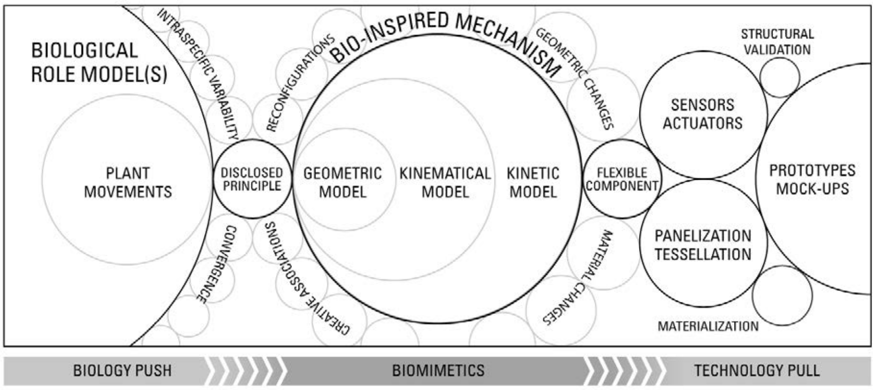
According to one of the latest definitions by the Association of German Engineers in 2011, "biomimetics combines the disciplines of biology and technology with the goal of solving technical problems through the abstraction, transfer, and application of knowledge gained from biological models." They continue by refining that "biological models in the sense of this definition are biological processes, materials, structures, functions, organisms, and principles of success as well as the process of evolution itself." (VDI Guideline 6220, p. 8).

This definition shows that the key idea behind biomimetics is not the imitation but the transfer of basic principles to technological applications. The motivation behind this is as simple as it is convincing: Over billions of years of evolution, biological structures have developed many optimized solutions to a variety of difficult tasks. And in fact, some of them are quite similar to those that technological developments have to face. Through selection and interaction, biological organisms have refined their characteristics and further developed their properties to such a level of perfection that they were able to adapt to constantly changing environmental conditions. This led researchers to believe that nature holds a plethora of multifunctional solutions that are particularly remarkable for having found successful compromises even to conflicting requirements (Speck & Rowe, 2006). The premise of finding inspirational solutions in nature to specific problems in technology becomes all the more exciting if one bears in mind that up till now more than 2.5 million different species have been identified and described. This means that the available pool of ideas and solutions is virtually inexhaustible.

4.2.2. General and specific challenges

The first of the two main challenges in biomimetics is that this approach offers only initial ideas, not finished solutions or a guarantee for innovation per se. In fact, innovation in the strict sense only takes place when the ideas and concepts are either implemented into new products and applications that have the power to penetrate a market or into services and processes that shift a prevailing paradigm. The second challenge in biomimetics is that the operational processes are still enigmatic. While it sounds comprehensive that initially conducted basic research can lead to new knowledge about a role model, it is much more difficult to imagine how the following transfer process of these insights can actually be achieved. This transition is so puzzling because it is neither based on precise rules nor on the intelligence of the involved persons but relies solely on their creativity and intuition. Creativity in this context does not mean the innate human characteristic to create something artistic but refers to the symbiosis of imaginative thought and practical action. In biomimetics, both of these aspects come together, which enable it to tap into different modalities for solving a problem. Depending on the situation this can be systematic thinking (i.e. purposeful and strategic as well as playful and intuitive approach), divergent thinking (i.e. approaching the problem from many directions and opening up new perspectives), or convergent thinking (i.e. decision-making based on experience, knowledge, and well-established rational heuristics). Exactly because of this bandwidth, biomimetics is equally exciting as it is difficult. In addition to these two general challenges, biomimetics also raises multiple questions in practical terms when being used for specific projects like this thesis. Up to now, it is not fully clear in which sequence the working steps should be applied and how they can be streamlined in a targeted way. This uneasy feeling arouses the desire to reflect on and eventually redefine the methodology of biomimetics as part of this thesis.

Figure 4.1: This diagram outlines a possible transfer process from the initial inspiration of biological role models, over bio-inspired mechanisms, to prototypes and mock-ups.



4.3. Mapping Repeating Themes and Emerging Trends of a Possible Transfer Process

Experience has taught that biomimetics is very rarely a linear process of successive steps. Instead, it seems like a multifaceted activity in which various specialists come together under a common theme and mutually exchange their expertise in a free way. Within this vibrant and elusive entanglement it is very difficult to identify individual work packages. Previous definitions of biomimetics have focused mainly on the motivations for entering the field it takes on in the first place rather than the precise workflow. Only very few researchers in the field have tried to reflect on the interrelationships. Speck and Speck (2008), for example, describe that a typical approach to biomimetics may either follow a biology push (bottom-up process) or a technology pull (top-down process). While the term biology push describes a development that is initiated from basic knowledge in biology, technology pull refers to the desire to solve a technical problem in order to improve an already existing product or process. For this thesis, however, it seems very difficult to maintain this linear understanding of biomimetics because the research here neither centers on converting one single role model into a product nor aims to solve a particular technical problem with a biological solution. Instead, the goal is to enter a new domain of knowledge in a systematical way. Therefore, the following sections aim to provide an expended understanding of biomimetics by outlining repeating themes and emerging trends that may indicate a broader framework. The map in Figure 4.1. is an attempt to assist the reader and facilitate a better navigation through the following chapters by introducing the key aspects of transferring plant movements into bio-inspired compliant mechanisms for novel kinetic structures.

4.3.1. Screening biological role models

Most of the investigations in this thesis started with an extensive screening of biological role models, in this case plant movements with high potential for translation into technical applications. Since the plant kingdom offers a vast range of models, the screening should be narrowed down early through a focused selection criteria. For example, one filter could search for organisms that have developed under high selective pressure because they often show sophisticated and optimized solutions for a given task (Reith et al., 2007). Another possibility could be to look for specific geometrical or structural characteristics that might prove useful for the further translation. Regarding the scalability of a plant-derived motion principle, for instance, it is beneficial when the deforming structure features large bending radii even in the zones of highest deflection. This aspect is important because too small radii in relation to a structure's thickness will result in very high stresses. Local stress peaks may make it impossible to rebuild a mechanism in another scale or out of another material. Finally, another possibility could be to search for role models that feature equal or unequal actuation principles and deformation behaviors. This approach is exciting because it shifts the attention to functional-morphological relationships and allows to compare multiple related plants movements to each other. Chapter 5 adopts this approach.

4.3.2. Disclosing motion principle

Once a promising role model is found, the next step is to disclose its motion principle. The challenge is to identify and locate all its components that play a key role for the deformation of the plant organ. Specific functional-morphological relationships in the mechanism as well as different forms of actuation are two layers of interest here. As seen in the preceding chapter, plants can move in various ways. They can be actuated by a displacement of water in the respective tissue or by the functional use of elastic instabilities. An additional point of interest is passive movement in plants when activated by an external mechanical force (Skotheim & Mahadevan, 2005; Dumais & Forterre, 2012; Poppinga et al., 2013). Dependent on the chosen model, revealing its underlying motion principle and locating the essential components in the mechanism can be very difficult. A helpful method that is as simple as it is effective could be to gradually trim the specimen and cut away everything that seems to be unrelated to the functioning of the mechanism and does not affect its motion behavior.

Once these examinations have revealed the general characteristics of the mechanism, it may be useful to expand the screening to other role models and thereby gain a broader understanding of the physical effects involved. Often, the disclosed mechanism 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 geometrical distortions. Furthermore, it may 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.

Finally, when the plants essential components and functional-morphological relationships are unveiled, the next step is to abstract them to the simplest mechanism, which is 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 essential characteristics of the mechanism. A subsequent reconfiguration of the identified building blocks may open up a broader design space of simple, compound, or even complex solutions. This holistic approach renders the possibility for far-reaching design explorations, beyond the direct copy of the biological role model and the one-shot product development.

4.3.3. Modelling bio-inspired mechanisms

As mentioned in chapter 2, the term mechanism is mainly used for a technical device that is capable of transferring motion, force, or energy. However, when reduced to its core meaning, this explanation seems also suitable for motion principles in biological structures, in particular when including the extended definition of compliant mechanisms. These devices can also transfer motion, force, and energy, but instead of joining rigid links with hinges, their mobility is based on the deflection of flexible members. In respect to their purposeful exploitation of flexibility and elasticity, compliant mechanism and plant movements are very similar. In detail and in scope, however, some biological structures may be partially ahead of their technical counterparts because their designs have not originated from a thinking process that is characterized by classifications systems and type affiliations. On the contrary, their typology-free approach to flexible mechanics makes them a fascinating starting point to inspire novel compliant mechanisms.

When it comes to the reproduction of biological mechanisms by computational models, it is important to recognize the possible hierarchical representation. According to the practical experience of the author, three levels of information define the digital modeling of a bio-inspired mechanism in particular. These layers relate to geometrical, kinematical, and kinetic properties of the mechanism and can be at the basis of individual models, which can also build up on one another in order to create positive feedback loops (Fig.4.1).

The first layer of information is a geometric model. It can be drawn in a conventional CAD environment and is a precise yet immovable representation of the plant specimen. This model focuses only on the mechanism's shape and structure. 2-D sections and 3-D scans can thereby offer helpful data to recreate the key features of the plant specimen. Since scans and sections usually provide an unnecessarily high level of detail, it is important to reduce their complexity and breaking them down to their essential components. Once a geometrical model is abstracted to its key elements, it is also possible to construct it in a parametric format. In this case, all topological relationships between the elements stay constant while the parameters that define their dimensions become variables. A parametric version of the geometric model offers high adjustability and makes it possible to quickly generate a series of similar mechanisms that differ slightly in size and proportion. This is beneficial because the studies are no longer confined to the direct translation of the plant but also allows for a comparative analysis within a larger group of similar models.

The second layer of information is a kinematical model, for which the previous geometric model can serve as a basis. The aim of a kinematical model is to study the motion of the mechanism. However, it considers only geometrical aspects of the movement without reference to masses or forces. In order to turn a geometrical model into a kinematical model, a series rigid links and connecting hinges replace all flexible elements in the mechanism. This can be done, for example, with CAD environments like Rigid Origami Simulator or Kangaroo Physics (Tachi, 2009; Piker, 2013). Both programs have a spring-based simulation capacity. By assigning degrees of constraint and degrees of freedom in the model, it becomes possible to determine a structure's kinematics. As a result, one can represent the movement of 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 can be achieved, for instance, by adding physical units and quantifiable spring stiffness to the system. This change allows for an analysis of forces and motion based on the calculation of virtual work. The result is a so-called pseudo-rigid-body model. It replaces in-depth nonlinear analysis with a closed form analytical description based on the theories from classical mechanics (Howell, 2001). Pseudo-rigid-body models enable fast calculation of the forces and motion in the system and thus are ideally suited for quick studies of a mechanism's general sensitivity and adaptability.

Finally, the third layer of information is a kinetic model. Compared to the previously discussed kinematical model, a kinetic model is not a rough approximation but a precise representation of the mechanism 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 geometrical changes, motions, and forces has to take place simultaneously since their deformation depends on the forces exerted on them. This circumstance complicates the analysis and synthesis of bio-inspired compliant mechanisms significantly. One remedy to this problem is the simulation of kinetic models with Finite Element Modeling (FEM). Fortunately, FEM tools have advanced so much over the last years that they can be used now to calculate the forms and forces of structures under large elastic deformations and to predict complex equilibrium states. In comparison to the previous models, the special advantage of FEM is that it can display nonlinear behavior and enables a look inside the structure while it is deforming. Thus FE-simulations offer a more complete mechanical description of the system. Furthermore, since they are based on the exact physical properties of the system, FE-simulations can not 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.

In summarizing the above, it should be noted that each layer of information and associated model has its strengths and weaknesses. The great opportunity lies, consequently, in the combination of all three models. To achieve this, however, one has to overcome the individual drawbacks and simplify the data exchange between them. A kinetic model that is based on FEM simulations, for instance, may be very precise in its results but often takes long to prepare and execute, which makes it less suitable to act as swift design tool in a creative process. Exactly this, however, can be the strength of a spring-based kinematical model. It may only be an approximation but can provide immediate feedback and allows the designer to interact with the model while the simulation is still running. Ideally, one would aim to bring all three models closer together and optimize their data exchange. This is really important because the difficulty of interconnecting the models is often the largest obstacle in the design process. While it is relatively easy in FEM, for example, to make changes to material properties or support conditions, modifying a model's input geometry requires a switch back to the pre-processing environment in CAD. In order to accelerate this process, it would be best to couple all models in such a way that changes in one automatically re-computes the 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 behavior of a bio-inspired compliant mechanism.

This information can then be used to systematically evaluate various models according to their mechanical performance or to fine-tune mechanism to the most effective setup for a given task.

4.3.4. Conceptualizing novel flexible components

The next step after modeling a bio-inspired compliant mechanism is its transfer to a flexible component that considers its practical use or possible implementation, as will be discussed in more detail in Chapter 6. Depending on the application scenario, the flexible component has to meet specific functional demands, material requirements, and load profiles. Furthermore, it may be required to orient the element in a special way or to conceptualize the flexible component in a functional array of related neighbors. In this case, issues like tiling symmetry, tessellation, and panelization of a targeted structure or surface may come into play and further affect the shape of the components to which one wants to apply the bio-inspired motion principles. This spatial arrangement also affects the possible locations for sensors, actuators, and control systems. In order to finalize the transfer process, all considerations may be brought together in the building of a prototype or mock-up that proves the sought after concept.

4.4. Summary

Aiming to support this thesis with a methodological background, this chapter presents the creative method of biomimetics as helpful framework for the further course of this research. However, since biomimetics is not yet fully recognized as a science it is difficult to find a precise description of the working processes therein. Therefore, it is particularly important to not only make general remarks about biomimetics but to envision its practical use for the context of this thesis. Mapping repeating themes and emerging trends that could be useful for studying biological models and transferring their motion principles into bio-inspired mechanisms is definitely one possible way to increase the applicability of biomimetics. However, it should be carefully noted that all the observations and suggestions made at this point only result from the author's personal experience and may have to be adapted or changed for other projects. Nevertheless, the mapped out working process provides a helpful guidance and step-by-step instruction that will be implemented in the next chapter and tested on specific case studies.

5. CASE STUDIES

Exemplary Plant Movements and their Transfer to Bio-inspired Compliant Mechanisms

> *'And thus, in contrast to the mere gaze, which by scanning organisms in their wholeness sees unfolding before it the teeming profusion of their differences, anatomy, by really cutting up bodies into patterns, by dividing them into distinct portions, by fragmenting them in space, discloses the great resemblances that would otherwise have remained invisible; it reconstitutes the unities that underlie the great dispersion of visible differences.'*
>
> **- Michel Foucault (The Order of Things, p. 293)**

5.1. Overview - How does it work exactly?

Referring to the classification of plant movements that was presented in Chapter 3 and to the methodology for transferring their motion principles into bio-inspired compliant mechanisms that was proposed in Chapter 4, the aim in this section is to illustrate the approaches and procedures of the previous chapters more clearly through the use of practical examples. To achieve this, Chapter 5 will go on by providing in-depth analyses of seven exemplary plant movements and illustrating a possible transfer process of their motion principles. Each of these case studies features a fascinating compliant mechanism, which is particularly promising for mechanical abstraction and further transfer into technical applications.

The following seven case studies have been selected because they represent some of the key motion principles in the plant kingdom, which are seldom used in mechanical engineering. This selection makes no claim for completeness. Instead this list is only meant as a first rough overview of types of plant movements that the author believes are very promising for further examination. The spectrum of these case studies is very broad and diversified. It ranges from plants that greatly differ from each other in size and structural setup to plants which contain differences in the complexity of the implemented mechanism. Some of the following examples were selected because they are based on comparable or even similar mechanical principles but show them in interestingly different configurations. Others were selected because they feature comparable movements but achieve those motions with very different mechanisms. The approach followed in the examination of these case studies aims to distinguish individual mechanisms from one another by referring firstly to the characteristic actuation type and secondly to the typical structural response of the moving plant organ.

The first case study is the stomatal aperture in plant leaves. The movement of this structure is based on multidirectional changes of two interacting cells that undergo a volumetric swelling and shrinking.

The second case study is the raising and lowering in the leaflets of *Oxalis* (Oxalidaceae). This plant's mechanism also employs multidirectional changes, but its motion is based on the entire cell cluster swelling and shrinking.

The third case study is the flower opening of *Lilium* (Liliaceae). The tepals of this flower deform strongly due to unidirectional changes of expanding edge curves.

The fourth case study is the blooming motion of *Ipomoea* (Convolvulaceae). It has a comparable mechanism to the previous case study and is also driven by unidirectional changes of expanding edges yet shows the principle in a slightly different configuration.

The fifth case study is the trapping motion of *Dionaea* (Droseraceae). This carnivorous plant moves due to bidirectional changes in its trap lobes, which get significantly amplified by an impressive snap-buckling effect.

The sixth case study is the trapping motion of *Aldrovanda* (Droseraceae). Even though this plant is related to the previous case study, it uses a different mechanism, which couples the unidirectional changes of a bending curve with bidirectional changes of adjacent lobe surfaces.

And finally the seventh case study is the pollination mechanisms of *Strelitzia* (Strelitziaceae). This deformation movement is driven by a punctual change that was triggered by a locally applied load at a specific point.

These seven case studies will be discussed in more detail in the following sections (5.2-5.8) with a focus on their mechanistically related abilities. While some of these plant movements are popular study objects in the biological research community, others will been investigated for the first time. All share, however, the unique interdisciplinary approach of this thesis that examines these case studies from a different angle and thereby sheds a new light on them. Each of the sections will present the biological role model, describe the relationships of its functional morphology, disclose the motion principle, abstract and transfer it to a simplified version of a bio-inspired mechanism, and test the mechanism's variability and consistency by modifying some key design parameters. Finally, each section will end with a conclusion summarizing the key findings.

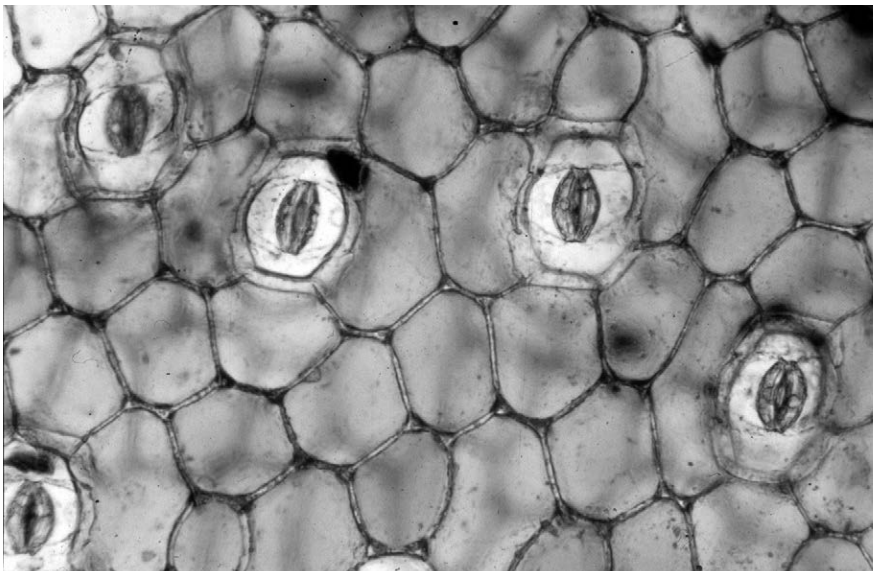


Figure 5.1: Stomatal pores in the epidermis of leaves enable the plant to exchange gases and thus are crucial for photosynthesis and evaporation.

5.2. Case Study 1: Stomatal Aperture

The first case study examines the opening and closing of leaf stomata (Fig. 5.1). This reversible movement is based on multidirectional changes of two expanding cells and is influenced by their distinct morphology and cellular buildup.

5.2.1. Biological role model

The stomatal aperture is probably not the first plant movement that comes to mind when screening for inspiration. And, in fact, among the following seven role models the stomata aperture represents a special case which belongs to a different scale level. Invisible to the naked eye, this plant movement is so small that it appears to be rather unspectacular at first glance. However, the stomatal aperture is one of the most important plant movements on our planet and among the best-studied by the scientific community. The reversible opening and closing of the stomata takes place in special pores in the epidermis of leaves, stems, and other plant organs. Figure 5.2, for example, shows the underside of a leaf with multiple stomata cells, of which a plant can have about 10,000 - 100,000 per cm^2.

Thanks to the opening and closing motion of these special pores, leaves can fulfill two essential tasks: They can exchange gases, in order to conduct photosynthesis and respiration, and they can permit evaporation and transpiration to assist the movement of water from the ground to the leaves, where it is needed to build carbohydrates. The plant must control this form of motion exactly in order to stay sufficiently hydrated and be able to survive.

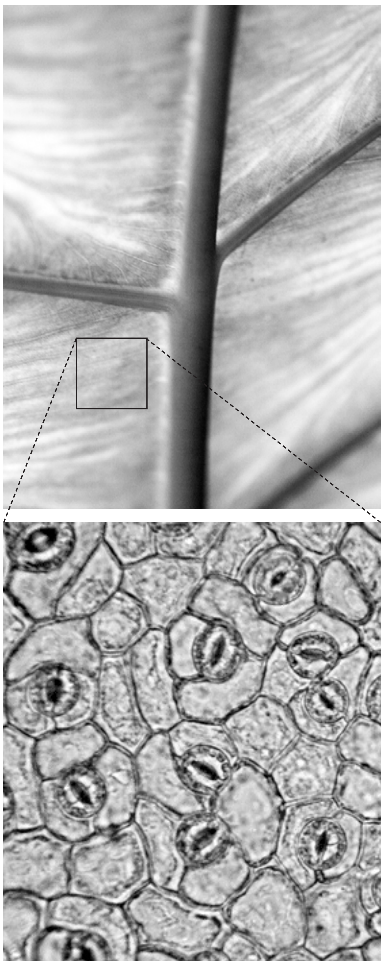


Figure 5.2: Underside of a leaf with stomata pores.

5.2.2. Functional morphology

Precisely because this reversible motion has such a fundamental importance, it was subject to various studies. While early research focused mainly on the shape and structure of the stomata pores (Von Mohl, 1856; Copeland, 1902; Ziegenspeck, 1938; Aylor et al., 1973), recent work aims to describe either the physiology of stomata cells including the biochemical processes inside (Meidner & Mansfield, 1968) or their responsive behavior in respect to environmental factors like changes in light conditions, water levels, and electrical signals (Wood & Turner, 1971; Buckley, 2005; Kaiser & Grams, 2006; Meckel et al., 2007; Dumais & Forterre, 2012). On the basis of these studies, a detailed picture of the mechanism's functional morphology can be established. In most plants, the stomatal complex consists of two kidney-shaped guard cells that are fused on both ends and flank a central pore (Tiaz & Zeiger, 2002). The opening and closing of the stoma pore is regulated by turgor pressure in the guard cells and thus represents an osmotic mechanism (Hill & Findlay, 1981).

5.2.3. Description of the movement

The guard cells can fill up or empty themselves with water by changing their inner solute concentration, which affects the water potential and causes an osmotic pressure gradient to the surrounding cells. When the turgor pressure of the guard cells is sufficiently low, for instance, the two cells are pressed together tightly and the pore is closed. When the turgor pressure increases, however, water enters the guard cells and the pore opens up (Fig. 5.3). The increase of turgor pressure is a response to an increase of solute concentration (in this case Potassium being actively pumped into the guard cells from the surrounding cells), which in turn decreases the water potential inside the guard cells and causes water to pour in from outside. As a result, the guard cells increase in volume drastically. In the context of this thesis it is very fascinating to observe that this volumetric actuation in the guard cells causes not only a longitudinal expansion along one axis but also a sideways bending of the cells. It is this multidirectional and curved deflection that forces the surrounding cells of the epidermis apart and thus opens the pore. The resulting motion is fully reversible and as soon as the turgor pressure drops, the excessive water leaves the guard cells and the stomatal aperture resets into its closed state again.

5.2.4. Disclosed principle

To better understand how the stomatal complex is capable of turning a local volumetric actuation into a multidirectional change and thus into a global opening movement, it is worthwhile to have a closer look at the underlying mechanism.

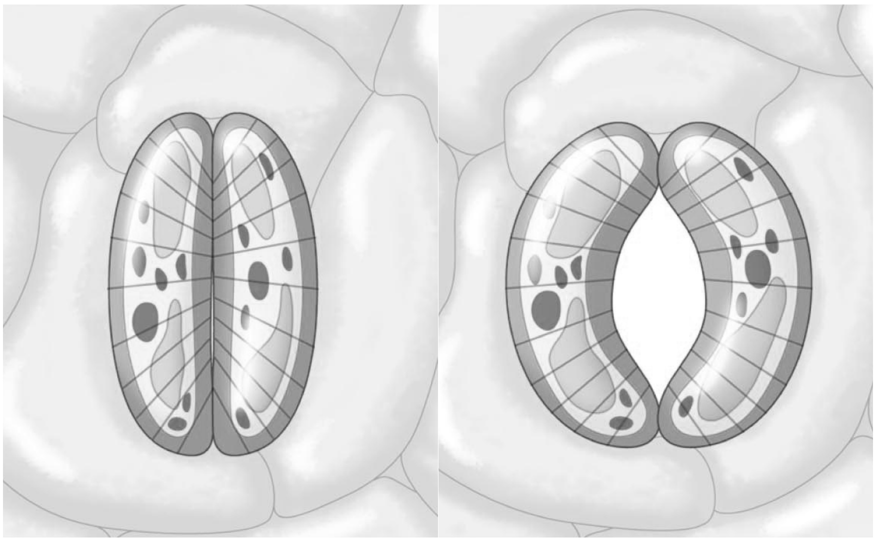


Figure 5.3: Guard cells in open and closed configuration. The thin lines on the guard cells illustrate the circumferential microfibrils, which are believed to be mainly responsible for the bending deflection.

The main principle in the stomatal aperture can be traced back to an interesting interplay between boundary conditions and the internal structural buildup of the guard cells. The individual deformations of the guard cells are inevitably linked to each other because their cell walls are fused at both ends. It can be observed that when the cells get filled with water, the fused cell walls remain unchanged, while the outer walls start to stretch symmetrically. Yet, this interconnection alone is not sufficient to explain the significant curvature change in the shape of the guard cells.

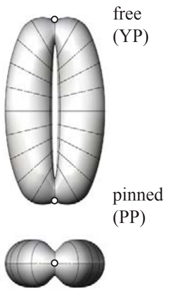
Early studies suggested that the bending behavior of the guard cells might be caused by an asymmetrical stiffness distribution. Von Mohl (1856) was the first to notice that the walls of the guard cells are thicker in the area where they face the pore and thinner on the outside. In a certain way, this gives the guard cells a structural orientation in the longitudinal direction with a gradient stiffness from one side to the other. It was this asymmetrical composition that made researchers like Schwendener (1882) assume that the cause for the distinct bending deflection might be located here.

Later research by Ziegenspeck (1938) and Aylor et al. (1973), however, disproved this assumption. Instead, they showed that the main reason for the bending deflection of the guard cells is the presence of circumferential microfibrils, which cause a specific anisotropic fiber lay-up in the cell (Fig. 5.3). Due to their orientation and high tensile strength, these lignin fibers significantly limit the traverse expansion of the cells when the internal hydrostatic pressure increases. As a result, the guard cells predominantly expand in length rather than in width and thus press against the neighboring guard cell and bend outwards.

5.2.5. Abstracted bio-inspired mechanism

Based on pictures and diagrams from the previously mentioned studies, the stomata was first rebuilt as a digital geometric model of 1500 mm length and 800 mm width. It features the two interconnected guard cells that share partitioning walls at both ends. The pore is modeled in the state in which the cells are close together and relatively small in volume. Additionally, the model features the characteristic microfibrils, which were modeled as cables on the cell surface, as well as specially subdivided surface segments at the inner flanks of the pore. In the second step, this setting was turned into a kinetic model by defining the boundary conditions and assigning material properties (Fig. 5.4). For this reason, the model was anchored in space with two supports, of which one is fixed and the other is capable of sliding in the y-direction. The soft behavior of the cell walls was recreated as a fictional membrane material with a Young's Modulus of E = 900 N/mm^2 and a thickness of 1 mm. The stiffer properties of the inner flanks were considered by assigning a GFRP-like Young's Modulus of E = 15000 N/mm^2 and a thickness of 2 mm. The microfibrils were remodeled as CFRP-like rovings with a Young's Modulus of E = 130000 N/mm^2 and a diameter of 5 mm.

To recreate the volumetric actuation of the mechanism, the cell walls were given a distributed load that pulls along the surface normal. Analogous to the biological role model, this form of actuation together with the distinct structural configuration triggers a primarily longitudinal elongation of the cells and a bending deformation that opens the pore. In this simulation it can also be observed that the opening mechanism has some limitations and comes to a natural end in which the aperture size is no longer changing but only the stresses continue increasing.



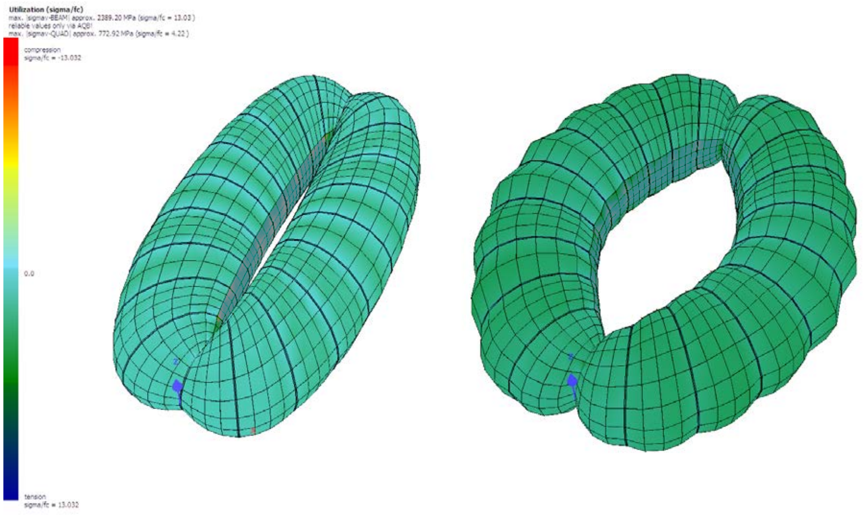


Figure 5.4: Kinetic model of the stomata pore in a finite element software features stiffer inner flanks and circumferential microfibrils. Increasing the inner pressure of the cells causes a bending deflection, similar to the biological role model.

5.2.6. Mechanical variability and consistency

While remodeling the stomata mechanism, the question arose in what way the settings of the geometric and the kinetic model affected the opening movement. This initiated a number of experiments with which to find the most important elements for the functioning of the mechanism. Twenty models with slightly different geometrical and structural features were simulated and compared regarding their mechanical behavior. Figure 5.5 shows the four most revealing models that allow to draw the following conclusions:

The first model, called Stomata 1, has neither distinctive features nor any form of structural orientation and consists only of two fused guard cells. An increase of pressure in this model results in a uniform expansion of the cells in all directions and a simultaneous closure of the pore.

The second model, named Stomata 2, represents the most direct translation of stomata complex as described in the previous section. This model has stiffer flanks, partitioning walls between the cells, and circumferential cables. Increase in pressure triggers the mechanism as expected and opens the stomatal aperture.

The third model, Stomata 3, features all the elements of the previous model but has double the amount of circumferential cables. This model seems to be more efficient in its capacity to redirect the pressure increase into a bending motion as can be seen in the wider opening of the pore.

Finally, the fourth model, Stomata 4, differs from the previous two by having the cables aligned longitudinally, which may constraint the expansion of the guard cells in one axis but does not support the opening motion of the mechanism in any way. Instead, a pore that features this setting closes tightly when the pressure gets increased.

5.2.7. Conclusion

In conclusion of this first case study, it can be said that the stomata pores in plant leaves perform a fascinating and essential movement. Here, the clever interaction of two connected cells is able to translate a volumetric and multidirectional swelling and shrinking deformation, due to pressure changes, into a directed bending motion that allows for opening and closing the pore on demand. Particularly exciting in this case study is the fact that the underlying mechanism is highly dependent on the cellular buildup in the micro scale. The experiments have shown that the orientation and density of the microfibrils play the major role for the functionality and efficiency of the stomata mechanism.

Stomata 1:
Has no additional elements and consists only of the two fused cells.

Stomata 2:
Features additional circumferential cables and stiffer inner flanks.

Stomata 3:
Has double as many cables.

Stomata 4:
Aligns the cables longitudinally.

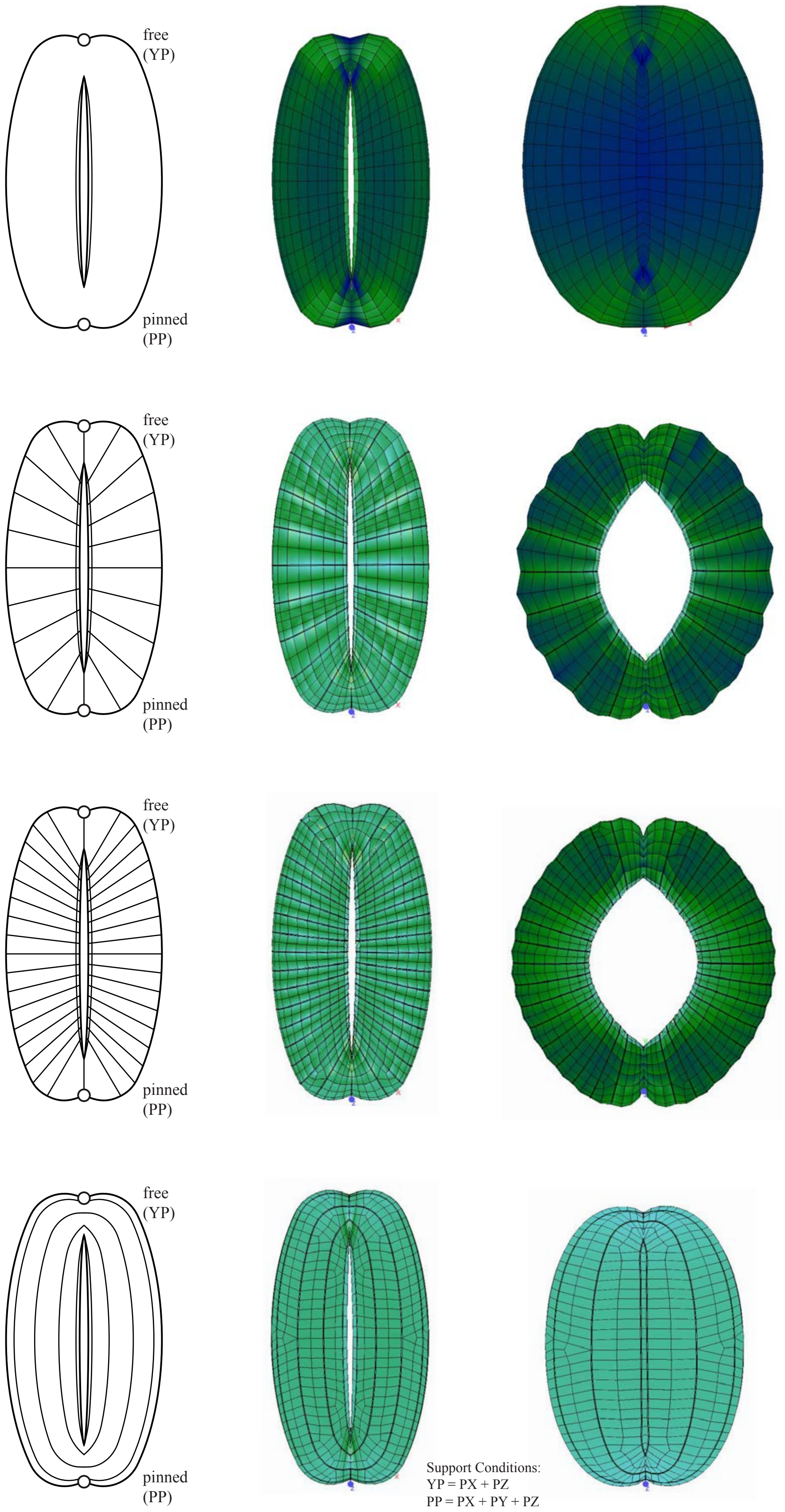


Figure 5.5: Guard cells with different structural features.

Figure 5.6: The leaf of *Oxalis triangularis* has a distinctive structure and consists of three triangular leaflets.

5.3. Case Study 2: Leaflet Movement of *Oxalis* (Oxalidaceae)

The second case study examines the leaf opening and closing of *Oxalis* (Oxalidaceae) (Fig. 5.6). This plant performs a nastic movement that is similar to the previous example based on multidirectional changes of cells. However, this example has a more complicated actuation principle, in which the volumetric swelling and shrinking of an entire cell cluster drives the motion. The cell cluster, or pulvinus, is a local thickening at the base of the leaflet.

5.3.1. Biological role model

Oxalis, commonly known as "False Shamrock" or "Purple Shamrock", is a perennial plant, which is originally endemic to South America. By now, *Oxalis* counts as one of the most widespread potted plants worldwide and is also available in Europe throughout most of the year. This plant has not only gained much popularity among hobby gardeners but also fascinated many scientists for centuries. Perhaps the most known study can be found in Charles Darwin's book on "The Power of Movement in Plants" (Darwin, 1880). In this book he uses *Oxalis* as an example for a typical nastic plant movement and illustrates how a specific environmental stimulus can trigger a distinct photonastic response. Since this fundamental observation is still relevant today, the plant is often studied in many botany classes around the world. *Oxalis* is also an interesting study object because it reacts to environmental stimuli by a complicated oscillatory movement of an entire plant organ. More precisely, the plant is able to adapt the spatial orientation of its leaves and leaflets in respect to continuously changing light conditions and thereby follows a circadian rhythm (Fig. 5.7). Fascinated by this repetitive diurnal behavior, multiple researchers have studied this plant movement and investigated its nyctinastic sleeping movement (Galston & Davies, 1970; Bünning, 1973). The widespread accessibility of this plant as well as its wide leaf area and sturdy structure make it fit for experimental observation. It is interesting to note that most of the previous studies have either examined the plant on a broader context (for example by investigating its interrelation to the environment) or on a cellular level by focusing on the internal changes of the vascular tissue in the pulvinus (Müller-Haeckel, 1975; Nakanishi et al., 2005). However, relatively little work has been done on the plant's post-actuation movement in order to describe the motion on the level of the plant organs. It is precisely the complex spatial movements of the leaflets and the structural deformations that happen during the motion process, which make this plant interesting in the context of this thesis.

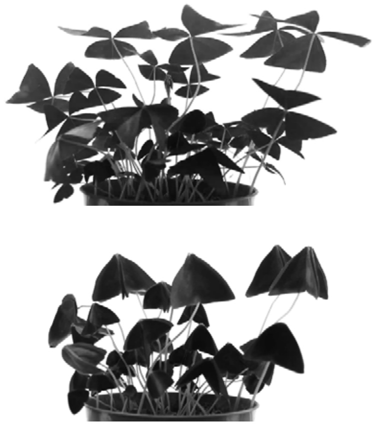


Figure 5.7: The leaves of *Oxalis triangularis* move in response to changes in light levels.

5.3.2. Functional morphology

In order to have a closer look at the plants anatomical and morphological features, the species *Oxalis triangularis* was chosen and examined further. A typical characteristic of *Oxalis triangularis* is its compound leaf shape in a trifoliate (ternate) configuration (Fig. 5.6). Here, every leaf is divided into three separate leaflets, which are all connected by a central stalk (petiole) and roughly have the same size. The leaflets have a deltoid, almost perfectly triangular form that is notched at the top and narrow at the base. The edge length of the leaflets is roughly 2.5 cm and the stalk is about 10 cm long. The rather thick tissue makes it difficult to see the leaflet's pinnate venation, in which secondary veins are paired oppositely. A closer look at the picture in Figure 5.8 reveals three additional morphological features that are very important for the following plant movement. First, one might notice that every leaflet thickens at the base of the petiole, where the leaflet comes in contact with the stalk. This multi-cellular cluster is called the pulvinus and is the main motor organ of the plant movement. Second, the leaflet has another noticeable feature identified as a midrib. Unlike the surrounding veins, this center vein is nearly perfectly straight. Apart from its main function as a conduit for water and solute, the midrib serves as a folding crease during the movement. This becomes more obvious when observing the plant over a long time period. During different stages of the motion, the leaflets move up and down, which results in a local deformation in the area of the midrib, quite comparable to a living hinge. Finally, another less obvious feature can be identified near the pulvinus, where the perimeter of the leaflet thickens up and forms edge-ribs.

Figure 5.8: Pulvinus, the central motor organ of *O. triangularis*, is located where the leaflet and the stalk connect. The central vein of each leaflet acts as a living hinge during the folding motion.

5.3.3. Description of the movement

The leaf-movement of *Oxalis triangularis* is a fascinating example of water-driven motion common in the plant kingdom. Dumais and Forterre (2012) provide a comprehensive review for this series of plant actuation. As mentioned before, the photonastic movement of this plant is a response to alternating light levels. During the day, when the ambient light intensity is high, the plant's leaves are wide open and fully exposed to the sunlight. At night when the ambient light intensity is low, the leaves are lowered and compactly folded. This adaptation to continuously changing light conditions follows a circadian rhythm. A circadian rhythm is an endogenous (self-sustained) oscillation that is entrained (adjusted) to the local environment by external cues, in this case triggered by daylight. According to previous studies, the plant requires about 30-40 minutes of light irradiation for a noticeable leaf opening (Nakanashi et al., 2005). The reasons for this motion are not quite clear yet. Some researchers assume that the plant uses that movement to protect its leaves when they are not needed while others assume that at night the lowered leaflets might channel condensed water down towards the roots of the plant. What can be said, however, is that the plant's diurnal movement is highly reversible. In principle the opening and closure happens every 24 hours, 365 days a year, enabling the plant to perform around 730 cycles annually. This number may indicate a very robust mechanism behind the movement yet needs to be approached with the usual caution. Of course, not every leaf lasts over the course of a year. Some wither after short time and are replaced by new ones.

In the context of this thesis, the movement of *Oxalis triangularis* is particularly interesting because it is based on a conjoint mechanism, in which two mechanical motions seem to be interrelated. There is a lifting and lowering motion of the leaflets on the global scale and a corresponding folding process of the leaflet in the local scale. In the primary motion, the leaflets change their orientation as a whole by rapidly rotating at the petiole, which acts as a distinct pivot point in the plant organ. In the secondary motion, a folding movement brings the lobes of the leaflets closer together which then allows for an efficient packaging size in the closed state.

5.3.4. Disclosed principle

Comparable to the previous case study of the stomatal aperture, the primary movement of lifting and lowering the *Oxalis* leaflets is also based on changing turgor pressure within specific motor cells. In this case, however, the cellular setup is much more complicated and consists of more than just two interacting cells. Here, the actuation is done by an entire vascular tissue.

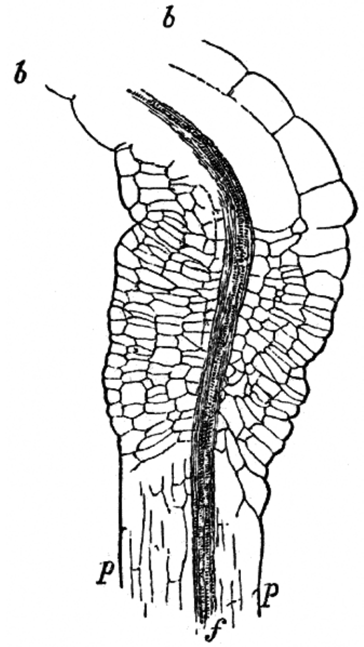


Figure 5.9: Illustration shows a longitudinal section throught the pulvinus of a *Oxalis rosea*. Marked with (p) is the petiole; (f) is a fibro-vascular bundle; (b) is the commencement of the blade cotyledon.

The pulvinus is a specialized structure between the base of the leaflet and the petiole. It can easily be recognized as a thickening of about 2 mm in diameter (Fig. 5.8). This multi-cellular organ serves two main functions. Firstly, it is a light-perceiving sensor (Hill & Findlay, 1981) and, secondly, it is the reactive part of the plant that drives its movement (Watanabe & Sibaoka, 1973). Interestingly, the pulvinus also fulfills a third function as a local living hinge, which can flex for many cycles without failure.

According to previous studies, the actuation of the pulvinus is water-driven and based on osmotic swelling and shrinking of two opposing cell groups (Hill & Findlay, 1981; Moran, 1990; Moran, 2007a, 2007b). The change in turgor pressure is initiated by an active transport of ions across the cell membrane, which is followed by massive water flux across the plasma membrane (Mohr & Schopfer, 1995). For a better understanding of how these changes in turgor pressure affect the pulvinus, it is worth looking at its cellular structure. The illustration in Figure 5.9, for example, shows a longitudinal section (Darwin, 1880). In the middle of the pulvinus is a vascular bundle (f) that crosses the structure longitudinally and probably absorbs most of the tensile forces. Surrounding this inner bundle is a more flexible, bulky cylinder of thin-walled parenchyma cells (b) and (p). The outer parenchyma cells act as motor cells and are considered to be the ultimate drivers for the movement (Cortizo & Laufs, 2012). These cells are separated into two groups, called extensor and flexor.

The extensor cells are located on the lower side of the pulvinus and the flexor cells are on the upper side. During leaf closing the turgor pressure in the extensor cells decreases while it increases in the flexor cells (Satter, 1979). This causes the leaflets to move downwards. During leaf opening, the inverse occurs, the flexor cells shrink and the extensor cells swell, which moves the leaflets upwards (Moran, 2007a). In this motion process, the location and type of cellular transformation in the motor cells have a decisive influence on the efficiency of the mechanism. A beneficial leverage is achieved by a lateral offset of the motor cells to the vascular bundle in the middle, and by a significant volumetric change of the cells. In fact, a single motor cell can change its volume by 25 % within 1 second (Braam, 2005). This effect gets additionally amplified by the surrounding tissue, in which individual cellular transformations are connected in series. With this mechanism, the plant is able to convert a small yet powerful, local actuation into a large and multidirectional movement of the entire organ.

While the primary motion in *Oxalis triangularis* has been the subject of various studies, the secondary motion has hardly been described. What drives the folding of the leaflet lobes is an open question.

One idea might be that the folding movement is a successive "passive" response, which is mechanically coupled to the primary motion. In this case the pulvinus would be the driver of both motions. This would mean, however, that the pulvinus bending is not only occurring in one plane, as Darwin's longitudinal section suggests, but instead consists of a three-dimensional deformation that also affects the pulvinus in its cross-section. In this case, the motor tissue would need to be active in two planes of perspective. An alternative idea is that the secondary motion has its own "active" driver. This assumption would require a separate actuator embedded in the folding crease itself. Having an actuator in the crease, however, would align it with the fulcrum of rotation and result in an unfavorable lever arm. In most mechanical systems, therefore, the actuators are positioned off-axis and apply a more beneficial eccentric force. From a technical perspective it would, therefore, be very interesting to know whether *Oxalis* has in fact an actuator in the crease and if so, how this folding mechanism works in detail.

5.3.5. Abstracted bio-inspired mechanism

Based on the previous morphological description, the plant was digitally rebuilt as an abstracted geometric model. While the shapes of the leaflets were simplified slightly to lower the complexity of the model, the internal proportions were preserved. The model has five distinct elements that allow for individual modification in the later simulations: leaflet lobes, edge-ribs, midrib, and two additional surface strips on each side of the midrib and the pulvinus. In the next step, the geometric model was turned into a kinetic model by assigning a size scale and material properties (Fig. 5.10). The leaflet surfaces have a GFRP-like Young's Modulus of E = 15000 N/mm^2 and a thickness of 2 mm. The properties of GFRP were also used for the edge-ribs and midrib, which were modeled as rods with a diameter of 5 mm and 2 mm. The pulvinus mechanism was greatly simplified and remodelled as two surface strips with different thermal expansion characteristics on the upper and lower side. An increase in temperature causes their bending and lowers the leaflet. The surface strips next to the midrib were given the inverted characteristics, which result in a bending in the other direction. As a result the leaflet folds closer together and thereby avoids contact to its adjacent neighbors. Thus, each leaflet requires less space and can be lowered even further down to the stalk (Fig. 5.12).

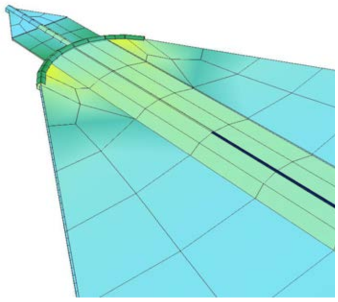


Figure 5.10: Kinetic model of the *Oxalis* features an abstracted and simplified mechanism that performs similar to the plant's pulvinus.

5.3.6. Mechanical variability and consistency

With the goal of addressing if the secondary motion is driven actively or passively, a series of physical experiments were conducted. They tested the resilience of the mechanism by cutting into the plant organ in three different ways and observing the consequences to the motion behavior.

In the first experiment (cut 1), one half of the leaflet was cut perpendicular to the edge-rib (Fig. 5.11). This cut subdivides the lobe's tissue in two portions: one that is still in contact with the pulvinus and another that is only connected to the midrib but no longer attached to the pulvinus. During the closing process, the primary motion remains unchanged. The secondary motion, however, can only be observed in the upper portion of leaflet that is still connected to the pulvinus while the lower portion seems to be decoupled and does not fold. From this experiment one may conclude that the secondary motion is driven by the pulvinus only and that there are no additional motor cells at the midrib. The folding movement seems to be dependent on the pulvinus rotating the edge-rib. In this scenario, moving the lower portion may, however, be very difficult since it is not suspended from above and the full weight of the lower portion acts now on the midrib.

In a second experiment (cut 2), one leaflet half was cut in parallel to the midrib (Fig. 5.11). The cut does not incise the pulvinus nor does it separate the leaflet halves at the notch margin. Both leaflet halves are now mainly separated portions but have two contact points at the base and the notch. While both of them have a direct connection to the pulvinus and still have their individual edge-rib, only one is fully attached to the midrib. During the closing process the primary motion remains unchanged; both leaflet portions rotate down to the stalk in the same manner. Interestingly, the secondary folding motion can be observed in both portions as well. From this experiment one may conclude that the secondary motion may be driven by the primary motion and can also appear when a leaflet half is decoupled from the midrib. It seems that a remaining connection to the midrib only affects the degree of folding positively, maybe because one half can push against the other and use it as fulcrum. The most important influencing factor in this test, however, seems to be the preserved connection of both halves to their edge-ribs, which transmit the actuation force from the pulvinus.

Finally, in the third experiment (cut 3), the leaflet was split so that the leaflet portions are completely separated from each other and have only one connection point at the pulvinus (Fig. 5.11). During the closing process, the primary and secondary motion remained unchanged. In this test all necessary elements that seem to be needed to perform the primary and secondary motion are still intact and active. Similar to the previous test one can observe that the secondary folding seems less effective, which may have to do with the missing fulcrum between the two halves.

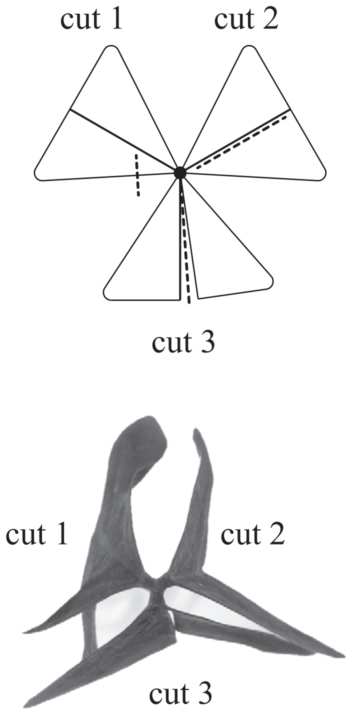


Figure 5.11: By cutting the *Oxalis* leaflets in three different ways, one can quickly test which elements play an important role for the secondary folding motion.

Based on these experiments there is reason to believe that the secondary motion may only be a “passive” response to the pulvinus deformation, which is mainly driven by the motion of the edge ribs. However, a clear statement to this assumption would require more work and experiments.

5.3.7. Conclusion

The leaf opening and closing of the second case study builds up on the previous example and illustrates another mechanism based on multidirectional changes of cells. In contrast to the first case, the motor organ in *Oxalis* is even more complicated and consists of an entire cell cluster. While earlier studies have already described its basic mechanism, the differential swelling and shrinking between an upper and a lower layer of tissue, the simulations and physical experiments conducted here suggest that the pulvinus mechanism might be even more complicated. The secondary motion of the leaflet halves cannot be explained with the common approaches. The folding movement of the leaflets, however, seems to play an important role since it results in an even more efficient packaging size. Even though the conducted physical experiments were only first quick tests, they suggest that the folding motion may also be driven by the pulvinus. If this is really the case, then more profound research would definitely be worth considering to evaluate the pulvinus as a three-dimensional mechanism. It might be inspirational to know how the pulvinus can drive both the lowering and lifting of leaflet in the one direction and at the same time the folding and unfolding in the other direction.

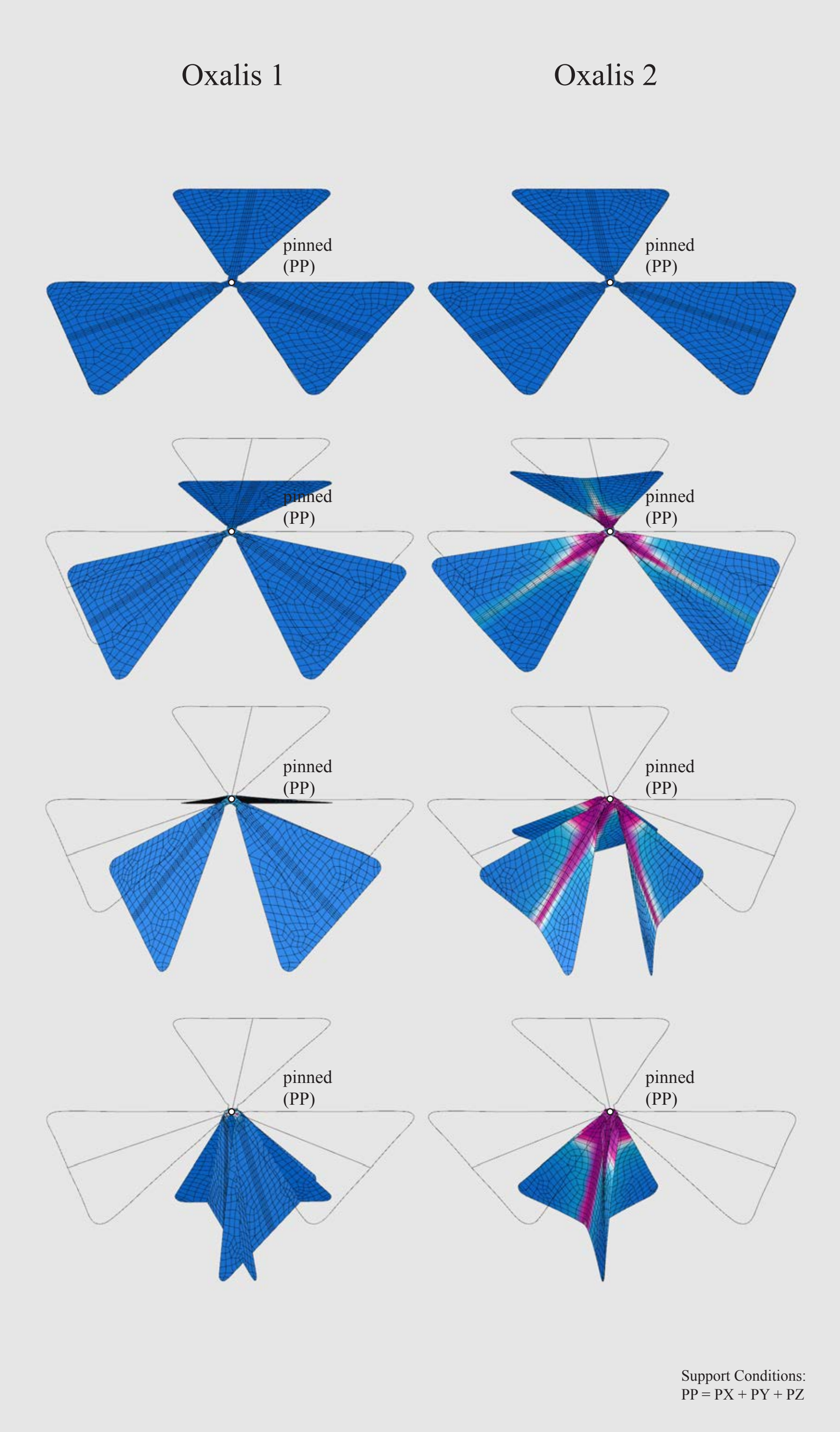


Figure 5.12: The pulvinus in the model on the left, Oxalis 1, only acts longitudinally whereas the pulvinus in the model on the right, Oxalis 2, acts both longitudinally and transversely. As a result, the leaflets fold together to a more efficient packaging size, which allows to lower the leaflets even further.

Figure 5.13: The flower of a *Lilium Casablanca* in full blossom. Its opening movement of this flower is driven by a differential growth that appears between the rapidly expanding edges and the inner lamina of its tepals.

5.4. Case Study 3: Flower Opening of *Lilium* (Liliaceae)

The third case study examines the opening process in the blossom of the *Lilium* (Liliaceae) (Fig. 5.13). When this flower blooms, its tepals perform a bending motion, which opens the flower bud and thus makes the reproductive organs accessible for pollination. This plant movement is fascinating because its actuation principle differs from the previously mentioned case studies in respect to its form-structure-function relationship. Here, the underlying mechanism is based on a differential growth rate that occurs between the tepal's inner lamina and its outer edges. More precisely, while the inner lamina retains its length during blooming, unidirectional changes along its edges cause a significant expansion of the tepal's periphery, which forces a bending motion of the plant organ and an opening of the flower bud.

5.4.1. Biological role model

The chosen role model for this case study is the lily; again one of the most frequently sold garden plants. Due to its popularity it is widely accessible and can be purchased in nearly every flower shop in the world. But when doing so, one has to pay attention. Even though many flowers have the term "lily" in their common name, they often are unrelated to true lilies and only share a superficial resemblance. The family of Liliaceae only comprises about 110 species that are regarded as true lilies. For the further examination the *Lilium Casablanca* was chosen. This type of herbaceous flowering plant is characterized for growing a large and often fragrant flower from its bulb. Lily flowers come in various colors ranging from whites, yellows, pinks, reds, and purples and often have distinct markings like spots and strokes.

5.4.2. Functional morphology

In the context of this research, *Lilium Casablanca* is a fascinating subject of study due to the relationship between its functional morphology and its mechanical behavior. This lily has a relatively large flower bud that is about 10 cm long and 2.5 cm in diameter. The bud consists of six tepals, which have nearly the same morphological features. They can be further subdivided into 3 inner tepals and 3 outer tepals. In their form they are almost identical and can be generally described as convex surfaces with higher curvature in lateral direction than in longitudinal direction. Each tepal features a softer lamina and a stiffer midrib. Regarding the form and function of this midrib, however, sepals and petals differ slightly from each other. Whereas the midrib of the outer sepals is rather featureless, those of the inner petals are bilayer composite structures. These midribs have a softer leafy part that is contiguous with the lamina and a stiff woody part that is in short distance to it. This gap in the midrib can be recognized as a longitudinal groove along the petal. When the bud is closed, this groove acts as a locking mechanism by clamping the margins of the neighboring sepals. This bond between petals and sepals not only increases the structural integrity of the closed bud but also supports the rapid deployment of the flower once the blooming starts.

5.4.3. Description of the movement

Shortly before blooming, the lily bud is tightly packed and provides enough space and protection to enclose the flower's sexual organs (Fig. 5.14). But 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. Often this movement is accompanied by a distinctive wrinkling effect that occurs along the lamina edges and which gives the lily flower a typical look.

5.4.4. Disclosed principle

Besides its general popularity among garden and plant lovers, the lily also fascinated the scientific community. Over the last decade, in particular the flower's opening process was the subject of various scientific studies (Bieleski et al., 2000; van Doorn & Meeteren, 2003; Liang & Mahadevan, 2011). Research groups like the one headed by

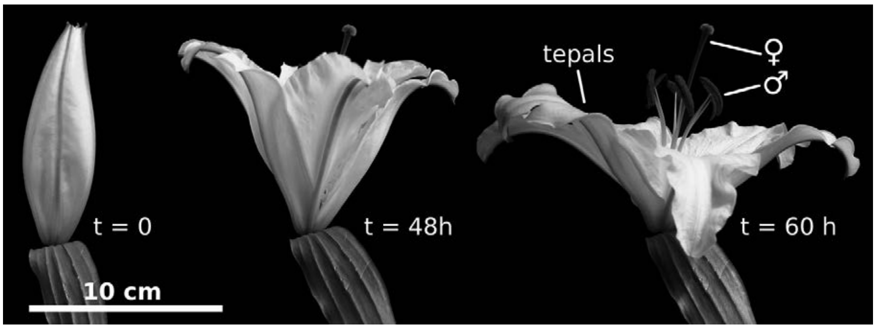


Figure 5.14: When the lily flower blossoms its densely packed bud bursts open and the tepals begin to bend outwards. The distinctive wrinkling along their edges are indicators for a differential growth mechanism.

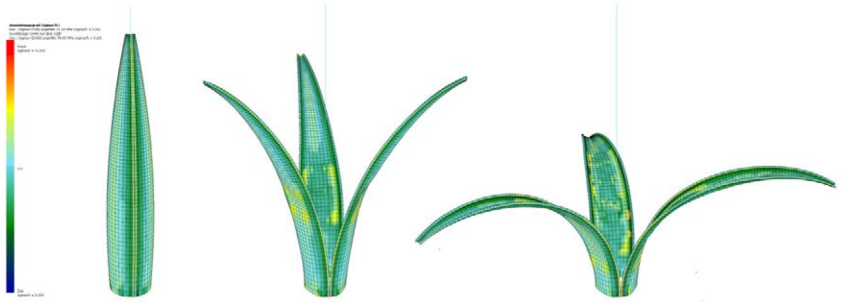


Figure 5.15: Kinetic model of the lily bud recreates its opening mechanisms by increasing the temperature in the tepal edges and thus enforcing a local expansion.

Liang and Mahadevan studied the flower's growth, geometry, and mechanics in great detail and revealed multiple new aspects. By combining time-lapse videos with photogrammetry, for example, they were able to map the flower's deformation sequence very precisely. These recordings were then used to create a mathematical model with which to describe the blooming of the flower numerically. In addition, they conducted a series of experiments, which enabled them to track down the mechanical principle responsible for the opening movement of the lily flower. According to their studies, the mechanism is driven by differential planar growth that appears along the tepal's edges. Here, an excessive expansion of the margin relative to the center causes a strain gradient in the lamina, which forces the tepal surface to deform in a specific way. This local mechanical effect is generally known to be responsible for the emergence of global saddle-shaped surfaces with rippled edges and was observed in other plants as well (Liang & Mahadevan, 2009).

5.4.5. Abstracted bio-inspired mechanism

This case study is a further example for a mechanism, whose abstraction requires a holistic approach. Here, a combination of kinematical and kinetic analysis is needed because the driver for the movement is based on differential growth, which causes internal changes of the material state. Since plant growth may include both cell elongation as well as cell division, this raises the question of how to mimic this process by technical means. Therefore, a set of experiments was aimed at finding a suitable mechanical concept with which to prove the proper functioning of the lily-mechanism in general (Schleicher et al., 2014). The approach chosen uses a temperature-controlled actuator that enforces edge expansion when heat is applied. Therefore, the lily bud was rebuilt as a 2000 mm high parametric model and imported to FEM. In preparation for the following simulation of the edge expansion, the model was assigned with two idealized materials for the tepal surface (thickness = 2 mm, Young's Modulus of E = 12000 N/mm^2, αT = 17 x 10-6/K) and for the tepal edges (diameter = 13 mm, Young's Modulus of E = 3200 N/mm^2, αT = 85 x 10-6/K). These materials differed, in particular, in their thermal expansion coefficient by a factor of 5. Now, if the temperature in the edge curves is increased by 70°C, which corresponds to an increase in strain by 0.6%, it results in a strain gradient that is comparable to the lily-mechanism and which forces the tepals to bend outwards (Fig. 5.15). Depending on the application scenario, an actuator like this could be built by combining materials with diverging thermal expansion coefficients like, for instance, GFRP and PMMA (acrylic glass).

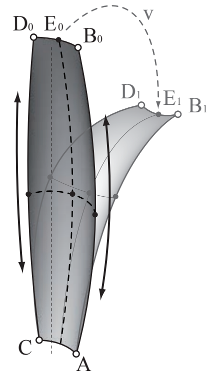
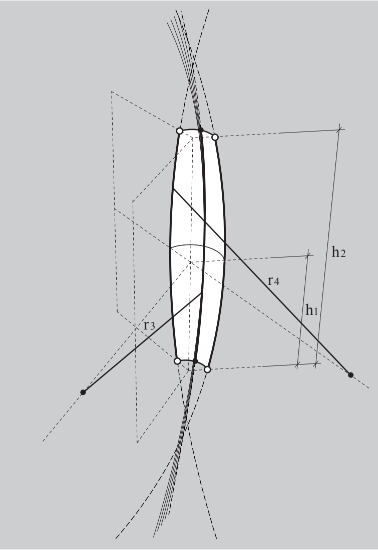
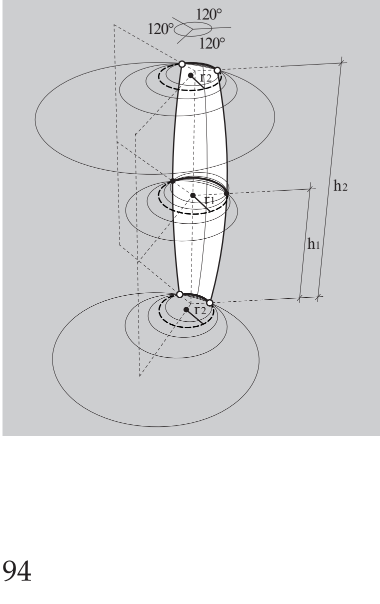


Figure 5.16: Geometric model of a lily tepal shows its main elements and principle of functioning.

Figure 5.17: Parametric version of the geometric model.





5.4.6. Mechanical variability and consistency

In this case study two interesting questions emerged regarding the mechanism's variability and consistency: How does the tepal's geometry affect the functioning of the lily-mechanism, and to what degree does this relationship limit the freedom to design other shapes that integrate this mechanism?

To investigate this question, the flower tepal was built as a parametric model (Fig. 5.17-5.18). This allows for a comparative study of multiple shapes that are equipped with exactly the same bending actuator but slightly differ in their geometry (Schleicher et al., 2014). While the parameters of the edge curves remained constant, the surface of the tepals was the variable and enabled individual modifications. In this model two radii (r3) and (r4) in the lateral axis determined the rotational surface that spans between the curves (Fig. 5.17). In the center of the surface, the cross-section is defined by radius (r1), whereas radius (r2) is responsible for the cross-section at the tips. Based on this setup, a series of 25 slightly different models was generated (Fig. 5.19). Viewing this group from back to front, radius (r1) increases gradually, which results in tepal surfaces with less curvature at the center. Viewed from left to right, it is radius (r2) that decreases gradually, which results in tepal surfaces that have a greater curvature at the tips. All models were linked to the FE-program and assigned with the same idealized material properties as described in the previous section. For actuation, the edges of all models were slowly expanded up to 1.1% of their individual length. For comparison purposes, the individually calculated load cases were saved at different temperature increments and imported back

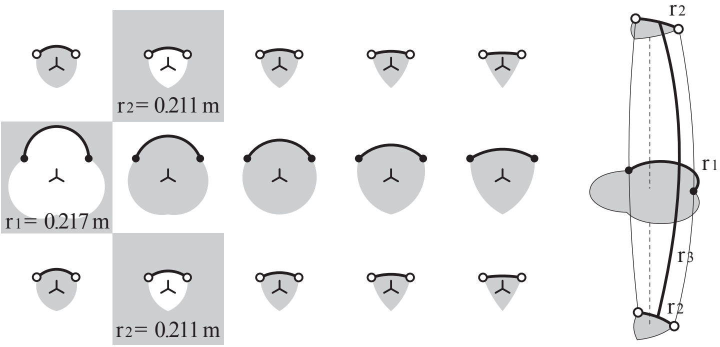


Figure 5.18: Parametric version of the geometric model allows for modification of the geometrical settings and generation of different tepal shapes.

into the CAD environment. A closer look at the models side-by-side revealed that their deformation behavior is all but uniform. Although made from the same material and driven by the same actuator, some models hardly deform at all whereas others show large deflections. The difference in behavior is due to the models' divergent structural stiffness, which arises from their geometrical shape before deflection. In particular, the settings at the center cross-section influence the models' mechanical response the most. Fig. 5.20 (left) shows one extreme, in which, a smaller radius (r1) 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 characteristic can offer more resistance and often form a constriction at the center when being bent. This compares to all the models that have a larger radius (r1). 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. 5.20 (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 the phenomenon of edge wrinkling, which was previously described to typically occur in the lily opening. Another setting may cause the formation of smaller buckles and ripples in the surface that stall the movement of the tepal for a while or cause a cascading breakdown.

5.4.7. Conclusion

The third case study of *Lilium* presents a fascinating new actuation principle that is based on local differential growth that occurs along the tepals' edges. First simulations have shown that this actuation principle can be recreated by using materials that expand to a different degree under heat. Comparative analysis between slightly different models has shown that one can effectively gear the motion behavior through the geometry of the actuated structure.

Figure 5.19: Comparative analysis of 25 slightly different models. Even though each model is driven by the same actuator and has the same material properties, their deformation behavior varies significantly. This is mainly due to the models' individual structural stiffness which arises from their geometrical shape before deflection.

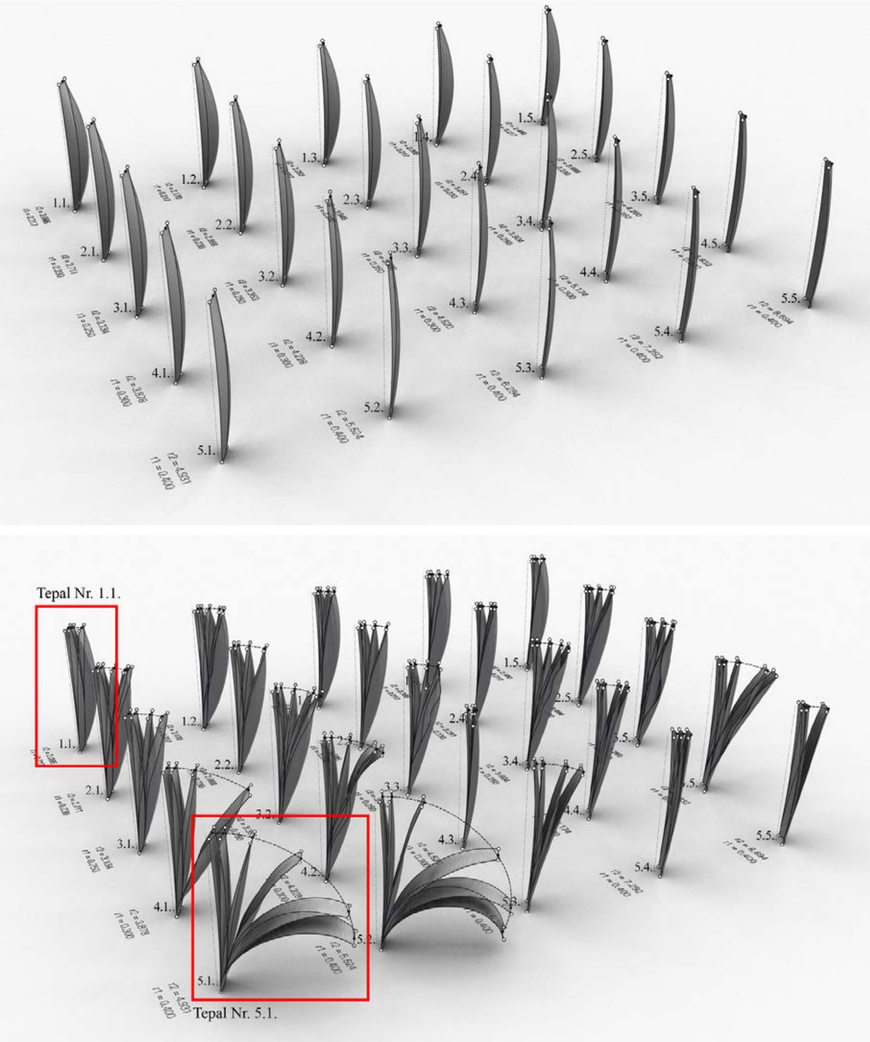


Figure 5.20: Especially the center radius highly affects the structural stiffness of the models and either makes the shape more resistant against deformation or more susceptible.

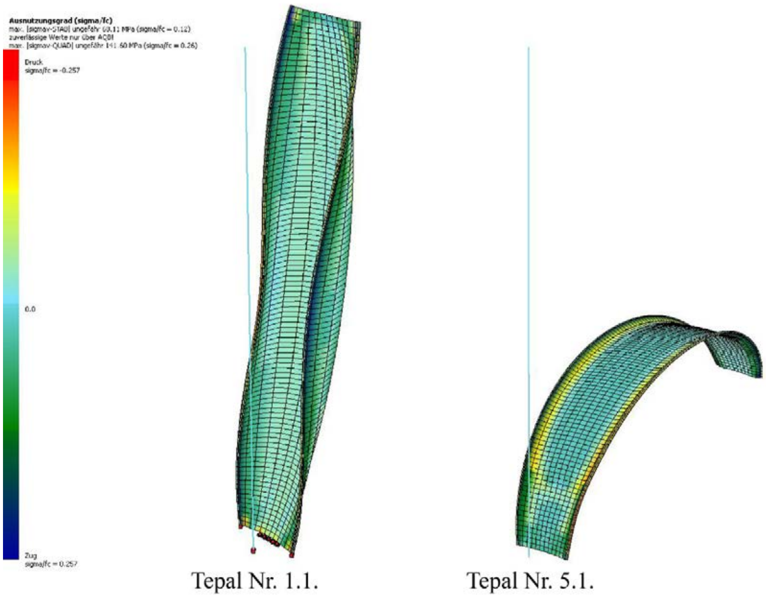


Figure 5.21: The sympetalous *Ipomoea alba* has a uniquely formed flower in which the five petals with their mid-petaline bands are fused together to one continuous corona.

5.5. Case Study 4: Flower Opening of *Ipomoea* (Convolvulaceae)

The fourth case study examines the opening and closing process in the blossom and senescence of *Ipomoea* (Convolvulaceae) (Fig. 5.20). The movement of this flower is based on a mechanism that is to some degree comparable to the previously described case study. Similar to the lily, the mechanism in *Ipomoea* is also driven by differential expansion effects and unidirectional changes that cause structural curves to elongate. The motion principle behind this plant movement, however, adds another layer of complexity to the system by enabling the flower to perform multiple complicated shape changes during its maturation and senescence.

5.5.1. Biological role model

The chosen role model in this case study is called *Ipomoea*. This plant is also known under the names morning glory, moonflower, bindweed, sweet potato, or moon vine. The genus of *Ipomoea* belongs to the plant family of Convolvulaceae, which has over 500 species. Herbaceous plants, shrubs, and small trees make up this family. Most of them are twining and climbing plants. Usually, they are native to tropical and subtropical regions but can also be found in

Europe. The following studies were conducted on the species *Ipomoea tricolor* (Morning Glory) and *Ipomoea alba* (Moonflower). As the name "Morning Glory" suggests, this flower typically opens early in the morning and usually starts to close by mid-afternoon of the same day. In contrast to this, *Ipomoea alba* shows a deviating behavior. The so-called "Moonflower" opens in the evening and normally only lasts through the night until it closes at dawn. What is interesting, though, is that both species have a very short transformation cycle in common, in which they perform various motions and shape changes within only a few hours. This fact makes them excellent study objects for examining movements related to maturation and senescence.

5.5.2. Functional morphology

Large and funnel-shaped flowers are characteristic of *Ipomoea*. Compared with other flowers, the ones of *Ipomoea* stand out because of their impressively formed corolla, which has a pentamerous and sympetalous symmetry. In this special flower configuration all five petals are fused together to one continuous corolla surface. It is this morphological feature, which makes the opening and closing of *Ipomoea* particularly interesting in the context of this thesis.

While other flowers can change their shape by sliding or overlapping their petals individually, *Ipomoea* has to adjust its shape by means of folding and bending its entire corolla surface. This special circumstance is particularly challenging from a mechanical point of view and suggests that *Ipomoea* might feature a highly refined mechanism that takes advantage of zones with globally and locally adapted stiffness distribution and specialized cell orientation. And indeed, the corolla of this flower is not a uniform structure but highly differentiated in its structural build-up. It combines a soft and thin lamina on the one hand and five leathery mid-petaline bands on the other. These bands are significantly thicker than the surrounding lamina and occupy the longitudinal middle third to fifth of each corolla segment (Heywood et al., 2007).

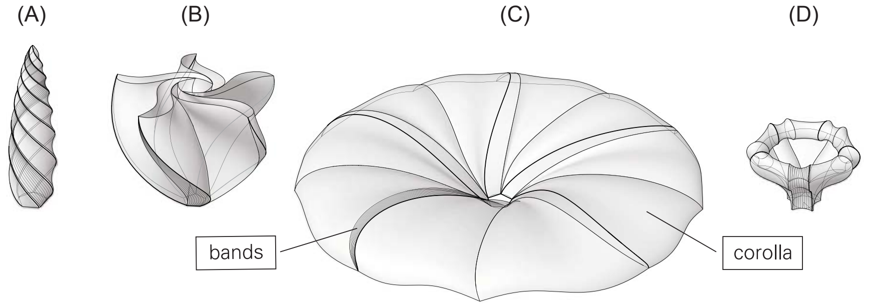


Figure 5.22: During maturation and senescence the *Ipomoea* undergoes different transition states. After the bud-state (A), it opens up in a spiralling movement (B) to form a wide-spanning flower (C) and rolls up after blooming (D).

5.5.3. Description of the movement

In order to describe the movement of *Ipomoea*, one needs to understand that this flower not only performs one but multiple movements and undergoes different transition states during maturation and senescence (Fig. 5.22A-D):

During its bud-state, *Ipomoea* is helically furled up into a robust and efficient packaging configuration that provides protection to the flower's sexual organs (Fig. 5.22A). In this state, the relatively stiff mid-petaline bands are arranged on the outside, while the more fragile parts of the corolla are folded within (Fig. 5.23). The five bands are twisted clockwise around a middle axis by about 540° and show a logarithmically increasing rotation angle towards the tip (Schleicher et al., 2010). In this special configuration, the bud is so densely packed that the bands touch each other along their ridges and together form a protective shell. From the outside, one may think that the adjacent bands are coadunate, but in fact they are only connected by a very thin lamina. This lamina will act as predetermined breaking point for the next transition state.

Figure 5.23: Cross-section of the flower bud shows the densely packed corolla before it unfurls.

The following opening process is highly complex and can be considered as an interaction of two individual movements. A spiral movement of the bands and an unwrapping motion of the corolla on (Fig. 5.22B). This motion sequence begins with a sudden burst of the bud shell, known as "bud popping." Once the thin lamina that connects the bands is torn apart, the five bands start to separate from each other and bend outwards in a slower helical movement. Besides this untwisting motion of the bands, *Ipomoea* shows another interesting motion, in which the corolla unfolds like an awning. It is not yet clear, however, if the corolla lamina is just pulled by the attached bands and thus is following their deformation movement passively, or if the corolla plays an active role in the opening process and helps to prevent any damage of its soft tissue.

When blooming, *Ipomoea* is finally demonstrating its impressive flower size (Fig. 5.22C). Within only a few minutes, the flower bud, which initially had a height of around 10 cm and a diameter of 1-2 cm, turns into a large flower with up to 8-15 cm in diameter. This can rightly be described as a wide-spanning structure. In this fully expanded state, various interesting observations can be made. Firstly, the blooming corolla forms a large cantilevering funnel that gains stability from its double curvature as well as from a rolled brim. Thereby, the corolla is stable enough to carry the load of various insect pollinators or withstand smaller wind gusts. Secondly, while in general the unfurled bands stretch the corolla wide open, many flowers remain having bands with a distinct curvature. The bands usually have S-shaped ridges and feature a little twist at their tips.

Figure 24-25: *Ipomoea alba*.

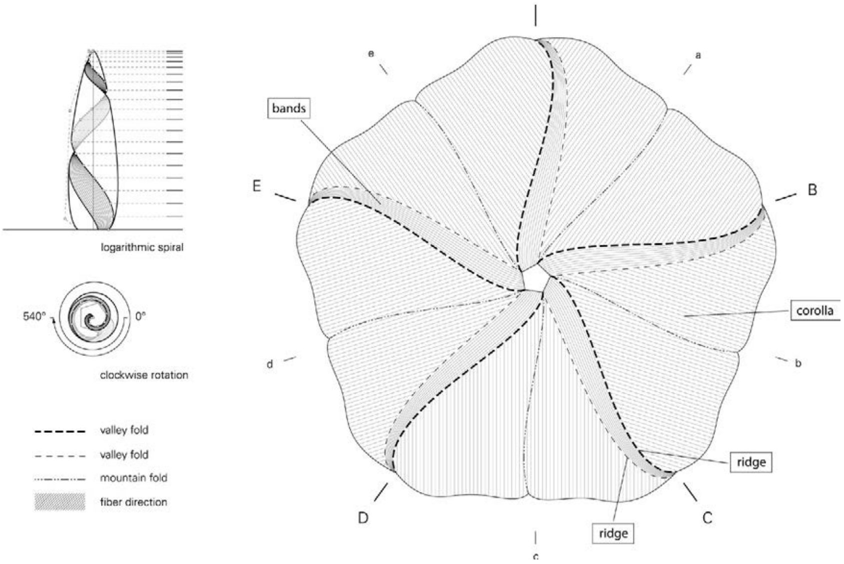


Figure 5.26: The flower of *Ipomoea* shows interesting morphological features. Its five petals are fused together to one continuous corolla. This corolla consists of softer laminas as well as five stiffer and S-shaped bands.

In the open state, it becomes more apparent that one of the bands' edges is slightly more curved than the other (Fig. 5.26). And finally, the open flower reveals that the cell orientation in the band tissue is different than in the corolla lamina. While the fibers in the bands seem to follow the S-shape of the bands, the cells in the corolla run parallel to the lamina crease, which presumably conforms to the rotation axis of its rolled-up state.

In the final state, when the flower is closing at night or when the senescence process begins and the plant starts to wither, the bands show yet another motion. In this movement, however, the flower does not fold back to its initial state. Instead, the bands roll up tightly and force the corolla into a toroidal shape (Fig. 5.22D).

5.5.4. Disclosed principle

Even though little is known about the exact geometrical shape changes of the flower on a global scale, its local transformations have been subject of previous studies. Some of these studies investigated the flower's behavior in response to alternating lighting conditions and temperature levels (Kaihara & Takimoto, 1981) or focused on acid-induced cellular changes (Kende & Baumgartner, 1974; Hanson & Kende, 1975; Phillips & Kende, 1980). In particular, the research by Phillips and Kende (1980) seems relevant here, since it identified the actuating elements that are responsible for the flower movement and located them in the petal bands. It was found that the structural changes, which are responsible for flower opening during maturation and flower closing during senescence, are controlled and driven by a specific group of inner epidermal cells on both edges of the mid-petaline bands (Phillips & Kende, 1980). Just prior and during the flower opening, this special cell group shows extensive vacuolation (loss of turgor pressure) and autophagic activity (degradation of cell components). Based on these cellular changes, this cell group performs a significant increase in size, a modification in shape, and reduction in cell wall thickness. These transformations, which happen on a cellular level, can also be read from greater distance since they force the edge ribs of the bands to elongate and bend. These asymmetric changes are quite similar to the differential growth effect in the tepal edges of the previously described lily. However, there are two main differences, which can best be described by looking at a cross-section (Fig. 5.27): On the one hand, the edges don't expand uniformly but instead show cell expansion mainly on their inner flanks, which creates shear forces even within the edge profile. On the other hand, the band's left and right edges have inner epidermal cells that are structurally and developmentally different from each other. Phillips and Kende refer to these as "closed loop" and "open loop." In their development, the open loop cells are ahead of the closed loop cells, which is reflected in the fact that they are vacuolated and enlarged prior to flowering, while the closed loop cells are still small and non-vacuolated.

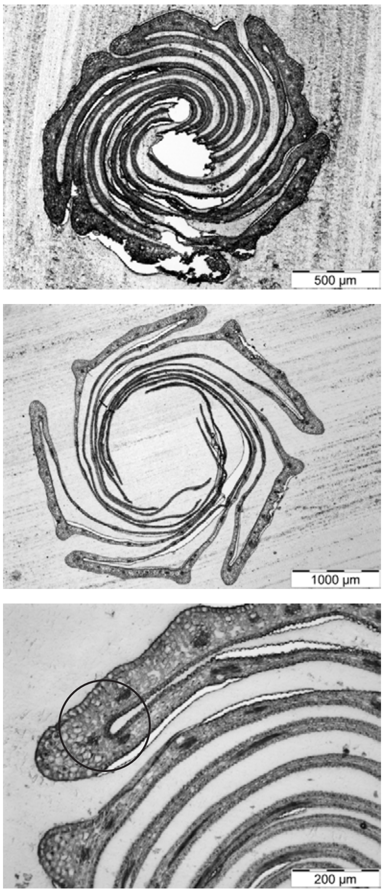


Figure 5.27: A series of cross-sections through the *Ipomoea* bud show the flower in its closed state and zoom to a specific cell group that is supposed to be the driver of the opening mechanism.

Up to now, it is not clear whether the differential expansion and the resulting unidirectional changes of the band's inner epidermal cells, is the only mechanism that drives the motion or if there are other principles involved that might additionally contribute the opening and closing of the flower. For instance, it is quite conceivable that the helically twisted bands may store a significant amount of elastic energy, which when suddenly being released may drive a stress relaxation until each band has fond another state of equilibrium. This effect is known as "bud popping" and was previously mentioned as one component of the opening sequence. Bud popping was observed in various other plants as well and quite often plays an important role (van Doorn & van Merteeren, 2003).

5.5.5. Abstracted bio-inspired mechanism

In order to test the previously described form-structure-function relationship of the opening mechanism in *Ipomoea*, one of its key structural elements, the mid-petaline band, was abstracted and rebuilt digitally. A previous study by the author showed a possible abstraction process of the plant's curved-line folding pattern (Schleicher et al., 2010).

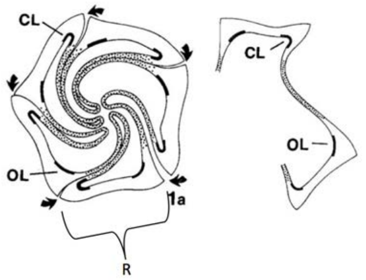


Figure 5.28: Phillips and Kende count a specific group of cells responsible for the motion and refer to them as closed loop (CL) and open loop (OL).

As a first step, a geometric model was generated to represent the flower bud in its closed state. Quite similar to the previous case study, this parametric model was generated based on one longitudinal and three circumferential circles located at the top, bottom, and lower third of the middle axis. Different in this geometrical model,

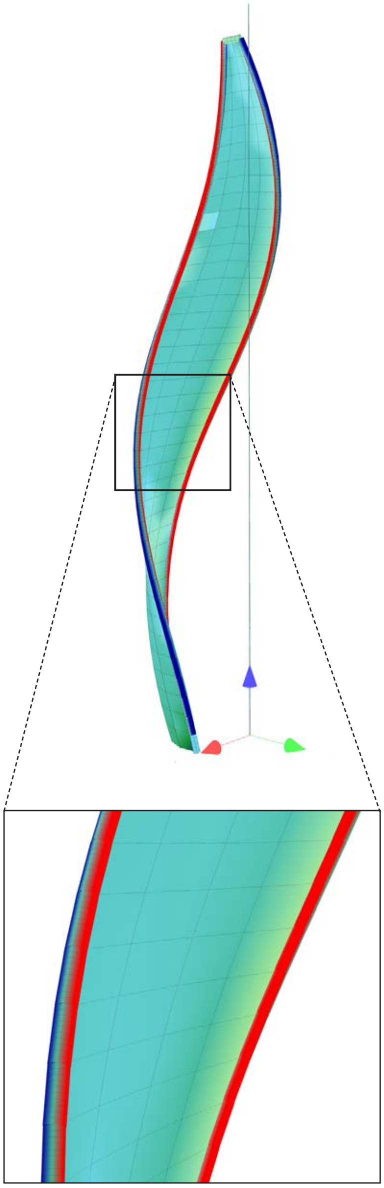


Figure 5.29: The edge ribs in this kinetic model of the *Ipomoea* can be actuated by local temperature increase. The two-layered structure of the ribs, however, only causes the inner flanks (red) to expand while the outer flanks (blue) remain their length.

however, is the possibility to twist the resulting shape around the middle axis either regularly or logarithmically by a predefined angle. Figure 5.29, for instance, shows a flower band that is 270 mm wide, 2000 mm long, and is twisted clockwise by $\alpha = 180°$.

In the next step this geometrical model was turned into a kinetic model. The data was exported from the CAD environment and imported to FEM. Here, it is possible to assign the geometry with specific material characteristics and boundary conditions like structural supports. Once again, idealized materials were used and allocated to the model. The twisted band was given a GFRP-like material (thickness = 2 mm, Young's Modulus of E = 12000 N/mm^2, αT = 17 x 10-6/K) whereas the edges of the mid-petaline bands were modeled as rods with a PMMA-like material (diameter = 25 mm, Young's Modulus of E = 3200 N/mm^2, αT = 85 x 10-6/K).

The differential cellular swelling that actuates the plant was simulated by means of thermal expansion. The local temperature of the edge rods was gradually increased by 75°C. As in the previous case study, such a rise in temperature inevitably leads to a linear elongation of the edges. However, the actuation principle in this case study was further refined to better represent the complex mechanism observed in *Ipomoea*. As an analogy to the biological role model, where only the inner epidermal cells are swelling, the edge rods in this kinetic model were not actuated uniformly and the rise in temperature was not distributed evenly. Instead the edges were treated like two-layered structures with an active and inactive layer. When heat is applied to one rod only its inner flank, which points towards the middle axis, starts to expand, while the rest remains passive (Fig. 5.29). The shear forces within the cross-sectional profile of the edge rods create a bending moment and drive the global deformation of the structure. This actuation principle is therefore distinguished from the lily-mechanism, which relies on the leverage created by the interaction between expanding rods and the adjacent surface. Nevertheless, the *Ipomoea*-inspired differential expansion implemented here is powerful enough to enforce a large global bending motion just by small local structural changes (Fig. 5.30).

5.5.6. Mechanical variability and consistency

While recreating the opening process in the *Ipomoea* flower, two questions arose regarding the mechanism's variability and consistency: Firstly, is this the only possible type of actuation, and secondly what effect does the twist of the bud have on the opnening behavior of the flower?

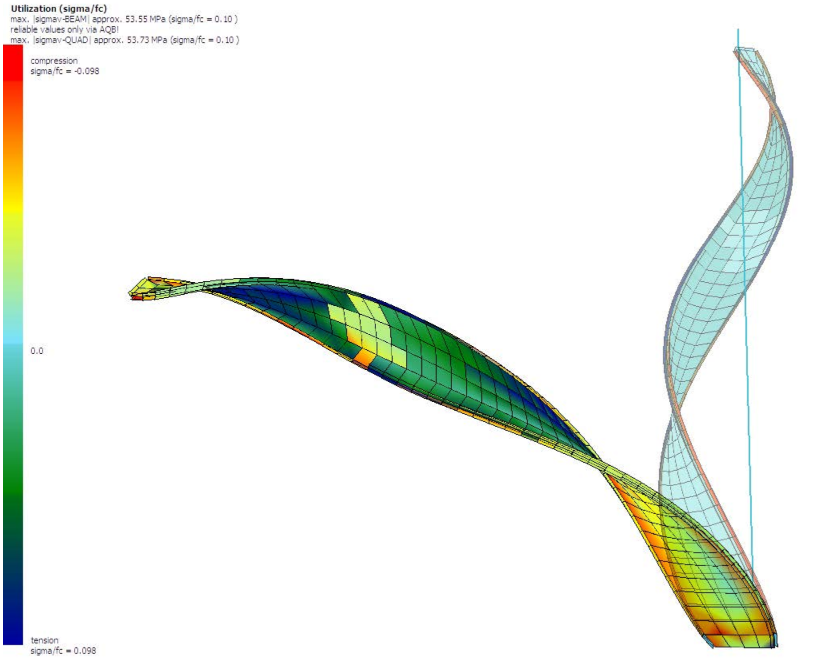


Figure 5.30: Kinetic model of the *Ipomoea* band unfurls by a local actuation of the inner flanks of the edge ribs.

In order to investigate the first question, the simulation of five nearly identical models has been carried out. These five models share the same geometry and material settings but differ in their actuation scheme (Fig. 5.31).

> The first model, tagged as Ipo 1, has expanding edges similar to the lily-mechanism (heat-controlled expansion over the entire cross-section of the edge ribs).
>
> The second model, tagged as Ipo 2, has differential expansion in both edge ribs but only the inner flanks are expanding.
>
> The third model, tagged as Ipo 3, has differential expansion only on the left rib and only at its inner flank.
>
> The fourth model, tagged as Ipo 4, has differential expansion only on the right rib and only at its inner flank.
>
> The firth model, tagged as Ipo 5, has differential expansion in both edge ribs as well as differential expansion of the entire band surface.

Having the opportunity to compare all five models with their different actuation schemes at a specific moment in time enables detailed observations and allows conclusions to be drawn regarding their motion behavior. Figure 5.31, shows the five models side by side at load case 19, which is equivalent to a temperature increase in the structure by 73°C. Probably the most remarkable discovery is that the model equipped with the lily-mechanism (Ipo 1) does not open at all and seems unable to unwind. This probably has to do with the unfavorable leverage between the expanding edges and the slender and nearly flat band surface. There is hardly any eccentricity to the lever arm. As a result the band grows in length but does not bend. Only the models that feature the *Ipomoea*-mechanism and perform a differential expansion of the edges (Ipo 2-5) can unfurl. This confirms the description of the plant's mechanism and the correctness of its abstraction. As perhaps expected, the model that features two actuators (Ipo 2) opens up the most. The models with just one active edge, however, are almost identical with little more stresses in the band of (Ipo 4) compared to (Ipo 3). This means that the mechanism doesn't prioritize the expansion of one edge over the other, which somewhat weakens the observation by Phillips and Kende (1980), who located the actuator to be only in the left edge. Finally, if a model features not only the differential expansion in the edges but also in the band surface (Ipo 5), one can observe that the opening is not that far progressed as expected. This may indicate a conflict between the actuated edges and the band surface that together seem less effective.

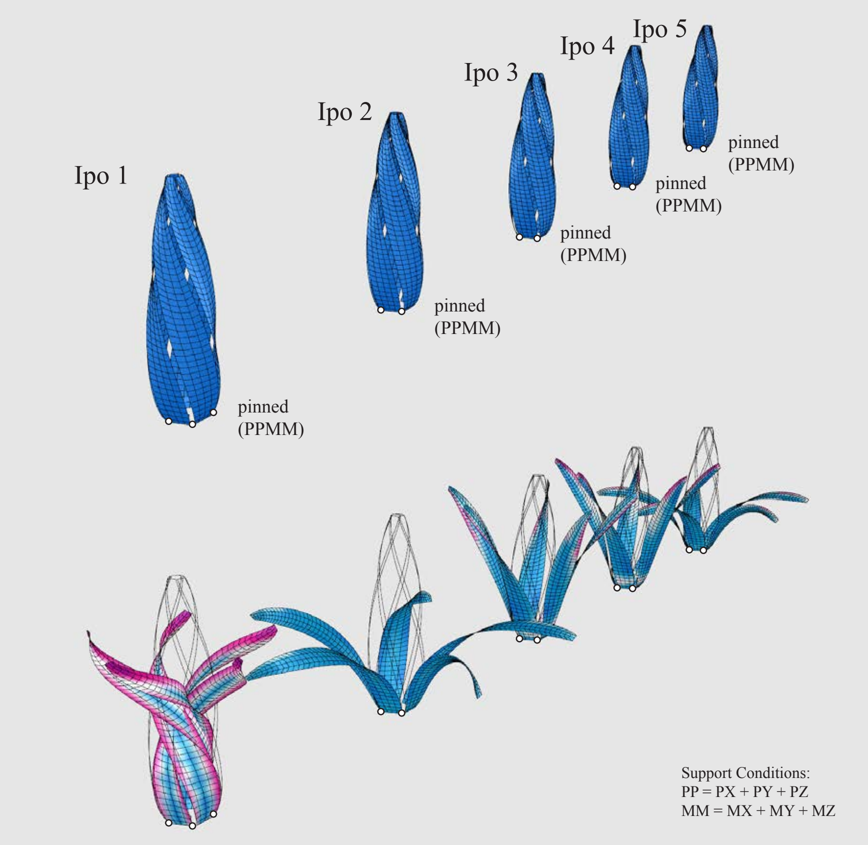


Figure 5.31: Experiments with different actuation principles.

The second set of simulations aims to determine whether the twist of the flower bud plays any significant role in the opening process or not. Five further kinetic models were built that all share the same actuation principle of Ipo 2, in which both edge ribs undergo a differential expansion of their inner flanks (Fig. 5.32). However, the models differ from one another in their degree of rotation:

The first model, tagged Ipo Twist 1, has a twist by 0°.

The second model, tagged Ipo Twist 2, has a twist by 90°.

The third model, tagged Ipo Twist 3, has a twist by 180°.

The fourth model, tagged Ipo Twist 4, has a twist by 240°.

The fifth model, tagged Ipo Twist 5, has a twist by 360°.

Figure 5.32 shows the models at load case 15, which is equivalent to a temperature increase of 57°C. Comparing them side by side, one can see that the twist is obviously no obstacle and does not hinder the opening movement. However, it also seems that the twist is not supporting the process exceedingly. It appears that the less the flower bud is twisted, the quicker and the more uncomplicated it can open up. In the direct comparison of the kinetic models, however, another side effect becomes more and more evident. All bands show a distinct torsion at the tips, which curl around the longitudinal axis. This behavior might be a direct result from the elongation of the edges and their differential expansion. While this curling effect was appearing in all simulations before, it is noteworthy that it became most visible in the model buds with a higher twist in their closed state. In principle, this curling effect can also be seen in many real *Ipomoea* flowers but there it is generally less pronounced. The fact that the digital simulations show that deformation behavior so strongly might suggest that the stiffness ratio between the band surface and the edge rods may not be quite balanced. Even more likely, however, is the assumption that it has to do with the missing corolla. The corolla might be capable of short cutting forces in the flower circumferentially and thus counteract the bands' individual curling behavior.

5.5.7. Conclusion

The opening and closing of *Ipomoea* flowers is a fascinating concept generator for deployable structures. Its motion principles, which are based on differential expansion and unidirectional changes in elongating structural curves, may hold a high potential for innovation. The here-conducted studies demonstrate an interesting take on analyzing the elastic motion behavior of these kinetic structures. However, the models in these studies are in part over-simplified. In particular they are all missing the corolla surface. Another indicator that the real plant mechanism might be even more complicated than the abstracted principle is the fact that the kinetic models all behave slightly different to the actual plant. This suggest that either the location and functioning of the plants motor cells would need to be examined more closely or the settings of the kinetic models would need to be refined. In addition, further studies would also be helpful to better understand the precise interaction between material stiffness and geometric constraints. More knowledge how to balance and optimize the two would definitely be valuable and could inform the design of shapes that use the same motion principle but gradually become freed from the direct translation of the plant shape. The presented preliminary studies, however, seem to be a good start in this direction. One can easily imagine that the flower opening and closing of *Ipomoea* may become an inspirational role model for the developing new movable umbrellas and awnings with integrated actuation.

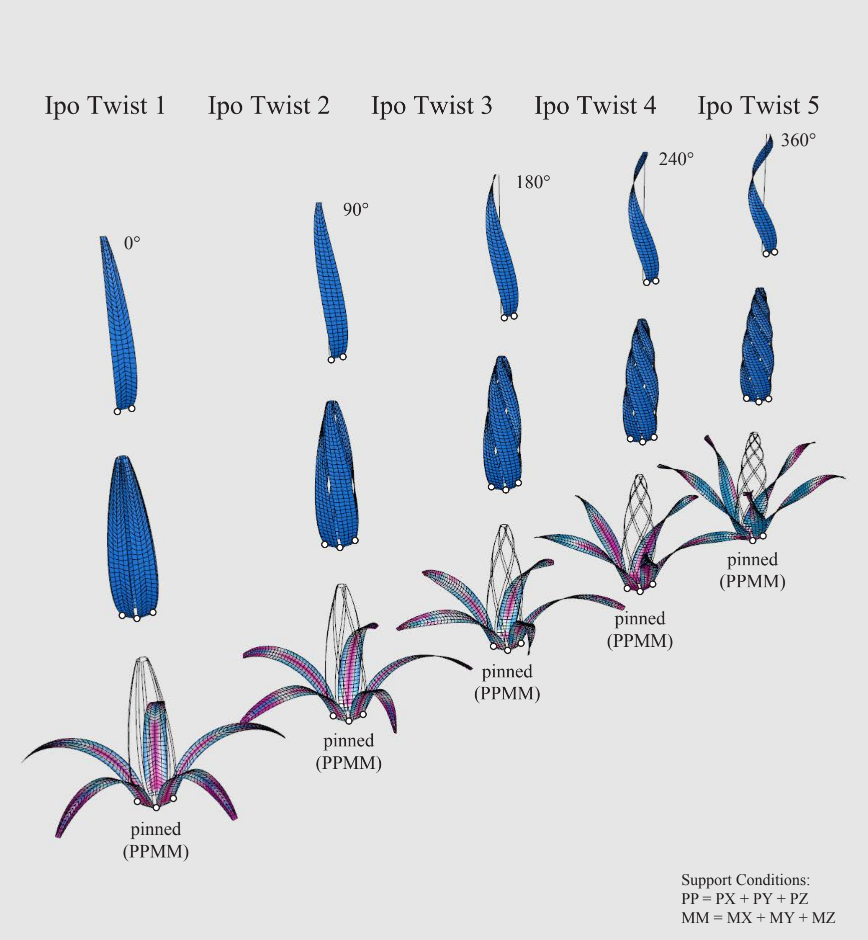


Figure 5.32: Experiments with differently twisted model geometries.

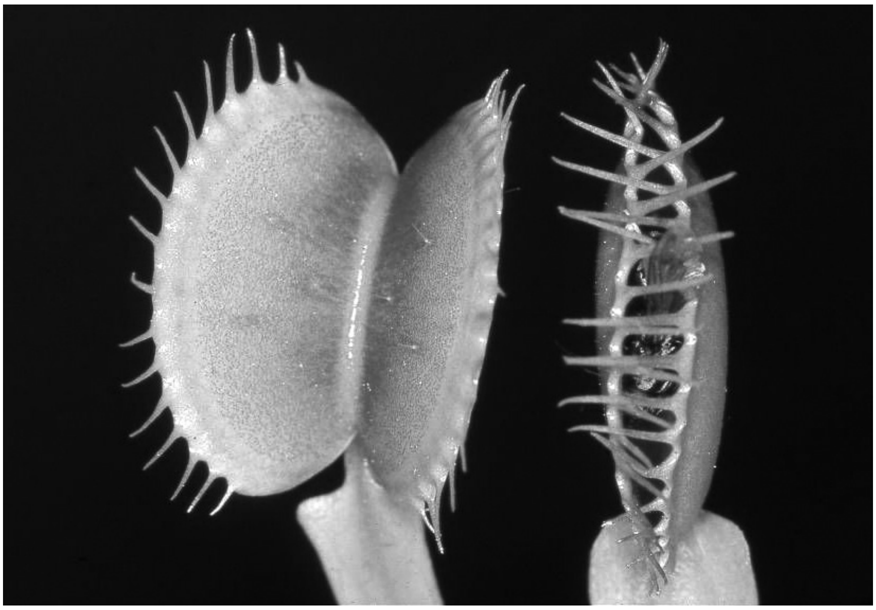


Figure 5.33: With its fast trapping movement the Venus flytrap can capture a variety of prey animals.

5.6. Case Study 5: Trapping Movement of *Dionaea* (Droseraceae)

The fifth case study examines the leaf movement of *Dionaea muscipula* (Droseraceae), commonly known as Venus flytrap (Fig. 5.33). This carnivorous plant features distinct snap-traps that can perform a very fast shutting motion to capture prey animals. The mechanism involves a complex interaction between elasticity, turgor pressure, and growth. The movement is first driven by bidirectional changes in the cellular tissue but then significantly accelerated by a snap-through buckling that appears in its lobes. Precisely because *Dionaea* utilizes structural instabilities to its favor and integrates failure behaviors like snap-through buckling in order to speed up its trapping motion, this plants is a fascinating model.

5.6.1. Biological role model

Among all the case studies that are presented in this thesis, the plant movement of the Venus flytrap is probably the most famous and enigmatic. Its surprisingly fast plant motion almost makes one think of witnessing an animal behavior; yet this plant does not feature any muscles or nervous system to process complex information, as animals do. This fact makes the Venus flytrap particularly fascinating. Its quickness and power seem so mysterious that Charles Darwin (1875) marveled the Venus flytrap and praised its movement as “one of the most wonderful in the world” (p. 231).

The Venus flytrap belongs to the family of Droseraceae. In this family are around 200 species, one of which is *Dionaea muscipula*. *Dionaea muscipula* is a terrestrial plant that is native to the subtropical wetlands of the East Coast of the United States. As it is typical for the Droseraceae family, *Dionaea muscipula* is a carnivorous plant that features especially pronounced trapping organs with which the plant is capable of catching and digesting small animals. These captured animals are primarily insects and arachnids, which provide the plant with nutrients such as nitrogen and phosphorous.

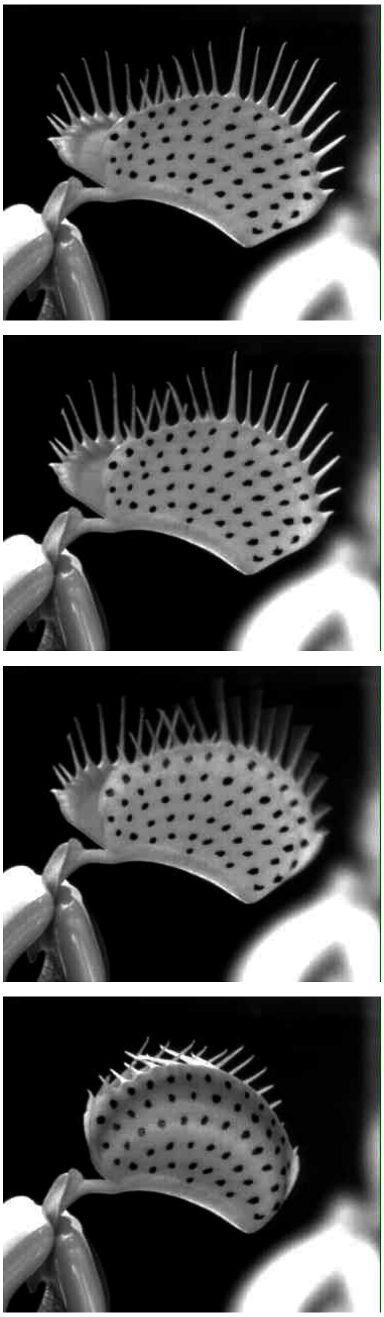


Figure 5.34: This time-lapse footage shows the deformation movement of the Venus flytrap. The black dots were added artificially in order to track the curvature inversion of the trap lobes by means of a photogrammetric measurement.

5.6.2. Functional morphology

Dionaea muscipula is a small plant, which develops a rosette of five to ten leaves from a subterranean bulb. Each leaf is divided into two regions: a flat petiole that is capable of conducting photosynthesis and a pair of terminal lobes, which form the actual trapping structure. With a size of up to 5 cm, this trap is big enough to capture a variety of animals. The trap itself consists of two lobes that are fused together along a shared midrib. The rather thick lobes are composed of multiple cell layers and have a distinct double-curved geometry. Most apparent, however, is their strong red pigmentation that they show on their upper surface. This color, together with the mucilage that they secrete along the edges, seems to be highly attractive to all kinds of animals and lures them into the trap. In order to prevent their escape, the lobes are fringed with thin yet stiff protrusions at its margin, which interlock like teeth of a zipper when the trap is closing. In addition to these teeth, the trap lobes have another interesting feature of particular importance. Protruding from the upper surface and distributed around the lobe's center are also three to four tiny hairs. These so-called trigger hairs are sensitive contact receptors that detect not only the slightest touch but also distinguish whether it was a living prey or an accidentally falling raindrop that caused the stimulus.

5.6.3. Description of the movement

When a prey enters the trap and touches the trigger hairs, not only once but at least twice, it causes a mechanical stimulus that initiates the plant's fast trapping motion. In this swift movement, the trap only needs 100 ms for full closure, which leaves the prey hardly any time for an escape. Within this very short time span, the trap closes by actively changing the curvature of its lobes. While in the open state, the lobes have been convex and bent outwards, their closed state is characterized by the fact that they are now in a concave geometry and form a tightly shut cavity (Fig. 5.34). A closer look at this movement reveals its sequential nature. The motion consists of three phases. The first phase begins with a slow initial bending, followed by a very fast snap-buckling, and finally ends with a slower closure movement. Based on theses motion phases, one can also refine the search for the responsible actuation principles.

5.6.4. Disclosed principle

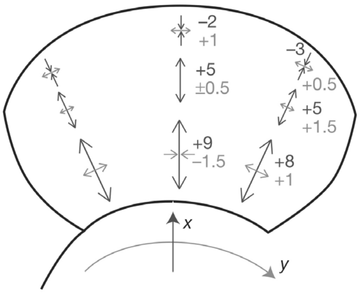


Figure 5.35: Strain field on the outer surface of the trap lobe shows a highly differentiated response to a stimulus, in which cells primarily expand along the x-direction.

Finding the motion principles behind *Dionaea's* rapid trapping motion has been a challenge to scientists for centuries and motivated many studies. Early work, for example, described in general the plant's motion behavior and morphological features (Darwin, 1875; Brown, 1916; Ashida, 1934; Stuhlman, 1948). With the progress of technology, it has become increasingly easier to also observe the plant's biochemical response and inner cellular changes as well as to discuss their significance for the plant movement (Hill & Findlay, 1981; Williams & Bennet, 1982; Hodick & Sievers, 1988, 1989; Forterre et al., 2005, 2013; Poppinga et al., 2011, 2013; Joyeux M., 2013). All this work contributes to a more detailed description of the plant's three phases of motion. However, since there are still unresolved questions, these movements will remain a subject of further studies.

There is currently no clear explanation for the movement of the first phase. It is generally accepted that the midrib, which connects the two lobes, plays no active role in the motion sequence since it keeps its shape and shows no change in curvature during the deformation process. Instead, the driver for the initial bending motion is assumed to be a hydraulic mechanism located in the surfaces of the trap lobes themselves. So far, it is believed that a stimulus of the trigger hairs leads to a generation of action potential in the cell tissue until a certain threshold is reached (Hodick &Sievers, 1989). As a result, the plant actively changes the turgor pressure in the cell layers either by osmotic swelling of the outer layer or by an osmotic shrinking of the inner layer. In a series of experiments Forterre et al. (2005) measured the strain field on the inner and outer lobe surface with fiducial markers (Fig. 5.34). Their data implies that the closure is driven by an anisotropic deformation, in which cellular changes happen primarily in the x-direction that is perpendicular to the midrib (Fig. 5.35). The resulting differential expansion is somewhat similar to the actuation of the previously described case studies only that it is here a part of a surface of the lobes. Once again, it is the small and local change of a cell group that causes a differential expansion and results in a bidirectional change of a global structure. In comparison to the mechanisms in *Lilium* and *Ipomoea*, however, the initial bending movement in *Dionaea* is much faster, which usually indicates the involvement of additional mechanisms. So it is not surprising that newer studies begin to challenge the hitherto valid explanation. Forterre et al. (2013), for example, suggest that additional growth processes might be involved in the movement as well. Already before the trap is triggered, the plant may have built up a pre-stress in the inner tissue of the trap lobes by cellular growth and thus have stored elastic energy within its structure. Once this energy would be released, a relaxation of the trap lobes would be capable of accelerating the motion significantly.

Regarding its speed, however, the movement during the second phase is particularly impressive. It is here where the trap lobes show the greatest amount of deflection when they suddenly inverse their curvature from a convex to a concave geometry. As it was mentioned before, *Dionaea* utilizes in this phase an instability failure to its favor. This effect is usually referred to as snap-buckling or snap-through buckling. Snap-through buckling is a particular type of transformation, in which a structure flips from one state to another. During this transition, the bistable structural system has a highly nonlinear force-displacement relationship. It leaves an initial stable equilibrium, passes through an unstable and indifferent equilibrium, and finally arrives in a stable yet alternative equilibrium state. To engineers, this fundamental mechanical behavior is well known and dreaded as undesirable failure since it poses the hazard of stress peaks and high fatigue (Suresh, 1998). *Dionaea's* mechanism, however, seems to deliberately take that risk in order to facilitate a large elastic deformation and thereby speed up its motion. Finally, in the third phase of the motion, the trap closes its lobes tightly and begins the digestion of the captured prey. It is interesting that the following opening movement of *Dionaea* is based on growth processes and the resetting of the trap takes several hours.

5.6.5. Abstracted bio-inspired mechanism

Once again, a digital model was generated to test the previously described relation between form, structure, and function of the *Dionaea* mechanism. 3-D scans of the trap served as the basis for further abstraction. The aim was to preserve the overall proportion and keep the specific geometry of the lobes. The resulting geometrical model shows the trap in the open state and features all key elements that are necessary for the movement. It has two double-curved lobes and a groove-like surface that connects them. For simplification reasons, the trap lobes were neither modeled with a brim nor with any teeth protrusions, since they play no active role for the closing movement. The model has a length of 1700 mm and a height of 1000 mm. Each lobe has a width of 1000 mm and is determined by the two main curvature directions and the radii in Kx = 3240 mm and Ky = 850 mm.

The geometrical model was then exported from the CAD environment to the FEM software and turned it to a kinetic model (Fig. 5.36). Here, all surfaces were given the same material characteristics of a GFRP-like material (thickness = 2 mm, Young's Modulus of E = 12000 N/mm^2, αT = 17 x 10-6/K). Furthermore, the boundary conditions were better defined by assigning additional bearings on either side of the groove-like surface and thus support the model in space. While the bearing on one end is fixed, its counterpart on the other end is movable along the x-y plane.

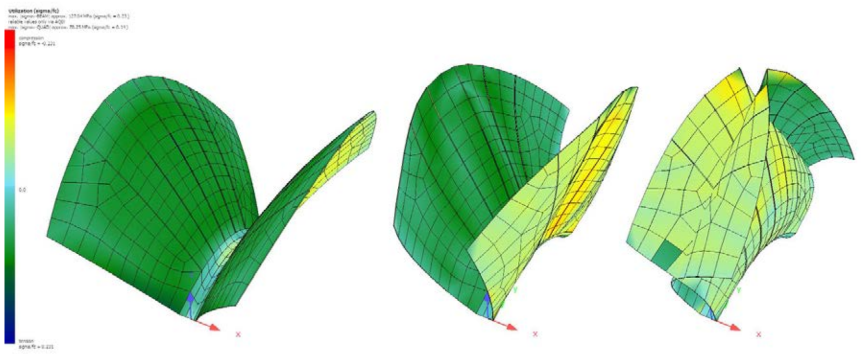


Figure 5.36: Kinetic model of the Venus flytrap. The differential expansion that is driving its closing movement was created by increasing the temperature of the lower side of the lobe and additional ribs until the surface suddenly shows a snap-buckling effect.

Similar to the previous case studies, the cellular actuation of the plant was mimicked by means of thermal expansion. Analogous to the descriptions of the plant movement, the heat was only applied to the lower side of the trap lobes surfaces. Even though this differential expansion caused a bending of the lobes, this actuation alone did not spark the desired snap-through buckling. This might be due to the fact that the thermally induced expansion acts in all directions equally. However, Forterre and his team (2005) suggested that the snap-through buckling might be caused by an inhomogeneous expansion of the cell layer, which actuates the structure in some directions more than in others. Unfortunately, this could not be done that easily in the used software and required a workaround. Therefore, five ribs were added to the trap lobes as an auxiliary construction, which does not exist in the biological role model in that form. When these ribs get exposed to the same differential heat actuation as the trap lobe surfaces, however, they expand along their longitudinal axis and provide an additional impulse, with which it was possible to trigger the desired snap-through buckling.

5.6.6. Mechanical variability and consistency

In order to explore the mechanical variability of the *Dionaea* mechanism, two further tests were conducted that mirror an experiment of Forterre and his team (2005). They searched for an experimental proof of the hypothesis that the closing mechanism is primarily triggered by differential strains in x-direction. Therefore, they cut *Dionaea's* lobes in x- and y-direction and observed the lobe curvature during the closure movement. These tests are based on the assumption that an incision in the x-direction eliminates the constraining effect of curvature in the y-direction and vice versa. As a result, the trap lobes would stay in their natural curvature unless they undergo an active change in the uninterrupted directions. According to their observations, an active change in curvature only happened in the trap lobes whose x-direction was not interrupted with a cut. This can be seen as a support of their hypothesis.

However, such a general statement cannot be given when making these experiments digitally (Fig. 5.37-5.38). Cutting the trap lobes of the kinetic model in x- or in y-direction seems to have no affect on the closure movement. Independent of the cutting direction, the kinetic model performs a snap-through buckling. Since it can only be speculated if the reason for this behavior lies in the setup of the kinetic model itself or in the used motion principle, further research on the closing mechanism of *Dionaea* and its digital simulation is necessary to draw a more informed conclusion.

5.6.7. Conclusion

Undoubtedly, *Dionaea* features the most complicated mechanism among the presented case studies. Unfortunately, the discovered methods to simulate the plant movement are only rough approximations at this point and should be viewed with great caution. Eventually, they might even be misleading since they include tricks like the addition of rib elements that do not exist in the actual plant. Therefore, it is too early to seriously investigate the mechanism's variability or consistency at this point. Nevertheless, the first tests indicate a great innovation potential and should thus inspire further investigations of future researchers.

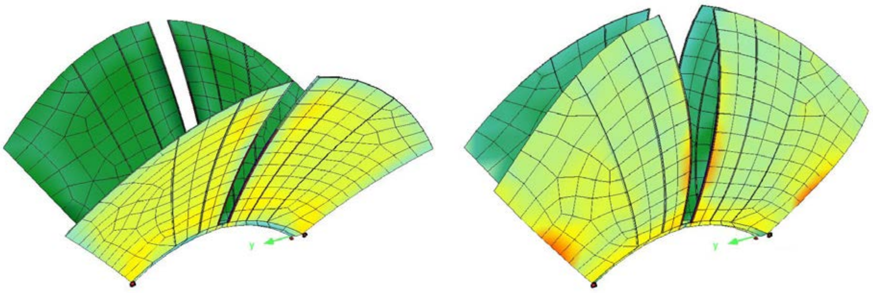


Figure 5.37: Despite a cut in x-direction, which was conducted to eliminate constraining effects in y-direction, this kinetic model is still able to perform snap-buckling.

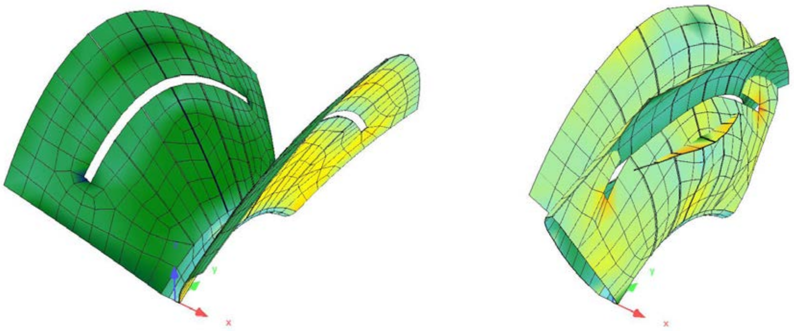


Figure 5.38: Also a kinetic model that was cut in y-direction is still able to perform snap-buckling.

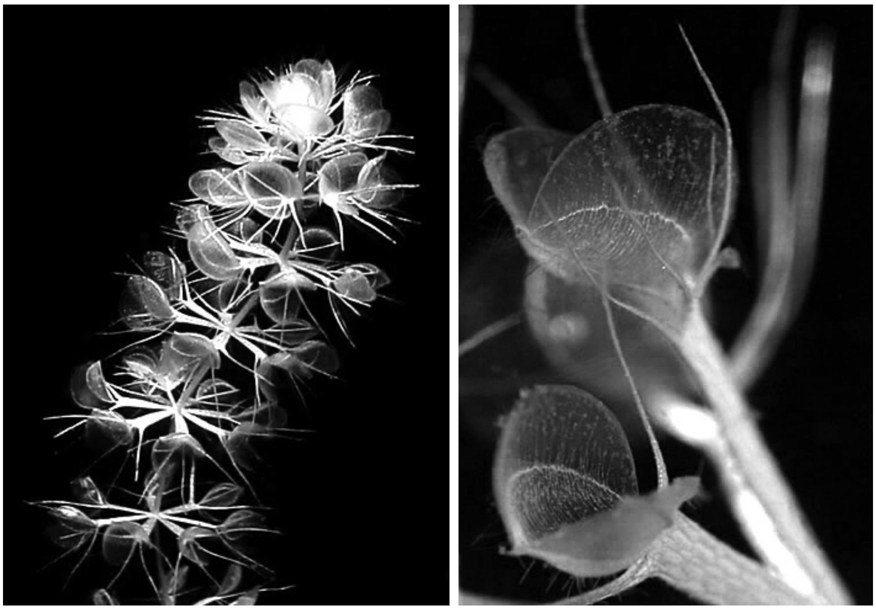


Figure 5.39: *Aldrovanda vesiculosa* is an carnivorous aquatic plant that can capture prey with its trap lobes.

5.7. Case Study 6: Trapping Movement of *Aldrovanda* (Droseraceae)

The sixth case study investigates the trapping movement of *Aldrovanda* (Droseraceae), a free-floating aquatic plant that is commonly known as the waterwheel plant (Fig. 5.39). Like the previously described *Dionaea*, the closely related *Aldrovanda* is also a carnivorous plant and features a distinct trapping organ. Even though the traps in both plants bear a close resemblance at first glance, the motion principles in *Aldrovanda* vary significantly and are thus worth a closer look. In contrast to *Dionaea*, the mechanism in *Aldrovanda* is not based only on a structural instability. Instead this plant couples the bending failures of two surfaces together and gains a significant mechanical amplification. Furthermore, *Aldrovanda* has found an interesting way of transferring the local actuation of a bending curve, which undergoes unidirectional changes, into a global bidirectional movement of its lobe surfaces. To achieve this, the plant uses curved-line folding, which is a hardly understood mechanical principle that may be a very promising design concept for compliant mechanisms in general.

5.7.1. Biological role model

Aldrovanda evolved in a completely different habitat than *Dionaea*, which might explain why it developed a different mechanism for trap closure. Unlike its terrestrial sister in the Droseraceae family, *Aldrovanda* is an aquatic plant. This means that its plant movement has to function underwater. The aquatic *Aldrovanda* is native to Asia, Africa, Australia, and Europe and can be typically found in acid bog pools with warm and standing water. Aside from its natural

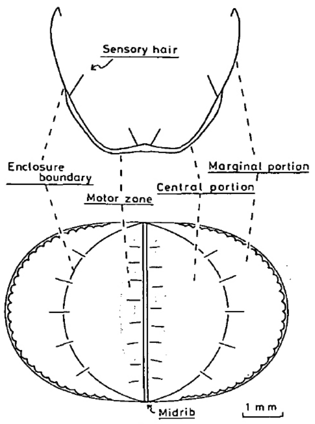


Figure 5.40: This cross-section and upper view shows the trap's monosymmetric morphology. The trap consists of a midrib, a central portion, and two sickle-shaped lobes that are attached to the central portion by a curved-line fold that is called the enclosure boundary.

occurrence, this plant is also popular among hobby gardeners and is cultivated worldwide. Within the *Aldrovanda* genus there is only one extant species known, which is called *Aldrovanda vesiculosa*. This free floating and rootless aquatic plant is rather small and has a length of about 2 to 30 cm. The plant is colloquially called the waterwheel plant because it produces numerous whorls of leaves that grow around a main stem like the spokes of a wheel. These whorls are supported with air bladders, which allow them to float in the water. Each of *Aldrovanda*'s leaves terminates in a little clam-like trap of approximately 5-10 mm in length. With these traps the plant is capable of capturing and digesting little aquatic organisms.

5.7.2. Functional morphology

The functional morphology of the trap leaves in *Aldrovanda* is somewhat comparable to *Dionaea*, yet decisively different regarding some key elements. Looking at the trap in a schematic cross-section and upper view (Fig. 5.40) reveals its monosymmetric morphology and shows two distinctive structural regions. First, there is a lens-shaped surface in the middle of the trap that is called central portion. This surfaces features a stiff midrib, which is connected to the central portion by a wrinkled transitional area called motor zone. Second, there are two sickle-shaped trap lobes that surround the central portion. These lobes are called marginal portion and are framed by an infolded rim at the perimeter. Both structural regions are of unequal stiffness. While the central portion has three cell layers, the softer marginal portion only has two. In addition to these characteristics, the trap has also another striking feature at the location where the portions come in contact with each other. Here, a curved fold and rib structure, called enclosure boundary, acts as a living hinge and links the structural regions together. Finally, the trap also features around 20 little trigger hairs that stand along the enclosure boundary and the midrib on the inner surface of the central portion.

5.7.3. Description of the movement

The trapping movement of *Aldrovanda* has five distinctive stages: open, shutting, narrowing, closed, and reopening. During the open stage the trap is in its sensitive and structural metastable condition. Here, the lobes stand apart from each other in an opening angle of roughly 60° and already have a light convex curvature. When a prey (e.g. a water flea) approaches the plant in the following shutting stage and accidentally touches the sensory hairs, the trap lobes move instantly. Within only a few milliseconds the trap lobes perform a complex deformation sequence with which they enclose the prey so quickly that an escape is nearly impossible. This movement is all the more astonishing when one considers that *Aldrovanda* is an underwater trap, which means that its lobes need to push water aside as they close without exhausting the prey during the process. In the following closed stage, the trap lobes have come into contact and trapped the prey in the hollow cavity between them. Once a prey is caught, the plant starts its digestion and produces specially adapted enzymes. Compared to the rapid closure, the movement in the reopening stage is rather slow and takes up to half an hour. This indicates that different motion principles are responsible for the opening and the closure of the trap.

5.7.4. Disclosed principle

Early on, *Aldrovanda* has been subject of multiple studies, which speculated about the hydraulic mechanism behind the plant's rapid trapping movement (Darwin, 1875, Ashida, 1934). Subsequent research, focused on the plant's biochemical response to prey stimuli and aimed to quantify the propagation of action potentials within its leaves (Iijima & Sibaoka, 1981, 1983, 1985). Only very little work has been done so far on the trap's post-stimulation mechanical behavior (Skotheim & Mahadevan, 2005; Poppinga & Joyeux, 2011) and its potential biomimetic applications (Schleicher et al., 2011). These studies, however, can serve as a basis for a more detailed description of the plant's motion principles. In the context of this research, the motion principles during the plant's shutting and narrowing stage are of particularly interest.

According to some of these studies, the driver for *Aldrovanda's* trapping movement is a rapid bending of the midrib and the adjacent motor zone in the lens-shaped central portion. In addition, Iijima and Sibaoka (1981, 1983, 1985) found that the bending of the midrib and the motor zone could be traced back to a hydraulic mechanism that causes a sudden contraction of local motor cells. The resulting uni- and bidirectional change of structural elements like curves and surfaces, which is caused here by a differential contraction, is very analogous and comparable to the previous case studies.

In the context of this research, it is very fascinating that the mechanism of *Aldrovanda* has an additional important asset besides its pure actuation principle, in form of a clever mechanical transmission and amplification via curved-line folding (Schleicher, 2011). In general, this type of connection combines convex and concave surfaces and attunes their deformation behavior. In this case, the deformation of the trap's central portion is coupled to the marginal portion in such a way that the bending of the center surface triggers a successive bending of the adjacent sickle-shaped lobes. With this clever trick, the plant is capable of amplifying a small local actuation into large global motion (Fig. 5.41).

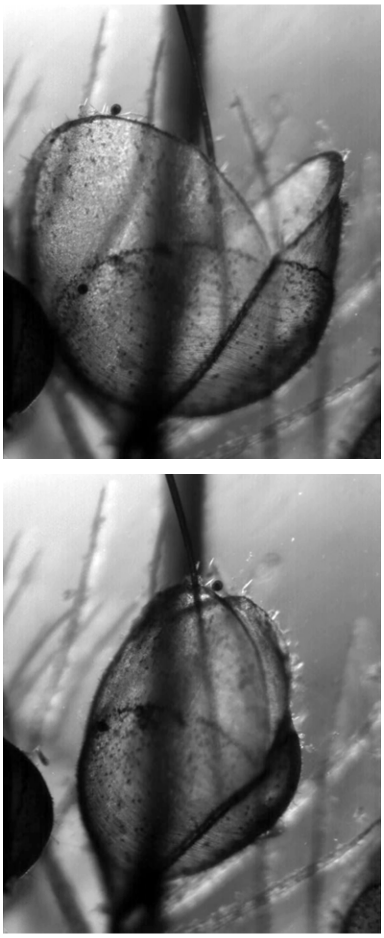


Figure 5.41: Touching the plants sensory hairs triggers the trapping mechanism and the lobes close within a few milliseconds.

5.7.5. Abstracted bio-inspired mechanism

In order to examine the validity of the previously described form-structure-function relationships in the trapping movement of *Aldrovanda,* a digital model was generated. Detailed photographs of the trap served as basis for the abstraction process.

The resulting geometrical model is a simplified version of the trap and is modeled in its open stage with an opening angle of about 60° (Fig. 5.42). The model has a length of 1500 mm and a height of 1000 mm. Each lobe of the marginal portion has a width of 1100 mm. Marginal portion and central portions have a slight single curvature. Furthermore, this model bears all the key members that are essential for the later movement: In the symmetry axis of the trap is a shallow curve that represents the midrib. The enclosure boundary between the central portion and the marginal portion is modeled as two curves with the radius r = 3500 mm and a sickle-shaped sub-surfaces. Finally, two further curves frame the trap lobes and form the rims.

As in the other case studies, this geometrical model was exported from the CAD environment into the FEM software in order to turn it to a kinetic model. All surfaces were assigned the properties of a GFRP-like material (Young's Modulus of $E = 12000\ N/mm^2$). The difference in stiffness between the trap lobes and the central surface was addressed by varying their thicknesses. While the central portion is 5 mm thick, the lobes only have a thickness of 3 mm. The curved-line flexure zone was given a thickness of 2 mm. The curves were turned into PMMA-like rods (Young's Modulus of $E = 3200\ N/mm^2$, $\alpha T = 85 \times 10\text{-}6/K$). The midrib has a diameter of 50 mm, whereas the curved-line rods at the flexure zone only have a diameter of 25 mm. Finally, the model is supported in space at the midrib with bearings on either end. While the support on one side is fixed the other side can slide on the x-y plane.

As in the simulation of the *Ipomoea* case study, the technique of provoking a differential thermal expansion was used here to actuate the trapping movement. Therefore, the local temperature at the midrib's upper flank was gradually increased, which triggers a bending motion of the midrib. As hoped, this gradual curvature increase of the midrib causes a simultaneous bending motion of the central portion and is transferred further to an even faster bending motion of the trap lobes (Fig. 5.42). The simulation of the kinetic model confirms the assumption that unidirectional changes, which were caused locally in the midrib, can drive a global bidirectional movement of the trap lobes and thereby close the trap. Decreasing the temperature in the midrib results in a slow relaxation, which opens up the trap again and resets it to its initial state.

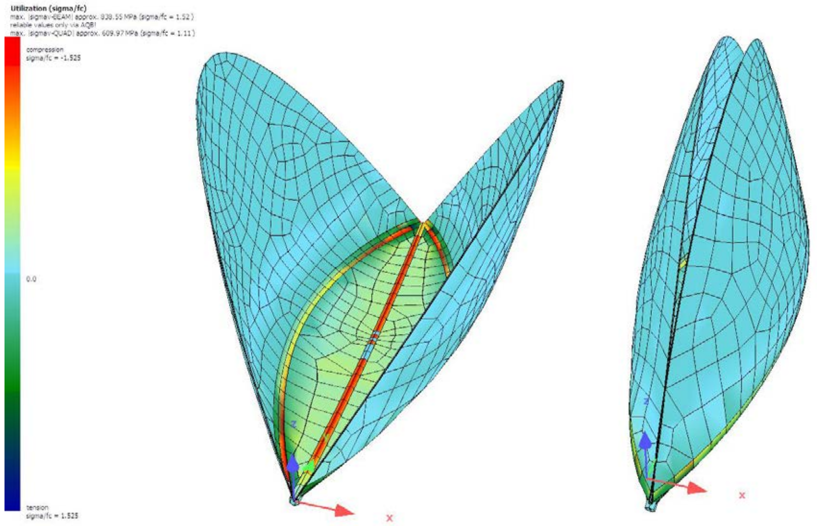


Figure 5.42: Kinetic model of the *Aldrovanda*. Increasing the temperature in the upper flank of the midrib causes a bending motion of the central portion that is transferred to a closing movement of the trap lobes.

5.7.6. Mechanical variability and consistency

During the abstraction from biological role model to simplified mechanism, one major question arose: which impact does the curved-line folding have on the effectiveness of the compliant mechanism? This leads to the follow-up question of whether small modifications of that elastic linkage either regarding its geometry or its stiffness properties could positively alter the mechanism's amplification ratio or stress distribution? To investigate the first part of the question regarding the amplification ratio, the role model was abstracted even further to a set of kinematical models, which focused only on the geometrical aspects of the movement. The goal of this experimental setup is to compare similar curved-line folding patterns that differ only in their radii (Schleicher et al., 2010; Schleicher et al., 2011). The basic pattern used for these models is a plane square with the corner points A,B,C,D and a diagonal length of d = 1500 mm (Fig. 5.43). Along the diagonal, two circular arcs cross point B and D. They divide the square surface into two distinct portions - a lens-shaped central portion and two symmetrical lobes. Four models were generated from the same planar square but with different arc radii:

The first model, A1, has a radius of 1700 mm.

The second model, A2, has a radius of 2500 mm.

The third model, A3, has a radius of 3500 mm.

The fourth model, A4, has a radius of 4500 mm.

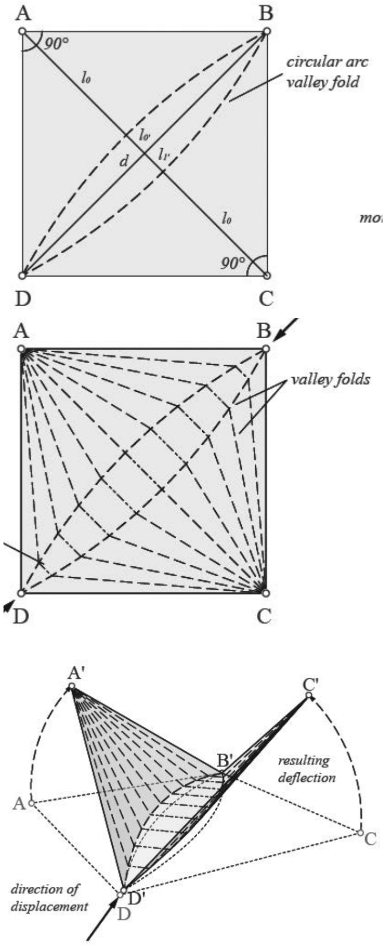


Figure 5.43: Geometrical and kinematical model of the *Aldrovanda* mechanism investigates the role of the curved-line folding coupling between center portion and the trap lobes.

The models were treated as pseudo-rigid-body models (Howell, 2001) and their deformation was simulated in the Rigid Origami Software that was developed by Tomohiro Tachi (Tachi, 2009). Using this tool has the advantage that one can start from a planar crease pattern and then calculating a continuous folding process of the surface with full control over every intermediate state of the folded shape. The system, thereby, uses crease angles of all fold lines as variables to represent a constraint origami mechanism that performs a one-DOF (degree of freedom) finite rigid motion. In order to import the folding pattern to the software, the surfaces were converted to a quad-dominant mesh with planar faces, in which the surface rulings are parallel in the central portion and pass through the corner points in the marginal portions. Furthermore, a folding direction was assigned to the creases by defining whether they are mountain or valley folds (Fig. 5.43). Finally, the models were given one fixed support at point B and a movable support at point D that is able to translate linearly in the x-y plane.

In contrast to the midrib-actuation of the role model, the motion principle that was chosen here is initiated by the displacement of one support. Consequently, when one moves the free support D to D′, the lens-shaped central portion starts to bend, which in turn triggers a flapping motion of the lobes and lifts point A to A′ and C to C′ (Fig. 5.43). With this technique it was possible to iteratively simulate the folding process for all four models and to document at which displacement factor the trap lobes came into contact (Fig. 5.45). The direct comparison between the models shows that the effectiveness of the transmission between the initial bending and the follow-up lifting of the lobes is highly dependent on the curvature of the curved-line. The less curvature the line has the more sensible the pattern becomes towards stimulus (displacement of the support) and the quicker the compliant mechanism performs a uniform movement. This sensitivity can be specified as ratio between the system's global length and the local displacement needed at the support to fully close the device (e.g. allow the lobe tips to touch). The resulting displacement ratio for the different models can be seen in Figure 5.44. In this comparison it becomes apparent that the models with the least curved fold are the most sensitive and respond the quickest as well as the most effective in converting a very small actuation into a large lifting motion of the trap lobes.

Figure 5.44: Measuring the ratio between support displacement and gained lifting motion of the lobes.

Analysis method		Model A1 r=1700	Model A2 r=2500	Model A3 r=3500	Model A4 r=4500
Rigid Origami Software	system lenght (mm)	1500	1500	1500	1500
	displacement (mm)	140	38	16	10
	displ. factor	**10,7**	**40**	**94**	**150**

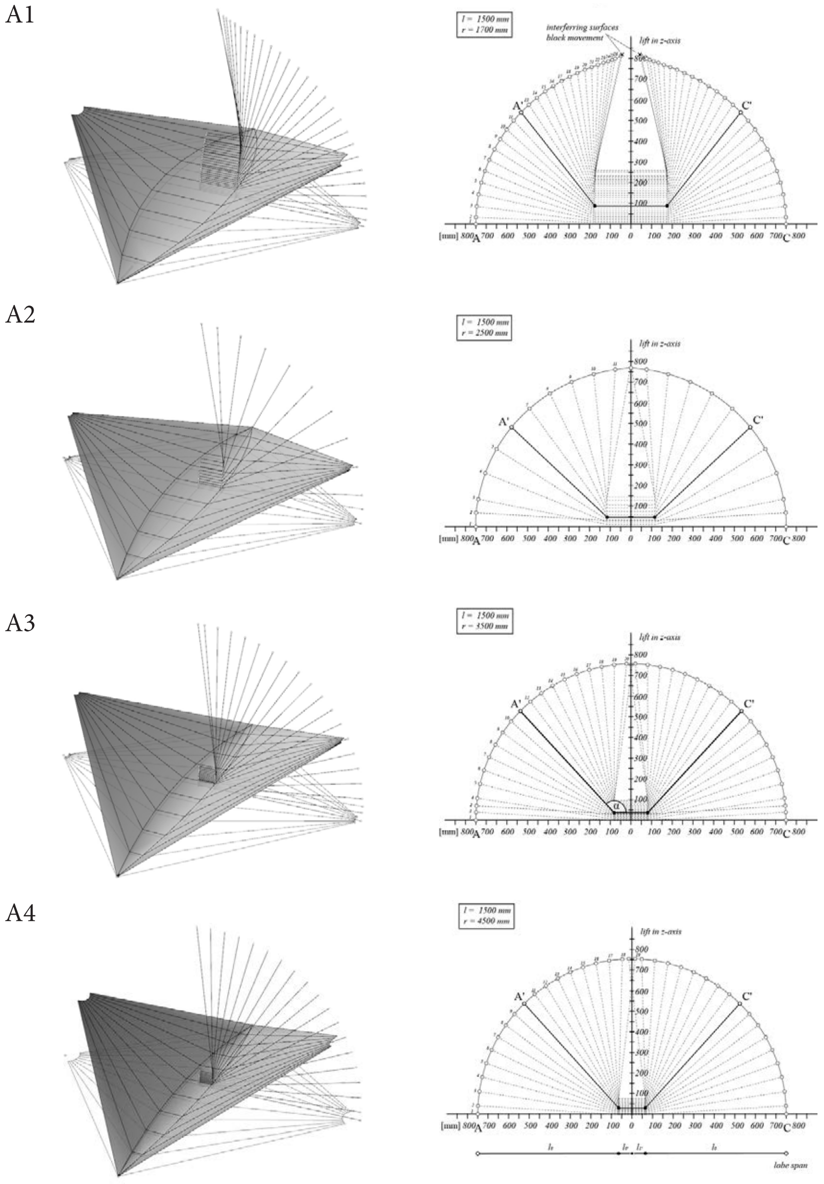


Figure 5.45: Sensibility studies of models with slightly different geometries reveal that the smaller the curvature of the curved fold the more sensible the mechanism and the more effective the transmission ratio between local actuation and gained global deformation.

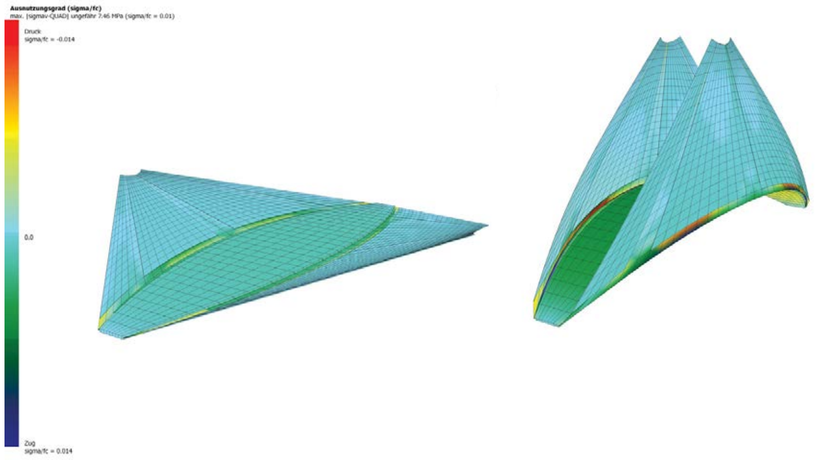
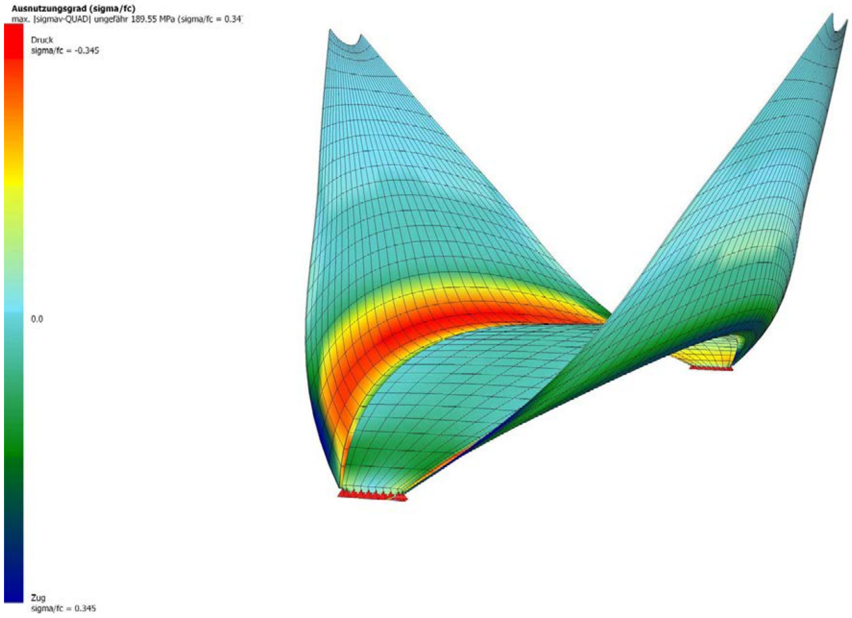


Figure 5.46: Kinetic model of the *Aldrovanda* mechanism. This model features a zone of lower stiffness along the curved-fold line in order to create a local living hinge.

Figure 5.47: In this kinetic model of the *Aldrovanda* mechanism, the curved hinge zone is wider and its stiffness properties differ little from the lobes and the central portion. As a result the stresses in the deformed shape are broader distributed and thus local stress peaks can be avoided.



To additionally investigate the second part of the question regarding the stress distribution in the flexure zone, eight kinetic models were generated and their movement simulated in FEM (Fig. 5.46-5.49). All eight models are based on the pattern used in the previous experiment for the kinetic model A3. Hence, they have a system length of 1500 mm and an arc radius of r = 3500 mm. Furthermore, they were assigned with GFRP-like material properties (Young's Modulus of E = 12000 N/mm^2) and have a global thickness of 2 mm for the marginal portions and 6 mm for the central portion. The variable parameters that differentiate the eight models are the stiffness of the living hinge and its width:

In the first group, all the models have a flexure zone with a constant width of w = 20 mm but varying thicknesses (Fig 5.48):

The model A5 has a living hinge with a thickness of t = 0.25 mm.
The model A6 has a living hinge with a thickness of t = 0.5 mm.
The model A7 has a living hinge with a thickness of t = 1 mm.
The model A8 has a living hinge with a thickness of t = 1.25 mm.
The model A9 has a living hinge with a thickness of t = 1.5 mm.

In the second group, the living hinges have the same thickness of 1 mm and stiffness E = 12000 N/mm^2 but differ in width (Fig. 5.49):

The model A10 has a living hinge with a width of w = 20 mm.
The model A11 has a living hinge with a width of w = 40 mm.
The model A12 has a living hinge with a width of w = 60 mm.
The model A13 has a living hinge with a width of w = 80 mm.

For the simulation of the movement, all models were exposed to the same actuation scenario, in which the support D was displaced exactly by 15 mm. Once the target coordinate was reached, the models were compared and evaluated with regard to the occurring stress concentrations.

The first group alternated the stiffness by varying the thickness and found the softer the living hinge, the lower the stress peaks (Fig. 5.48). Furthermore, the compliant mechanism only functions when a sufficient difference in stiffness between the flexure zone and the surrounding surfaces is provided. Otherwise, the flexure zone will not act as a living hinge and may hardly transform the initial bending motion into a closure movement, as it can be seen in the model A9. This circumstance also explains the decrease of stresses in this model.

The second group varied the width and found the wider the flexure zone, the lower the stress peaks (Fig. 5.49). Although this is at the expense of a smaller transmission ratio, which means that the trap lobes do not raise up as high, this effect is still very fascinating because the stress peaks in the wider flexure zone are significantly lower in comparison to those in the models that have sharper creases. This mainly has to do with the fact that the local bending radii are much larger for a wider flexure zone. The advantage of this is that one can spread local stresses over a wider area and thus improve material utilization and reduce the risk of failure (Fig. 5.47). With this strategy, one can compensate local weaknesses in a mechanism through global strengths.

5.7.7. Conclusion

In summary of the sixth case study, it can be said that the trapping movement of *Aldrovanda* features a mechanism that is particularly fascinating because it couples the bending of multiple structural surfaces and even amplifies their interaction by means of curved folding. This basic principle has great potential for innovation. The simulations presented here show that it is not only possible to recreate the plant's compliant mechanism but also test its functional aspects and mechanical advantages in various ways. The conducted sensitivity studies and comparative analyses between multiple kinetic models with various geometrical characteristics and material properties resulted in important insights. These studies systematically expended the knowledge about the mechanism's form-structure-function relationships, which may not only help biologists to better understand the motion principles in *Aldrovanda* but can also be of great value for engineers in the development of kinetic structures inspired by this role model.

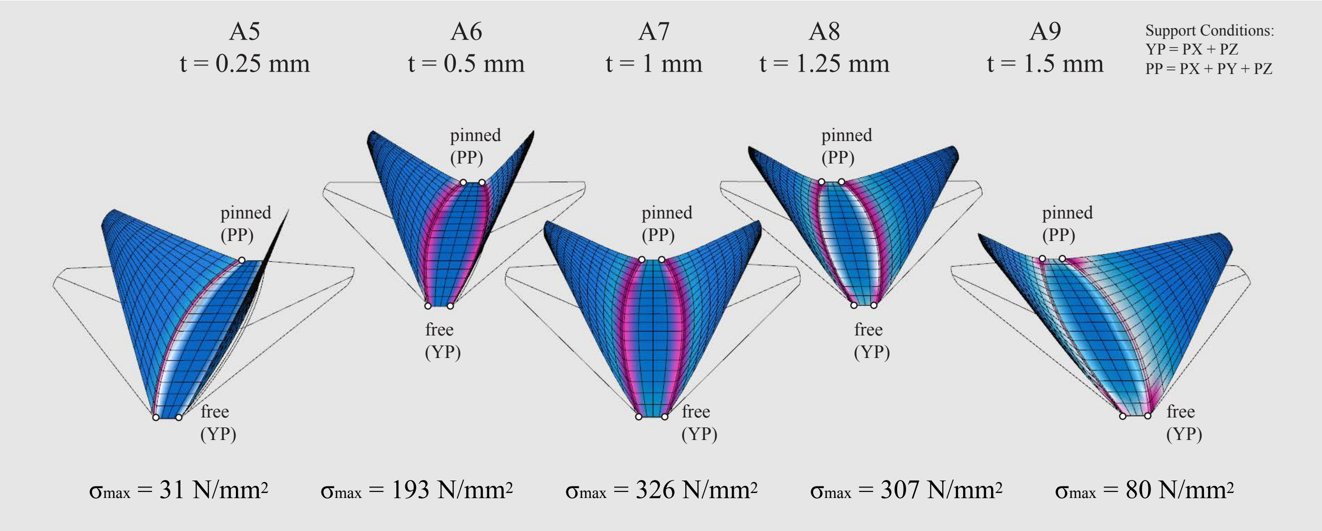


Figure 5.48: Comparative analysis of multiple similar kinetic models that only differ from each other in the thickness of their curved-line fold and thus in the local stiffness of the living hinge. Based on this comparison, it can be concluded that a softer flexure zone results in lower stress peaks and secondly that the flexure zone would need to be sufficiently softer than its surrounding, otherwise the mechanism loses its capacity to function.

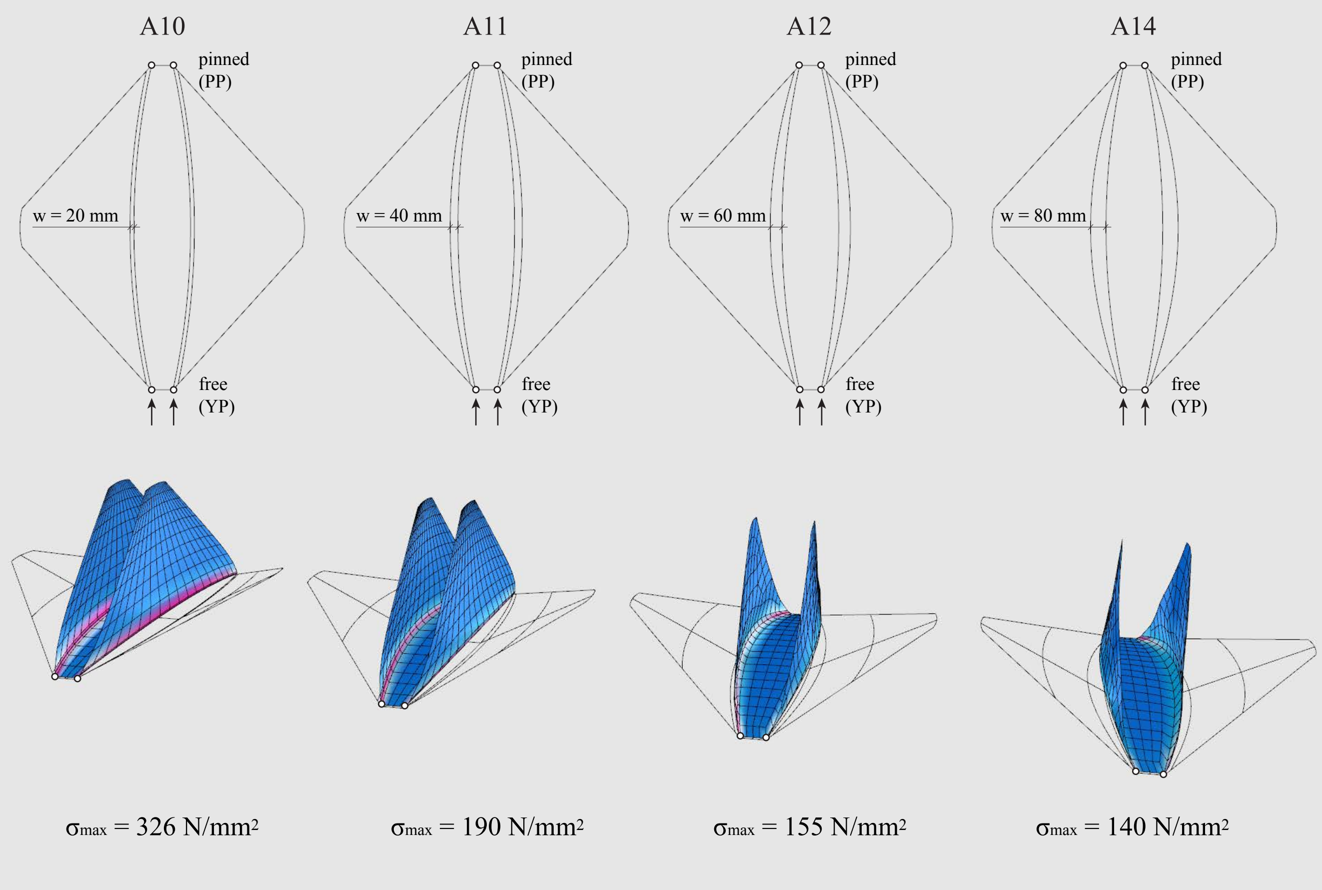


Figure 5.49: The second comparative analysis looks at similar kinetic models that diverge from each other only in the width of their implemented flexure zone. Once actuated in the same way, the models with a wider flexure zone have significantly lower stress concentrations than the models with a narrower flexure zone.

Figure 5.50: This southern masked-weaver bird is triggering *Strelitzia reginae's* pollinating mechanism by locally applying its body weight.

5.8. Case Study 7: Pollination Mechanism of *Strelitzia* (Strelitziaceae)

The seventh and last case study investigates the valvular pollination mechanism of *Strelitzia* (Strelitziaceae), commonly known as the Bird-Of-Paradise flower (Fig. 5.50). In contrast to the previous case studies, this plant is not based on hydraulic actuation but instead triggered by the application of an external load to a specific point. Initiated by this punctual change, *Strelitzia* fascinates by performing a non-autonomous and reversible deformation movement.

5.8.1. Biological role model

The chosen role model for this case study is called *Strelitzia*; a very popular plant that is cultivated worldwide because of the exotic appearance of its flower. Originally, however, this plant is native to the temperate and sub-tropic climate in South Africa, where it is also known under the name Crane Flower or Bird-Of-Paradise flower. The *Strelitzia* genus belongs to the plant family of Strelitziaceae and comprises five species that have flowers in different sizes (Endress, 1994). One of these species, for example, is *Strelitzia reginae*, which was investigated further in the context of this research.

Strelitzia reginae is a perennial, ornithophil plant. This means that the sexual reproduction of this long-living plant is dependent on birds, in this case cape weaver birds, which transfer pollen when they fly from one flower to another. In return for this service, the plant rewards the birds with its delectable nectar (Rowan, 1974; Skead, 1975; Coombs et al. 2007).

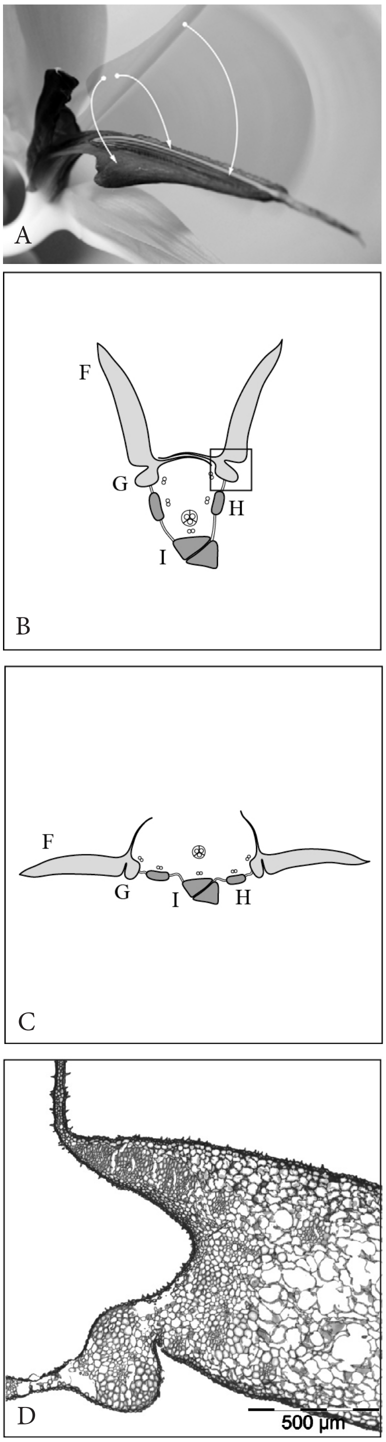


Figure 5.51: When triggered locally by applying a load, the perch not only bends downwards but also opens up and reveals the pollen. Key elements for this mechanism are a lateral rib and lamina flap that are coupled and deform together.

An important role in this interaction between flower and bird is played by a very fascinating compliant pollination mechanism that enables a targeted transfer of pollen as well as provides its protection against predators and nectar thieves (Darwin, 1876; Stebbins, 1970; Stiles, 1978; Frost & Frost, 1981; Wolf & Stiles, 1989; Fenster et al., 2004; Whitney & Clover, 2007; Cronk & Ojeda, 2008; Coombs & Peter, 2009).

5.8.2. Functional morphology

The plant's specialization on birds as the main pollinators is reflected in the functional morphology of *Strelitzia reginae*. To attract birds and to facilitate pollination, the flower provides a peculiar landing platform in the shape of a protruding perch. This perch consists of two adnate petals with a brilliant blue color (Fig. 5.51A). Depending on the species, the perch has a length of about 50-300 mm. A closer look at a diagrammatic cross-section through the perch of *Strelitzia reginae* reveals its monosymmetric set-up (Fig. 5.51B). Particularly striking are three reinforcing ribs (G, H, I) on both sides that are loosely connected with an extremely thin layer of cells. It is also noticeable that while the lower lateral ribs are merged with each other, the upper ribs are attached to large flap-like lamina wings (F). Small flanges on these lamina wings close the cavity and cover the anthers. Furthermore, the upper rib (G) and the lamina (F) are the essential elements in the plant's compliant mechanism, as well be shown in the following.

5.8.3. Description of the movement

When a bird lands on the flower and sits on the perch, its weight causes the structure not only to bend downwards but also triggers a simultaneous secondary movement. In this secondary movement, the two flap-like lamina rotate sideways and expose the previously enclosed anthers as well as another cavity that contains nectar (Fig. 5.51C). Once the pollen is freely accessible it sticks to the bird's feet and feathers and gets carried away when the bird flies to the next flower. Without the applied weight of the bird, the open perch resets itself to a protective closed state again by releasing stored elastic energy. What is particularly fascinating in this context is the fact that this plant mechanism is not only reversible but also highly repetitive. While the flower is naturally visited by birds only a few times during its life span, the flexure mechanism itself is reliable enough to perform over 3000 cycles with only slowly increasing fatigue (Poppinga et al., 2010).

5.8.4. Disclosed principle

Since it is obvious that an external loading of the structure at a specific point is the trigger of this plant movement, the question here is not where the actuation element is located in the structure but how the plant is capable of transmitting this local impulse into a desired global motion. It is this question that motivated a series of novel investigations and enabled a profound description of the involved mechanism and its innovative potential for bio-inspired products and constructions (Lienhard et al., 2009, 2010, 2011; Lienhard, 2014; Poppinga et al., 2010, 2013; Schleicher et al. 2010, 2011, 2014).

The underlying mechanical effect that is responsible for the distinct deformation of the perch is called "lateral torsional buckling" and is occurring between the flap-like lamina and the adjacent lateral rib (Lienhard et al., 2009) (Fig. 5.51D). These two elements interact with each other in a way that can best be demonstrated with a physical model (Fig. 5.52). Even though this highly abstracted model shows the mechanism in a different material composition, it is a quick way to showcase the fundamental relationships. Here, the plant's mechanical elements are recreated as a stiff beam element to which an elastic fin is attached perpendicularly. When one bends this beam, high tensile forces occur in the upper edge of the fin. The developing stresses can become so strong that the fin reacts with a subsequent out-of-plane bending when a critical point is reached. By deflecting to one side or the other, the fin dodges these peak tension forces and deviates into a less strained equilibrium position. The fin bends up to 90° in relation to its initial position. The motion comes to an end when the fin has reached a new double-curved configuration, which is less strained than the shape would have been without buckling.

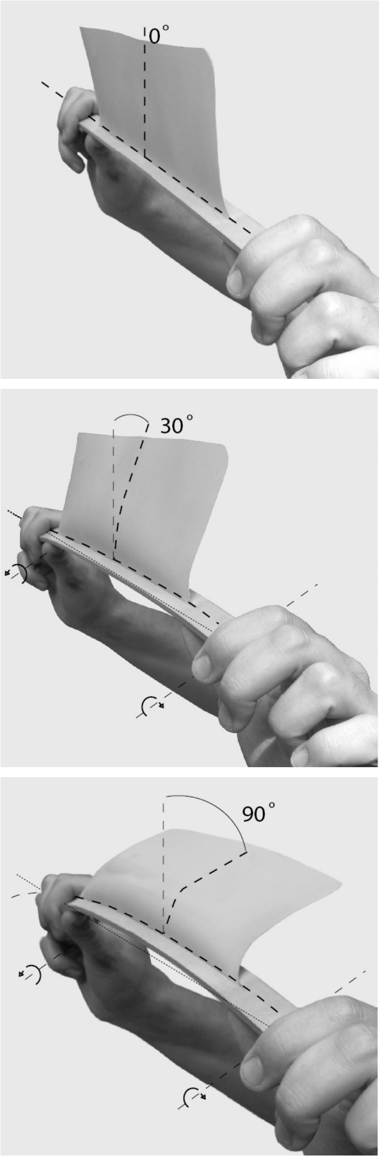


Figure 5.52: A physical model that consists of a stiffer beam element and a softer fin illustrates the *Strelitzia* mechanism. When the beam element gets bent the high tensile forces enforce a flapping motion of the fin - a failure mode that is known as later torsional buckling.

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 (Simitses & Hodges, 2006). However, this mechanical effect is usually perceived as a dreaded failure mode that needs to be avoided. In plant kingdom, however, there exists no negative connotation to this phenomenon and instead is just part of a specific mechanism. In comparison to that, the man-made idea to functionalize this failure mode and to embed it in a mechanism in order to amplify a coupled deformation is called Flectofin® and was successfully filed for patent (Knippers et al., 2011).

5.8.5. Abstracted bio-inspired mechanism

To gain a better understanding of the previously described form-structure-function relationships, *Strelitzia reginae* was remodeled digitally. A quick geometrical model provides a simplified and abstracted version of the perch and includes the key elements of the mechanism. It consists of a bundle of five curves, each 2000 mm long, which fuse together at their tips. The gaps between the curves are filled with narrow and long surface bands. In addition, the model also features the all-important flap-like laminas, which are attached to the upper curves.

This model is then exported into the FEM environment to create a kinetic model (Fig. 5.53). Here, the bundle of curves is turned into a series of cantilevering rods that are anchored only on one end. These rods were assigned with GFPR-like material properties (Young's Modulus of $E = 12000$ N/mm^2). The upper and lower rods were given a diameter of $d = 4$ mm while the other two only have a diameter of $d = 1$ mm. The surfaces in the model were given the material properties of GFRP as well. The flap-like lamina has a width of $d = 250$ mm and a length $l = 2000$ mm. Furthermore, the lamina were given a thickness of $t = 5$ mm, which is five times thicker than the surface bands in between the rods that only have a thickness of $t = 1$ mm.

For the actuation, a vertical force (in global z-direction) was applied to the tip of the rods. The iterative simulation of the deformation shows the desired structural response, in which the rods are not only bending downwards but also cause a sideways flapping of the fins. Even when deleting all other elements of the model and keeping only the fins with the adjacent rods, the model shows the same movement. It can thus be concluded that the underlying motion principle is in fact only based on the interaction between the upper edge rod and the flap-like lamina.

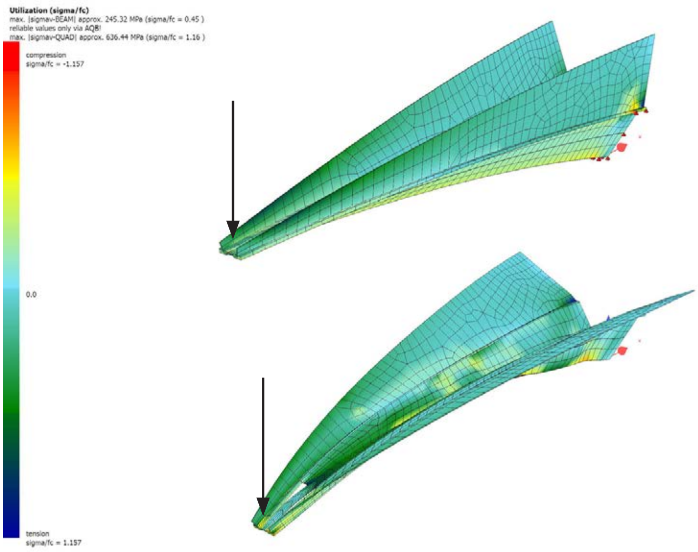


Figure 5.53: The kinetic model of the *Strelitzia* perch shows the same mechanical response to a locally applied load as the biological role model does.

5.8.6. Mechanical variability and consistency

The next question becomes whether the mechanical effect of lateral torsional buckling remains functional even if modifications to the mechanism are made. Different kinetic models were generated and studied for their deflection behavior. All models were reduced to a few key components and either investigated geometrical changes or tested different structural boundary conditions.

The first set of experiments investigated to which degree different Euler buckling modes affect the flapping motion (Euler, 1744) (Fig. 5.54). The models consist of a beam element out of GFRP (length l = 2000 mm, cross-section 40x20 mm, Young's Modulus of E = 12000 N/mm^2) and a thin rectangular fin (length l = 2000 mm, width b = 200 mm, thickness t = 2 mm, Young's Modulus of E = 12000 N/mm^2). All models are identical, apart from their support conditions:

The model S1 is pinned at the top and pinned at the bottom.
The model S2 is pinned at the top and clamped at the bottom.
The model S3 is clamped at the top and clamped at the bottom.
The model S4 is free at the top and clamped at the bottom.

The deformation was triggered through a vertical displacement of the top support by 20 mm. All models underwent lateral torsional buckling, though the effect of boundary conditions was considerable. As to be expected, the model S1 deflects the most, which is not surprising since this mode is the most susceptible to buckling and has the most favorable lever arm to flip the fin.

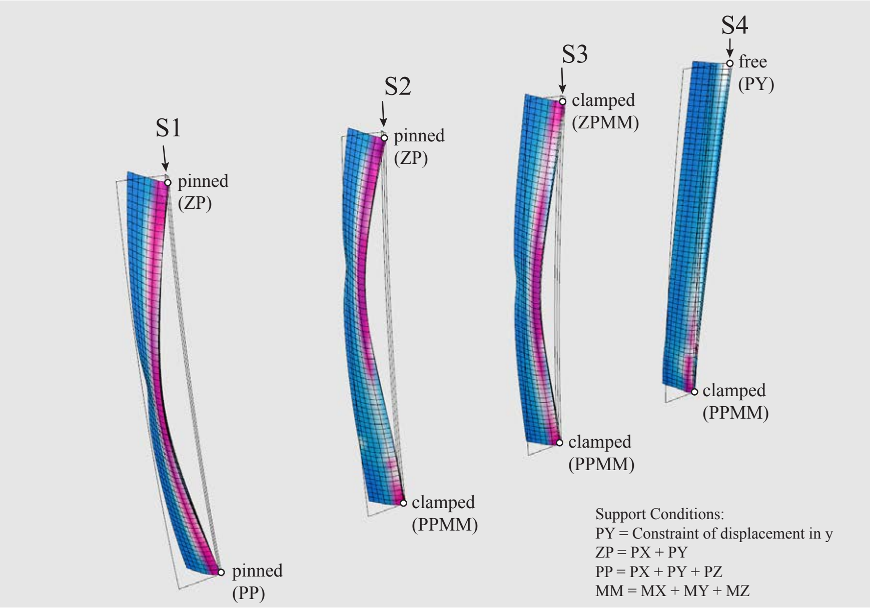
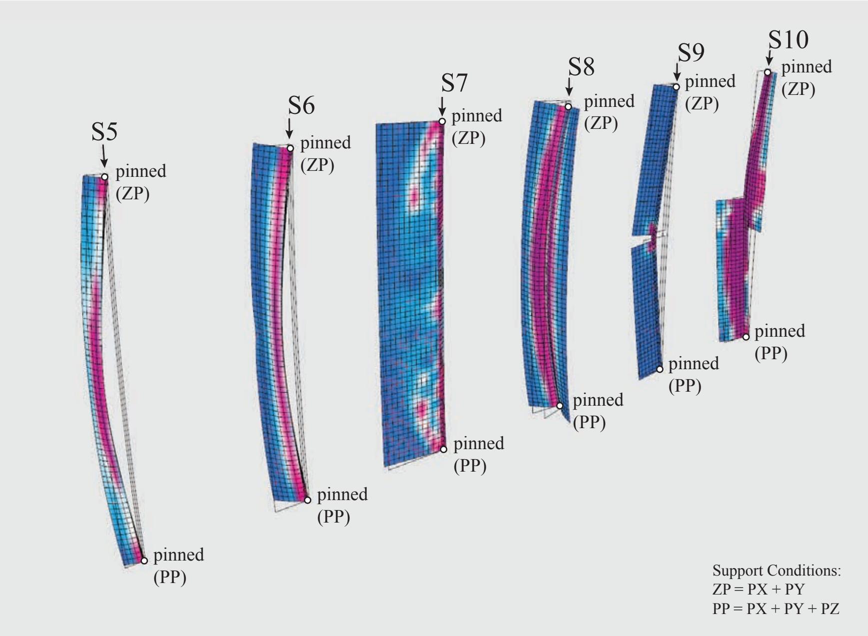


Figure 5.54: Testing the mechanical behavior of the *Strelitzia* mechanism for different constraint Euler buckling modes.

Figure 5.55: Testing different lamina geometries attached to the same beam element.



The second set of experiments aimed to analyze how small changes to the fin can affect the mechanism. Based on the model S1 from the previous experiment, six additional models were generated. These models either feature a fin in a different size or have more than one fin attached to the beam profile (Fig. 5.55):

The model S5 has a fin with the width of b = 100 mm.
The model S6 has a fin with the width of b = 200 mm.
The model S7 has a fin with the width of b = 400 mm.
The model S8 has two fins at an angle of 30° to one another.
The model S9 has a split fin with a gap of 20 mm.
The model S10 has two fins that slightly overlap by 200 mm.

From the simulations of the models S5-S7 it can be concluded that the wider a fin is, the more it increases the beam's resistance towards buckling and as a result the fin does not deflect that much. The model S8 shows that the deformation of the beam element can trigger the flapping motion of two fins. For this simulation it was particularly important that the fins stand in an angle to each other, otherwise they would not have flipped in different directions. Slight imperfections in the model geometry, as for example pre-bend or tilted surfaces, facilitate the simulation significantly and help the fin to deform into a specific direction. Particularly revealing are the simulations of model S9 and S10. Their deformation is significant insofar as it demonstrates specific limitations to the design freedom. While the lateral fins in S9, for instance, increase the beam's rigidity, the gap between them creates a local living hinge. As a result, the fins stay straight and only the gap zone starts to bend. By attaching the two lateral fins in such a way to the beam that they overlap, as done in model A10, one can overcome this local drop in rigidity and create a better transition between the elements. This can be seen in model A10 where the fins buckle to the side. However, this model also reveals another design constraint that needs to be considered. The deflection of the fins in A10 is not happening simultaneously. Instead, one fin flips before the other, which creates a zone of lower rigidity again, and as a result that fin deforms even more as the support displacement progresses while the other fin of the model stays nearly straight.

5.8.7. Conclusion

The seventh case study has presented one of the most exciting compliant mechanism by looking into the pollination of *Strelitzia*. The disclosed principle of this flower is particularly fascinating since its movement is not actuated by the plant itself but instead triggered by the local application of an external load to a specific point. This means that it becomes significantly easier to set the mechanism in motion both physically as well as digitally. The conducted experiments have shown that this motion principle is not only versatile but also very efficient in its capacity to transfer a small and local input actuation into a large and global output deflection.

5.9. Summary

It is needless to say that all seven case studies are just a first start and their initial investigation obviously just scratches the surface of a much deeper and more profound source of inspiration. Nevertheless, the compliant mechanisms that were revealed in these role models are absolutely fascinating and render a promising potential for further transfer into technical applications. Therefore, more research should be conducted not only to widen our knowledge about these seven plant movements and their mechanisms but also to expand our insights further by comparing them with the motion principles that underlie other plant movements. The suggested methodology for gradual abstraction and transfer of the biological motion principles into geometrical, kinematical, and kinetic models has proven to be very helpful and this approach could surely be used for other case studies as well. The tests on the mechanical variability and consistency of the motion principles have shown that the derived bio-inspired mechanisms are not necessarily limited to a strict copy of the plants but instead also give the opportunity for modifications and new designs. It is this circumstance that makes this research even more exciting and allows to envision some practical use of this knowledge and possible implementation in the field of architecture, as will be shown in the next chapter.

6. IMPLEMENTATIONS

Flexible Facade Shading Systems in Architecture

'Architecture today is very much a team game. Increasingly designers work as generalists who try to combine the work of specialists to best effect and so explore new territory.'

- Hugh Whitehead (qtn by Jane Burry in http://goo.gl/WiBpv)

6.1. Overview - what could be a practical use?

This chapter is devoted to the question of whether the previously described bio-inspired compliant mechanisms may actually have a practical use and, if so, whether they can only replace already existing technical solutions or exhibit potential to open up new and enriching fields of applications.

To answer this question more thoroughly, this chapter will venture out by envisioning a concrete implementation of bio-inspired compliant mechanisms and reflect on the advantages and disadvantages when confronting these systems with a problem set from a specific area.

Generally it can be said that a design approach, which deliberately includes a structure's flexibility and elastic material properties, offers an extremely wide range of applications and may affect many industrial sectors. Due to the author's specialization and professional experience in architecture, however, this field of application was selected to showcase the new possibilities. Within architecture, one area in particular was identified that could greatly benefit from the use of bio-inspired compliant mechanisms: The design and construction of facade shading systems. Here, flexible kinetic structures could not only provide an improvement to already established product categories but may also open the door to new market niches and conquer unoccupied areas of businesses.

6.2. Significance of Facade Shading Systems

Current trends in architecture show a steadily growing demand for intelligent and adaptive facade shading systems. With kinetic structures like blinds and louvers it is possible to react to changing light and weather conditions, reduce radiation loads, guide ventilation, and regulate the amount of daylight that enters the building. By actively or passively mediating between external environmental factors and internal user demands, shading devices

Figure 6.1: MyZeil Gridshell

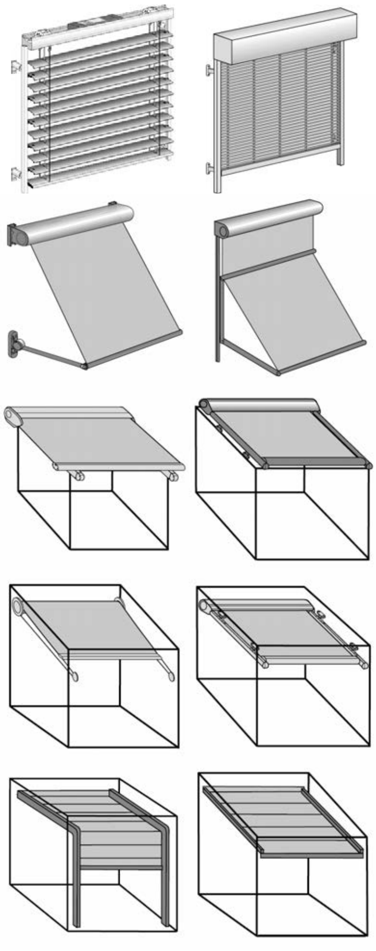


Figure 6.2: Typical product catalogue of commonly used facade shading systems.

can create a beneficial microclimate and are largely responsible for the living quality and energy efficiency of our built environment. In order to make our architecture more sustainable it is therefore also crucial to constantly rethink the way we conceptualize these shading systems.

The importance of facade shading systems for climate-optimized buildings becomes clearer in a study by the European Solar-Shading Organization (ES-SO) (Standaert, 2005). According to this study, building facades and their glazed areas in particular are mainly responsible for extreme overheating in the summer and up to 40% heat loss in the winter. As a consequence, common building types like modern office buildings, for instance, are heavily dependent on intensive air conditioning. The use of artificial cooling, however, is one major reason why buildings have become the largest energy consumers in Europe. In fact, the study states that more than 40% of the primary energy consumption is attributable to the construction and operating of buildings. With an efficient shading system in place, however, office buildings could easily function without the energy-intensive mechanical cooling. Using an adaptive shading system that blocks the sun in the summer and captures passive energy in the winter could yield significant savings. The study speculates that the energy consumption of buildings in Europe could be reduced by approximately 41 million tons of oil (10%) and approximately 111 million tons CO^2 per year. In addition to the possible energy savings, the study also offers the prospect of a huge commercial outlet. In 2011, the market for facades reached a total of 12 billion Euros worldwide, 6% of which is accounted to shading systems.

6.3. Geometrical and Mechanical Challenges

If adaptive shading devices play such a significant role for the climatic performance of a building, the question arises why they are not yet widely implemented. One reason is due to the fact that modern building facades pose very difficult geometrical and mechanical challenges.

Traditionally, shading devices like blinds, shutters, and louvers, are conceptualized as standardized modules for punctuated facades. These facades typically have regular glazing elements, which allows for shading devices whose mechanics can be based on orthogonal grids with clearly defined axes, 90° angles, and normative proportions. For this common application, the building industry has developed over the course of the last century an immensely varied and long-proven range of products (Fig. 6.2). However, a mechanical system that is based on uniformity also entails great limitations, especially when using it in application scenarios

Figure 6.3: Kong Bar-Restaurant in Paris with external shading system. 18 blinds protect this glass roofing and absorb 97% of the sun's heat. Interestingly, however, this system has geometrical limitations and cannot easily be applied to the double-curved areas of the facade.

other than the planar and parallel configuration. This problem has even been exacerbated by the increasing influence of digital technologies on today's architectural design and manufacturing. Due to novel planning tools, architects have acquired a significant design freedom that often manifests itself in building facades with complicated curved and freeform geometries as well as thousands of individually shaped panels (Fig. 6.1,6.3). Applying a traditional shading device to this kind of facade is very difficult or sometimes even impossible. Conventional shading devices can only meet this challenge at the expense of additional mechanical complexity and individual customization (Fig. 6.4-6.7). As a consequence, the shading devices become over-complicated, heavy, susceptible to failure, maintenance intensive, and often require large amount of operation energy. Therefore, most shading systems that feature kinetic structures for curved facades are in reality not of-the-shelf products but very expensive, custom-made constructions.

Developers often try to avoid high acquisition and operating costs by planning curved facades either without any sun protection or by placing the shading devices on the inside in order to protect them from harmful environmental influences. However, both strategies offer no solution to the problem since a total lack of sun-protection results in user-unfriendly buildings and placing them to the interior makes them far less effective. In fact, the performance of a shading system and thus the energy consumption of an entire building greatly depend on the position of the device. Recent studies have shown that if a shading device is applied on the outside of a facade, its efficiency can be 3-5 times higher (Hausladen et al., 2006) than on inside. However, a shading device that is placed on the exterior is also exposed to harsh weather conditions like rain, wind, water, heat, cold, and pollution. All these factors pose a major challenge to its fragile mechanics. However, placing the sun protection behind the facade is a poor alternative. Its lower performance increases the building's energy consumption and constantly requires artificial cooling of the heated spaces. A possible remedy to this problem could be the use of facade shading systems based on bio-inspired compliant mechanisms. Their flexible mechanics are more resilient and less prone to interferences from harsh weather conditions. These beneficial characteristics open the possibility to place the shading device on the exterior of the facade, which could make these systems a plausible and eco-friendly alternative to conventional solutions.

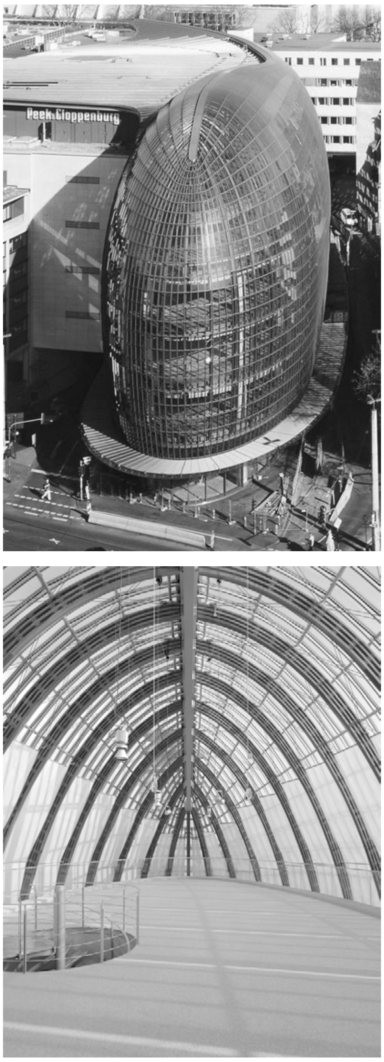


Figure 6.4: Shading system inside the double-curved facade of the Peek & Cloppenburg building.

6.4. Conceptualizing Flexible Shading Systems

The goal for this section is to test the hypothesis that bio-inspired compliant mechanisms can be transferred to flexible facade shading systems for large-scale architectural applications. Therefore, three motion principles of the previously discussed plant movements were chosen and adapted to tackle typical geometrical challenges related to double-curved facades (Schleicher et al., 2010, 2014).

6.4.1. Panelization of double-curved facades

Before implementing a flexible shading system on a double-curved facade, one first needs to understand the basic approach and difficulties for the panelization of freeform geometries in general. Usually, the goal is to approximate a given surface with a group of glass panels or metal sheets that can be fabricated at reasonable costs. In doing so, it is important to preserve the initial design intent and to achieve a desired aesthetic quality that results in a controlled panel layout and surface smoothness. Production costs and surface quality, however, are highly dependent on the panelization process, with which a larger surface is subdivided into smaller patches. A common problem hereby is that the panelization of a complex input surface usually results in thousands of individual patches with many more or less similar panels. The size, number, and geometrical complexity are the factors, which make these panels so expensive. Moreover, it makes a big difference whether or not each panel needs to be custom-made or if there is any possibility for mass-production. While planar panels are the most cost-effective solutions, some surfaces need to be addressed with individually shaped freeform panels. For the production of curved panels, however, it is necessary to fabricate special molds, which increases the costs significantly. That is why it is so important to find an optimized panelization process that either generates many flat panels or reuses the same molds for their production.

Since the rationalization of this process plays such a significant role and a manual layout of panels for freeform surfaces is rather infeasible, multiple researchers and companies have specialized over the last years in developing a series of helpful computational and mathematical tools for surface panelization (Pottmann et al., 2007; Eigensatz et al., 2010). Programs like EvoluteTools or Weaverbird, for example, provide a series of mesh modeling, editing, and optimization tools. With their help, it became much easier to find a paneling typology that matches desired quality requirements as well as minimizes production costs.

However, since the main driver in the panelization of freeform surfaces are costs and surface quality, other functional objectives, as for example the shading of these panels, have a much lower priority and are addressed only in a post-design phase, when the geometry of the panels is already decided. As a result, the detailing of the shading devices has to be adapted to a given irregular panelization geometry. Even though most subdivision strategies aim to use only one consistent mesh topology (e.g. quad-dominant meshes with planar faces) and can produce geometrically differentiated triangular or quadrilateral polygons, the panels in such a mesh are all but similar. In fact, the panels may drastically differ in size, shape, and angles. These panels are not congruent versions of each other and can't be achieved by mere translation, rotation, or reflection. These geometrical characteristics usually prevent the application of traditional mechanical devices.

Figure 6.5-6.7: Interior shading system at the Fiat Lingotto factory. The adaptation of the shading system to the challenging geometry was achieved by an increase of mechanical complexity.

6.4.2. Panelization of an ellipsoid

To test whether it might be possible to clad a freeform facade with flexible shading systems, the challenging geometry of an ellipsoid was chosen as a test-surface. For the subdivision of this surface, a so-called conformal mapping method was used (Sechelmann et al., 2013). This approach is particularly helpful because it enables a subdivision into planar elements of different sizes, but similar in shape and angles. The panelization process followed a series of steps: Firstly, a three-dimensional ellipsoid surface was constructed by using three ellipses (Fig. 5.8A). Secondly, a net was generated on this surface based on the so-called lines of curvature (Fig. 5.8B). These lines have the special characteristic that they align with the principle curvature directions and are angle-preserving when they intersect. Thirdly, based on the intersection points of these lines, a quadrilateral mesh was drawn. The resulting quadrilateral mesh consists of completely planar quads, which can be illustrated by their touching inner circles (Fig. 5.8C). This property is very important, especially because quadrilaterals in a quad mesh are not necessarily always planar. In particular for applications in architecture, however, having a planar mesh is crucial in order to clad the surface with less expensive planar glass panels. In the final step, the panelization tool was further improved so that it provided more control over the individual properties of the quadrilaterals (e.g. counting direction of the vertices) and thus also over their connection logics (e.g. orientation of the faces) (Fig. 6.8D,E). This last step has particular importance for the implementation of cladding patterns, as will be described in more detail in section 6.5.

6.4.3. Curved-line folding facade inspired by *Aldrovanda*

As mentioned in the introduction of this chapter, most facade shading devices only work when being applied to planar and strictly rectangular panel geometries. In order to clad freeform facades, however, one would need to find a mechanical system that is more adaptable to geometrical variations. For this reason, bio-inspired compliant mechanisms are particularly interesting because they can remain functional even when being distorted in shape or scaled in size (Schleicher et al., 2010; Lienhard, 2014).

One of these promising systems, as described in section 5.7, is the compliant mechanism that was progressively abstracted from the motion principle of *Aldrovanda*. Its curved-line folding has a surprising geometrical adaptability and mechanical resilience. To better illustrate its potential, the mechanism was applied as parametric component on various test-surfaces. Therefore, the kinematical model, which was described in section 5.7.6., was used as a basis and slightly adapted for the task. Instead of building the model based on one regular square only, it was referenced to the distinctive shapes of multiple quadrilaterals in the mesh. In order to do so, however, it was necessary to loosen some of the previously fixed parameters, while simultaneously preserving some key proportional relationships that are crucial to guaranteeing an achievable folding sequence with feasible bending radii (Fig. 6.9). This modification made it possible to individually align the corner points (A,B,C,D) of the kinematical model with the vertices (0,1,2,3) of every quadrilateral (Fig. 6.8D). In the next step, the diagonal length for every quad was determined and a specific fraction of it was used as input parameter to generate the lens-shaped central portions and the two lobes. Finally, the curved-line creases were generated based on the proportional values of the components and the degree of distortion in the quadrilateral. By following this approach it is possible to panelize an ellipsoid with curved-line folding mechanisms, as can be seen in Figure 6.11.

When the geometrical and mechanical interdependencies are preserved, all these components should be movable and can be simulated kinematically. Furthermore, it is also possible to transfer these components into a kinetic model for further processing and

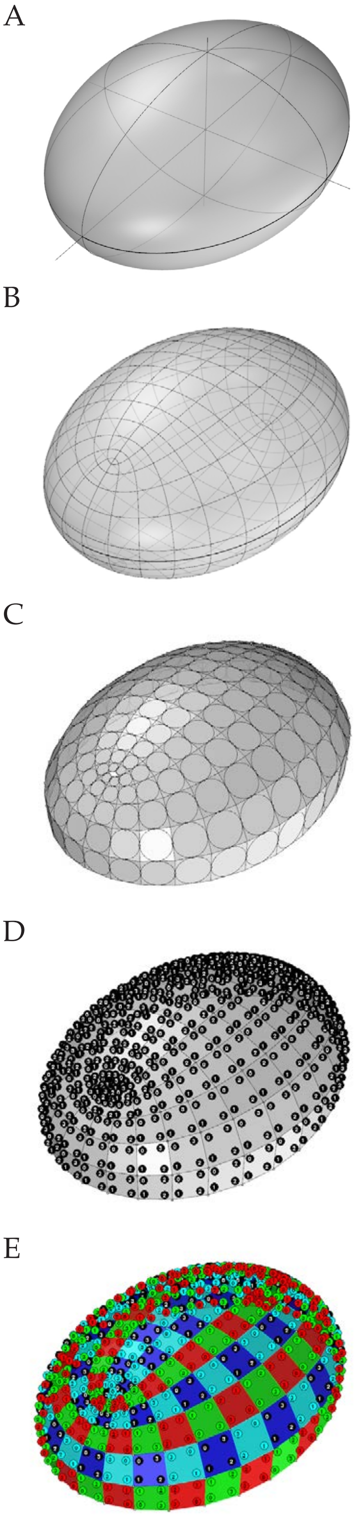


Figure 6.8: Strategy to panelize an ellipsoid test body with a conformal mapping method.

structural analysis. To control the motion, each component has one corner point that is fixed in space (A), while the opposing one (C) can slide along the diagonal of the quad and thus initiate the folding motion (Fig. 6.9). Due to the folding of the flexible components one can control the amount of sun protection. If the devices are wide open, they will provide a maximum of shading. If they are folded up tightly, they allow for more sun exposure (Fig. 6.11).

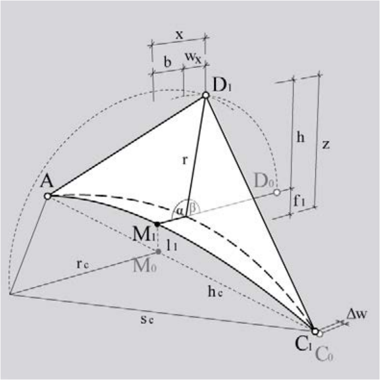


Figure 6.9: Parametric model of the *Aldrovanda* mechanism. It allows for geometrical changes of the shape while at the same time preserving some key relationships that are necessary for the functioning of the mechanism.

During these experiments, two interesting side effects appeared that could potentially drive further research on flexible facade shading systems. The first observation has to do with the fact that each of the individual components shows a different response to a given actuation due to their unique geometry. To synchronize the sensitivity and speed of motion in the system, one either has to trigger every single component with a unique actuation input or fine-tune its geometry by customizing the shape of every central portion and curved-line fold. The second observation concerns the

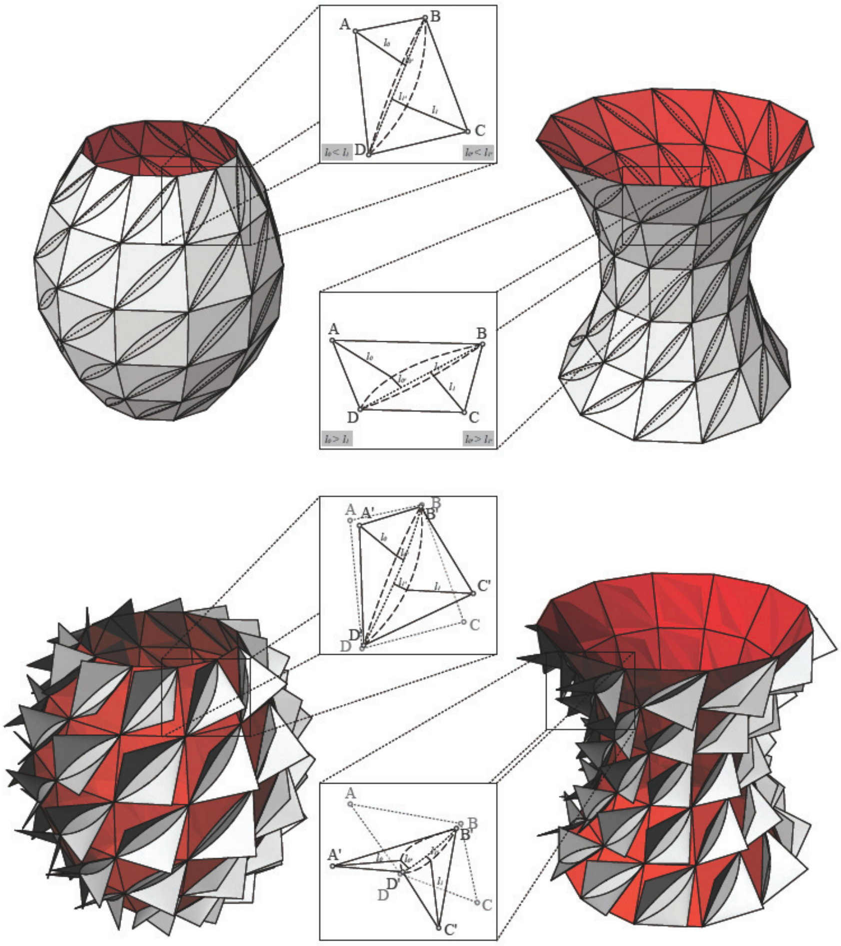


Figure 6.10: The curved-line folding mechanism stays functional even when being applied to convex or concave targed surfaces.

wide range of freeform surfaces that can be panelized and clad with bio-inspired compliant mechanisms. In principle, it is also possible to populate triangular meshes or non-planar quad meshes. This can be achieved by taking advantage of the fact that one can also model the flexible component in an already intermediate state of the folding process. This way, one can address four-sided polygons that are not planar, called skew quadrilaterals. Due to this geometrical adaptability, one can populate both synclastic and anticlastic surface geometries as well as many other freeform designs (Fig. 6.10).

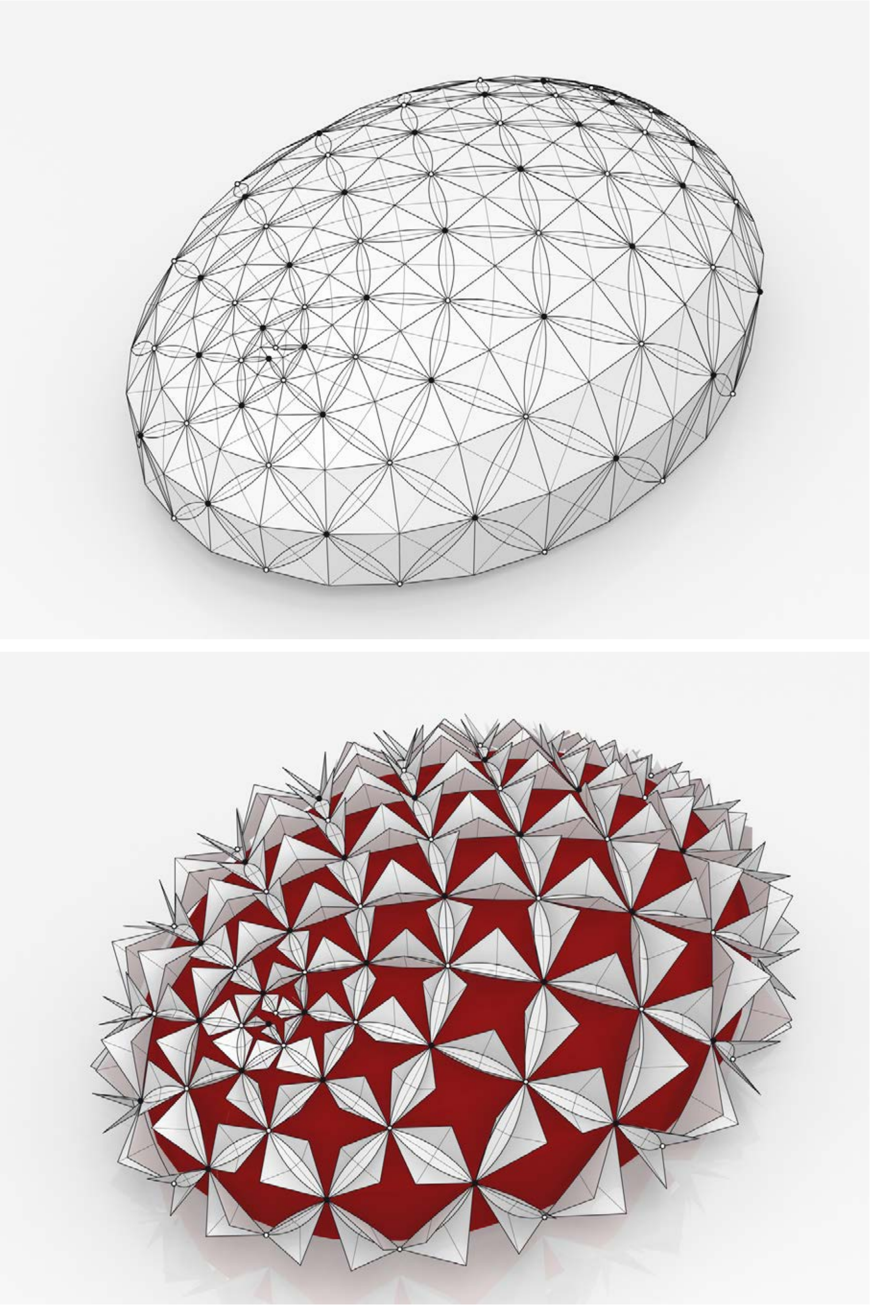


Figure 6.11: Ellipsoid test body clad with *Aldrovanda*-inspired curved-line folding mechanism. The components perform an opening motion even though each of them has a unique geometry.

6.4.4. Shingle facade inspired by *Lilium*

In addition to the previous example, other bio-inspired compliant mechanisms can be implemented as flexible facade shading systems. One of them is the principle inspired by the movement of *Lilium* (see section 5.4.4.). Considering the implementation of this mechanism is interesting because its actuation cannot be done purely on a geometric level but also needs to include the interplay of forces and material properties. Thus, the simulation of the kinematical

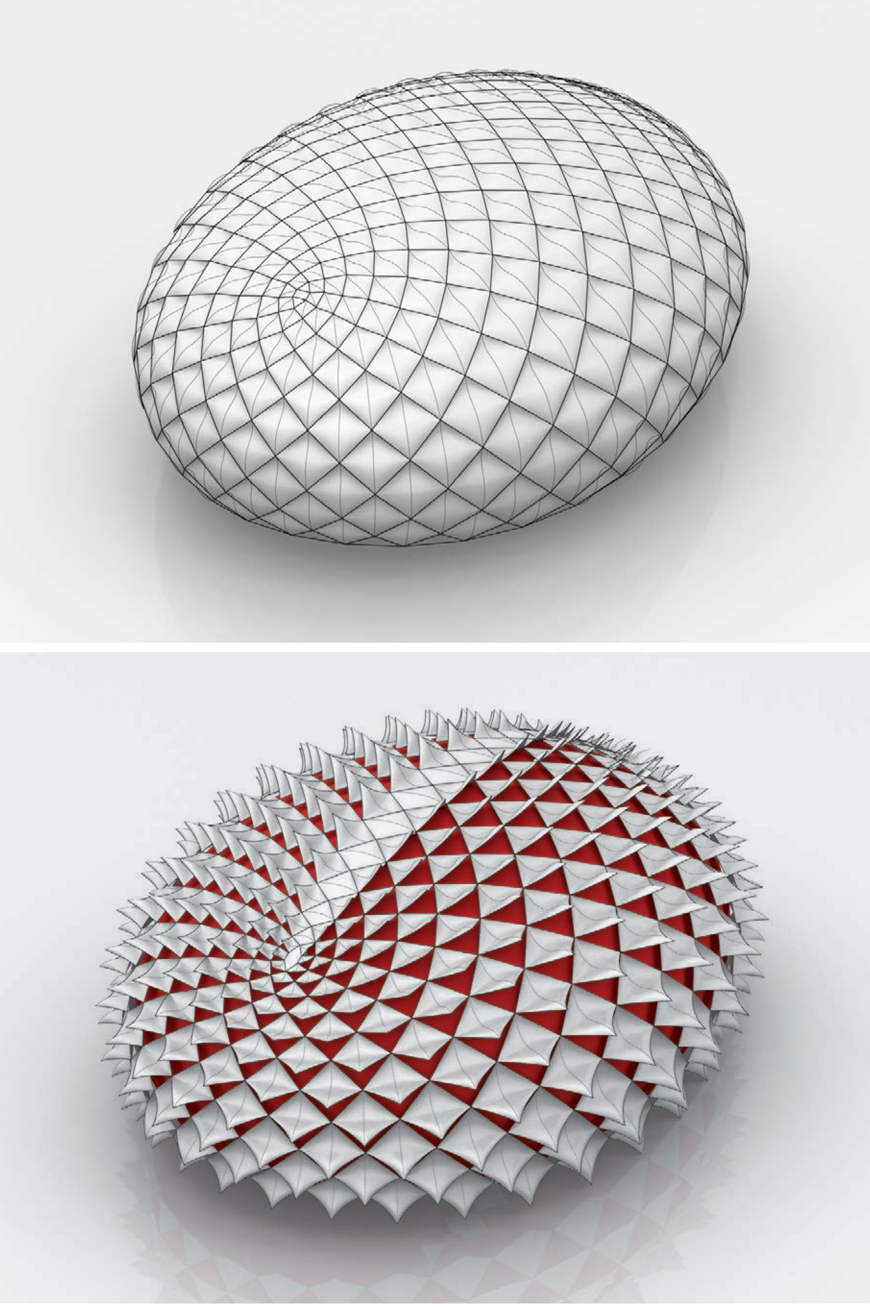


Figure 6.12: Cladding of the ellipsoid test body with the *Lilium*-inspired compliant mechanism.

model needs to be closely connected to a kinetic model in the FEM environment. In the first step, the lily-inspired mechanism was further abstracted by morphing the plant's tepal shape into a four-sided shingle (Fig. 6.14). Similar to the biological role model, two adjacent edges perform as actuators and drive the deformation of the shingle as they expand. To prevent cascading buckling effects and to enhance the leverage in the mechanism, the shingle surface is slightly undulated. This distinct shell geometry is beneficial because it is flexible in the moving direction while being rigid enough to transfer compression loads, for example due to wind pressure, to the main structure of facade.

Since the movement and simulation method of the lily-inspired component differs from the previous example, the panelization of the test-surface needed to be adjusted (Fig. 6.13). Firstly, it was necessary to model in true dimensions. Therefore, the ellipsoid was generated from three ellipses with the diameter of d1 = 8 m, d2 = 5.85 m, d3 = 3.90 m. By meshing this surface, one achieved differently sized panels and thus shingles with individual parameters. In the next step, all shingles were transferred into the FEM environment and assigned with material properties, boundary conditions, and heat-sensitive actuators. Despite their differences in scale, all shingles were given the same properties for their surfaces (thickness t = 2 mm, Young's Modulus of E = 12000 N/mm^2, αT = 17 x 10-6/K) and for their actuating edges (diameter = 20 mm, Young's Modulus of E = 3200 N/mm^2, αT = 85 x 10-6/K). Only this way was it possible to test whether the same material and actuation settings would

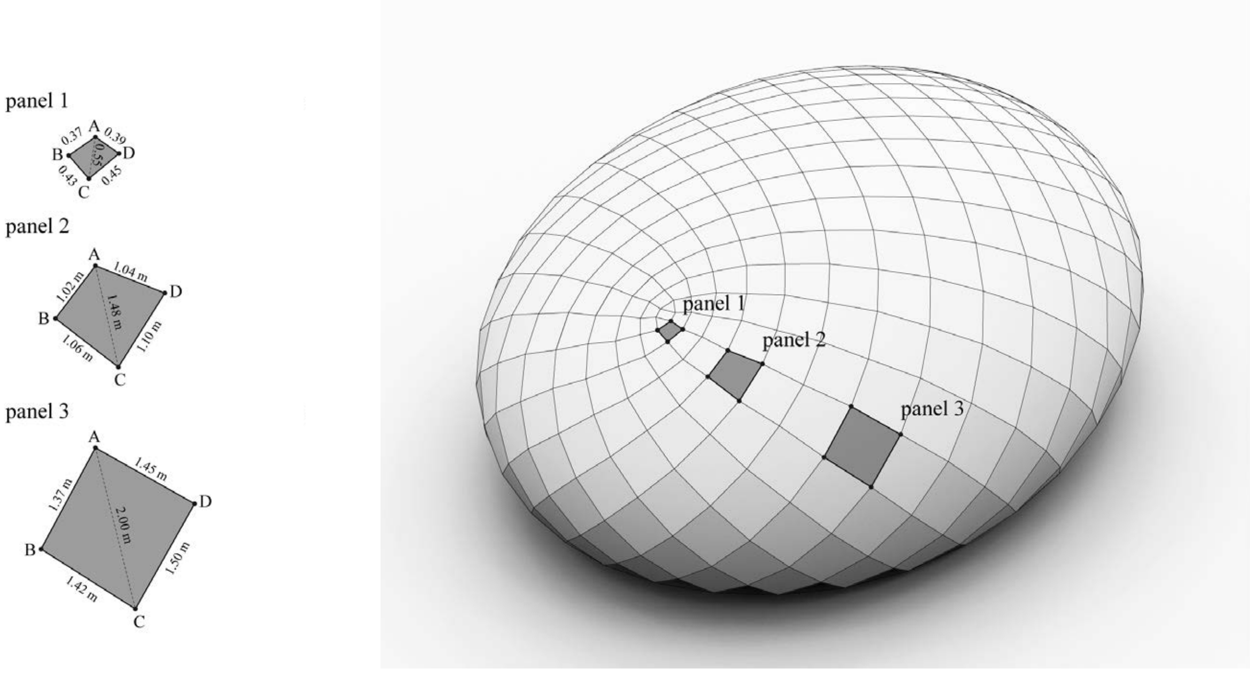


Figure 6.13: In order to clad the ellipsoid with the *Lilium*-inspired component, the test surface was given true dimensions and the panelization logic was modified.

function for all shingles, independent of their size and shape. Figure 6.15 shows, for example, the kinetic simulation of a small, medium, and large shingle. Based on these simulations, it was possible to clad the entire surface and generate open and closed conditions of the facade (Fig. 6.12).

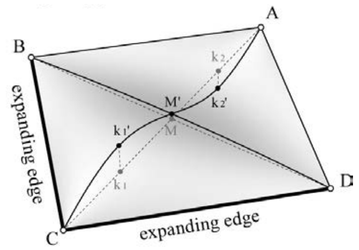


Figure 6.14: Parametric geometrical model of the *Lilium*-inspired shingle.

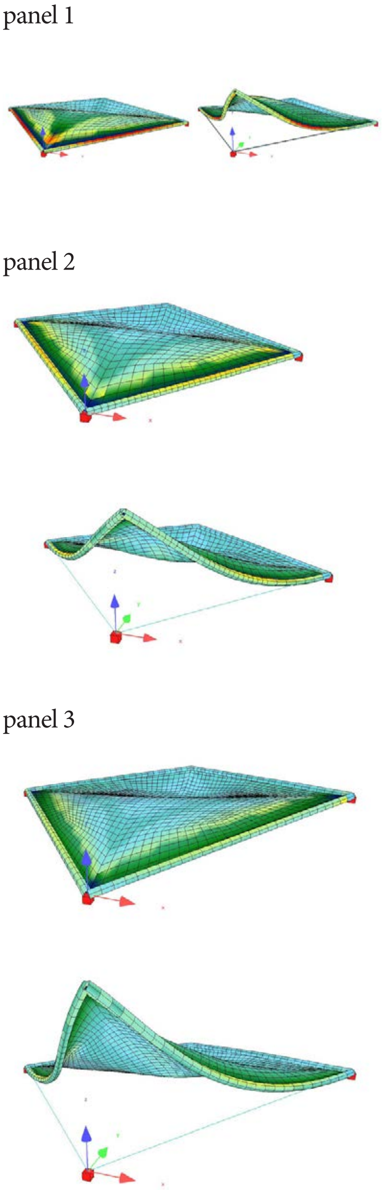
6.4.5. Flectofin® facade inspired by *Strelitzia*

Similar implementation strategies can also be applied to a third compliant mechanism that was inspired by *Strelitzia*. Here, the abstracted principle described in section 5.8 became the starting point for a number of development steps and resulted in the so-called Flectofin® Facade concept (Lienhard et al., 2011; Schleicher et al., 2011). The basic shading device consists of two lamellas that are attached to one beam element (Fig. 6.16). This doubles the effective shading area while requiring only one actuator. The interaction between lamellas and beam element was tested intensively in the digital and FEM environment in order to understand the relationship and adjustability of the various parameters. A holistic approach took physical and geometrical constraints into account by coupling the kinetic model of the FEM environment with the kinematical model and the panelization of the facade (Fig. 6.17). All information was integrated into one parametric design tool, with which it is possible to populate a given freeform surface with a desired number of shading devices (Fig. 6.18). In addition, this parametric design tool also allowed the simulation of the individual opening and closing movement of the Flectofin® devices. Here again, a small deflection of the beam element causes a sideways flapping of the lamellas. The Flectofin® component is thereby capable of achieving an opening angle between -90° to +90°. This freedom of movement is sufficient to fully cover and protect the facade in the open configuration. In the closed state, the effective shading area of the Flectofin® reduces drastically and affects the view from the inside only marginally.

Despite its functional performance, the intriguing movement of the lamellas also has a very strong visual effect on the facade. It creates different impressions of the surface ranging from elegantly curved and contiguously covered to sectionalized and almost spiny. This special aesthetic can even be intensified by choreographed movements of the individual Flectofins®, for example by actuating them with a small time delay.

6.4.6. Synergistic effects of tessellations and tiling symmetries

While studying different panelization and cladding methods for freeform facades, it became increasingly clear that the arrangement of the bio-inspired compliant mechanisms on the surface has a huge impact on their functionality and efficiency. Depending


panel 1

panel 2

panel 3

Figure 6.15: Kinetic model of a small, medium, and large shingle.

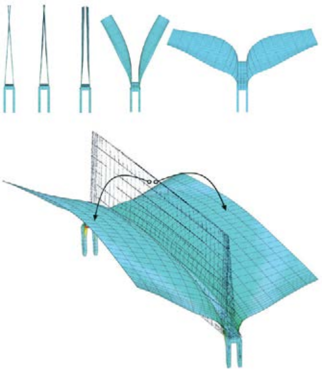


Figure 6.16: The *Strelitzia*-inspired Flectofin features two lamellas on one beam element and thus doubles the effective shading area.

on the chosen mechanism, some patterns are more suitable than others. This may be due to the fact that some components require a specific orientation in order to function properly as a sun protection. Another reason may be that only a specific tessellation can prevent an undesired interference or ensures a beneficial contact between the devices. Therefore, the tiling that is used to clad the facade offers another level of design freedom, in which smart formations and clusters of devices can create significant synergy effects. For example, neighboring components can be arranged in such a way that the location of their actuators coincide and only one actuator is needed to effectively drive an entire group.

In the previously discussed design tool, this idea was already integrated by providing more control about the quads in the mesh and their distinct reference to the flexible components. With this tool it became easy to generate different symmetry patterns either by changing the counting direction of the vertices in a quad or by

Figure 6.17: Exemplary free-form facade geometries with adaptable Double Flectofin® in open and closed configuration.

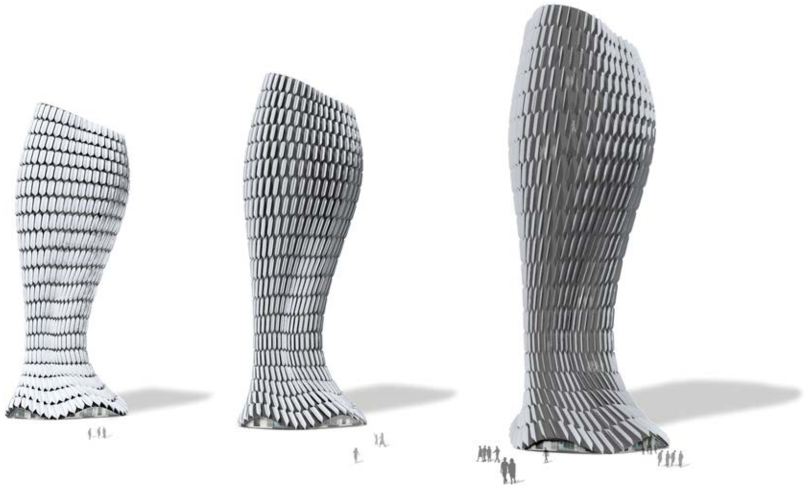
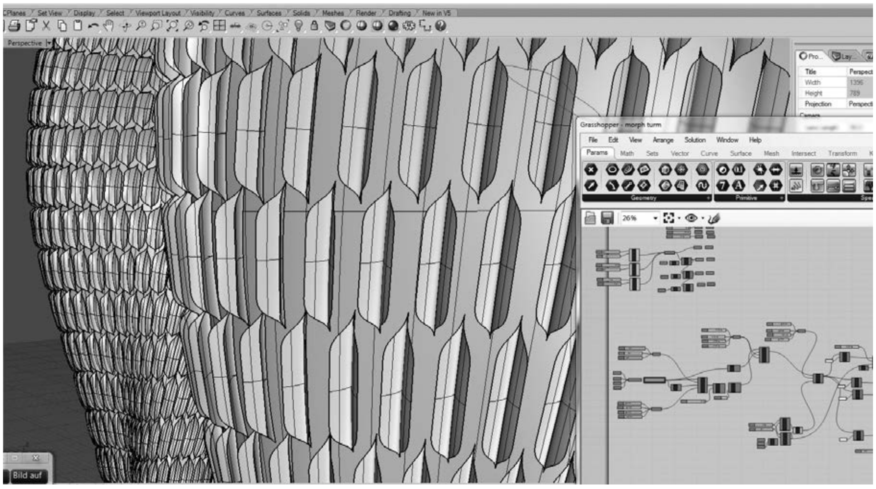


Figure 6.18: Exemplary free-form facade geometries with adaptable Double Flectofin® in open and closed configuration.



Title Perspect
Width 1396
Height 789
Projection Perspect

flipping its face orientation. Thereby, a single component can be attached to a panel in various ways and multiple components can be repeated in different types of tessellations. Changing the references allows for three key manipulations: translation, reflection, and rotation (Fig. 6.19). Based on these manipulation techniques, one can repeat a component, for instance, in seventeen wallpaper patterns, also known as planar crystallographic groups (Coxeter & Moser, 1972). A small selection of different tessellation patterns that can be generated with the *Aldrovanda*-inspired mechanism can be seen in Fig. 6.20-6.21.

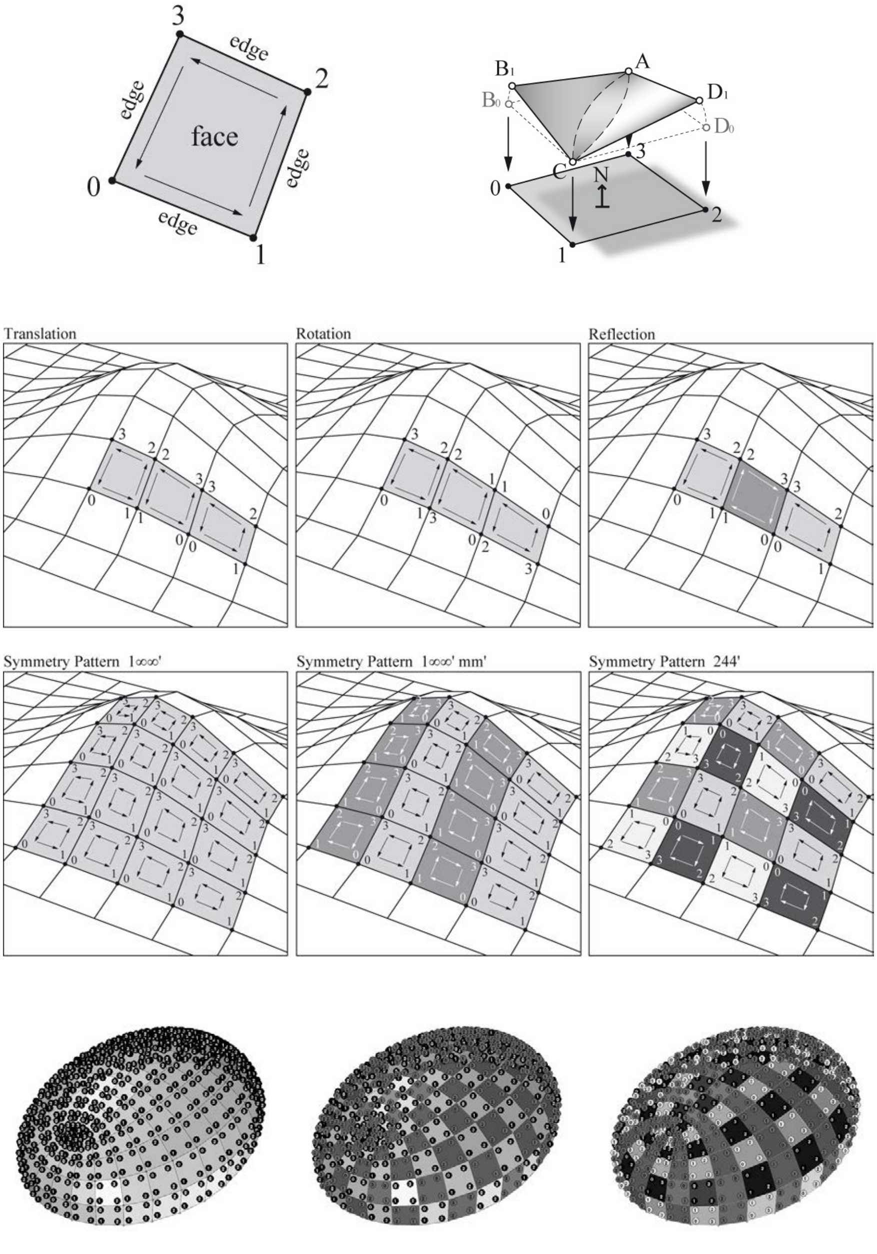


Figure 6.19: By controlling the numbering of mesh vertices and their relation to the applied bio-inspired component, one can generate different cladding symmetries and tessellation logics.

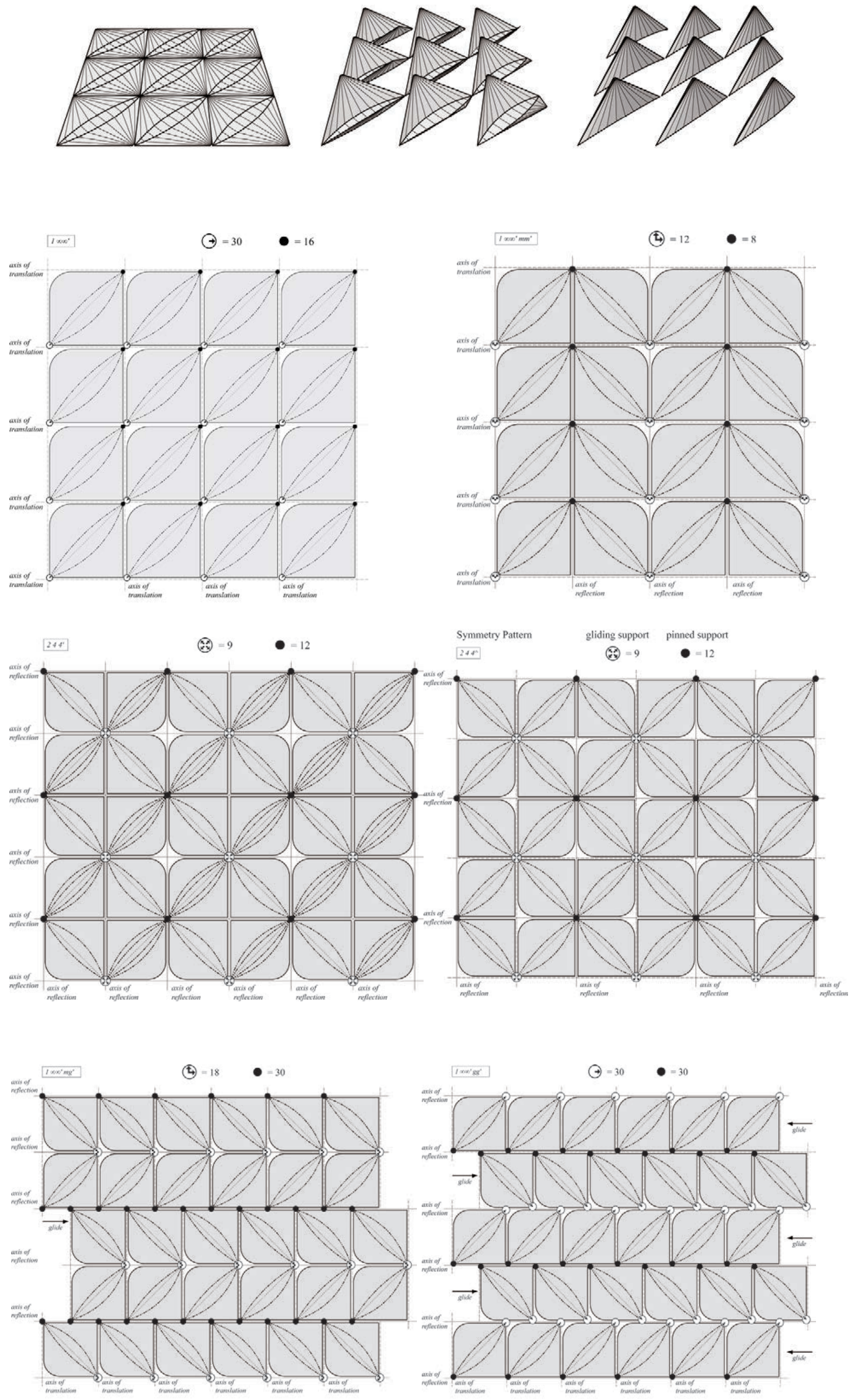


Figure 6.20: Individual components can be arranged in various symmetries, for instance, in the 17 wallpaper patterns.

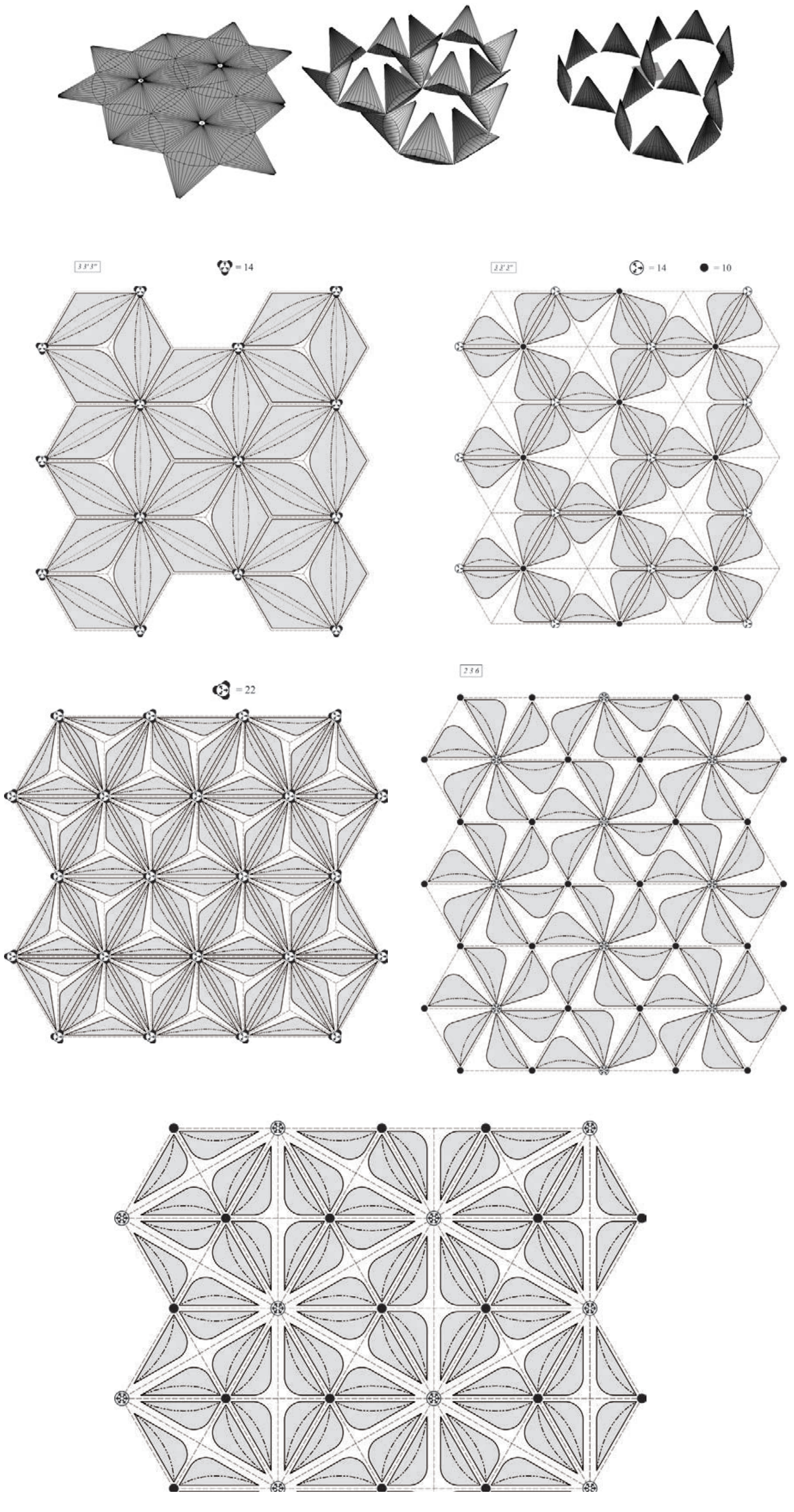


Figure 6.21: Some of these symmetry patterns bring synergistic effects with them and allow to drive a cluster of multiple components with the same actuator while others might be unfavorable and just increase the number of necessary fixtures and actuators.

6.5. Materialization and Prototyping

The use of flexible facade shading systems inevitably raises a string of questions regarding their materialization. One is left wondering whether there are any materials available that are flexible and strong enough and, if so, whether these materials can be used for constructions that need to be both load bearing and movable. To help address these questions, this section will refer back to the particular challenges of compliant mechanisms, which were discussed in section 2.5.4. The aim of this section is to seek out promising groups of materials and fabrication processes that either are already available today or are about to become more widely accessible in the near future.

6.5.1. Suitable materials for elastic kinetic structures

Unlike most conventional kinetic structures, materials for bio-inspired compliant mechanisms need to be chosen to maximize flexibility rather than stiffness. In order to follow that important guiding principle, one needs to remember that stiffness and strength are not the same, which allows the possibility of making a structure both flexible and strong (Howell, 2001). Unfortunately, it is all too easy to mix up the relationship between stiffness, strength, and deflection. A structure is of low stiffness when a small load can cause a relatively large deflection. Yet this characteristic reveals nothing about its strength. The term strength is a material property that specifies the stress that a structure can withstand before failure. The amount deflection under a given load, which appears before a structure is failing, is dependent on its stiffness and rigidity. A structure's flexural rigidity, however, results from its material properties and its geometry. Thus, one has two options to effectively maximize the flexibility of a structure either by changing its material settings or modifying its shape.

First of all, the selection of the starting material has particular importance. If one is searching for a suitable material for elastic kinetic structures, it is very helpful to have a closer look at the ratio of a material's strength to its Young's modulus. Figure 6.22, for example, lists various materials according to their strength-to-modulus ratio. In general, it can be said that those materials with a higher ratio can undergo much larger deflections and achieve smaller bending radii before plastic deformation and failure than those with a lower ratio. By directly comparing the material groups in this list, it becomes noticeable that the lowest ratio can be observed in the group of metals, followed by woods and fiber composites. The highest values can be found in the group of plastics and polymers. This material group seems to be particularly well suited for compliant mechanisms and elastic kinetic structures. It is not without good reason that plastics like polypropylene are the most frequently used materials for living hinges in shampoo bottles or other types of packaging. However, their relatively low Young's modulus indicates the disadvantage of this material group since it already implies that small external forces can cause very large deflections. For large-scale architectural applications, which often face a serious combination of dead loads, life loads, and environmental loads, this characteristic is rather unfavorable. These loads can cause significant forces, and therefore it is more reasonable to choose materials with a higher Young's modulus, as provided by some woods or fiber composites. Besides the initial selection of material, its respective fabrication and processing are also of particular importance. Here, especially the two groups of thermoplastics and fiber reinforced polymers offer promising production methods and thus will be further examined.

6.5.2. Thermoplastics and 3-D printing technology

Thermoplastic polymers are generally well studied and already widely established in many industries. Thanks to manufacturing processes like injection molding, objects made out of thermoplastics and thermosetting polymers can be produced in nearly any form as long as their shape doesn't conflict with the molding process itself and can be taken out of the mold cavity. Thermoplastic polymers are also widely used in architecture for a variety of parts, from small components, larger panels, and wide spanning membranes. Recently, however, these polymers are gaining more and more importance because of the rise of 3-D printing technology. Due to the ever-greater precision and increasing resolution of 3-D printers, it became much easier to customize the geometry and internal structure of plastic parts. In addition, recent advances in material depositing make it even possible to fine-tune a print down to 16-micron layers or allow for using different materials with various structural and aesthetic qualities in one and the same process.

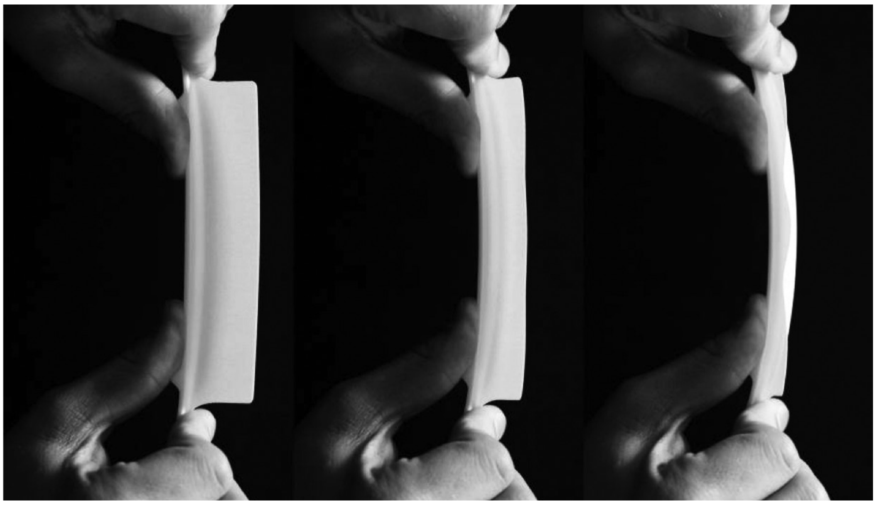
Material	Flexural Young's Modulus E [N/mm^2]	Flexural strength Fyk [N/mm^2]	strength-to-modulus	min. bending radius[1]
Steel - S355	210000	355	**1,7**	493*t
Spring Steel	210000	1100	**5,2**	159,1*t
Aluminum	70000	330	**4,7**	176,8*t
Ash Tree	18100	58	**3,2**	260,1*t
Plywood	11000	51	**4,6**	180,1*t
Bamboo	19129	213	**11,1**	74,8*t
GFRP - P	23000	300	**13,0**	63,9*t
CFRP - HAT	165000	2800	**17,0**	49,1*t
Polyamid 12	1200	45	**37,5**	22,2*t
RGD5160-DM	2600	75	**28,8**	28,9*t
Polypropylene	1500	55	**36,7**	22,7*t

[1] Min. bending radius r is dependent on thickness t and 60% of tensile strength

Sources: Lienhard, 2014; EOS GmbH; Objet Geometries Ltd

Figure 6.22: This list compares various materials for their suitability to be used for compliant mechanisms. A helpful indicator in this context is the ratio of material strength to Young's modulus. Materials with a higher ratio can undergo larger deflections before failure.

Figure 6.23: Fully functional Flectofin® model that was 3-D printed as 'onepiece mechanism' by Selective-Laser-Sintering (SLS).



3-D printers like the EOS Formiga series or Objet's Connex printer offer flexible nylon-based materials such as Polyamide 12 or RGD5160-DM. With this technology it is possible to laser-sinter small models of the Flectofin® principle, for example, which feature an adapted stiffness distribution and are fully functional as soon as they come out of the printer (Fig. 6.23).

6.5.3. Fiber-reinforced polymers and composites

Perhaps the most promising material for the translation of bio-inspired compliant mechanisms to larger scale architectural applications, however, is the material group of fiber composites or so-called fiber-reinforced polymers (FRP). FRPs synergistically combine the benefits of two or more constituent materials in their matrix and fiber reinforcement. While the polymer matrix surrounds and supports the fibers, the fiber reinforcement enhances the matrix with its special mechanical and physical properties. The binding matrix usually consists of thermosetting and thermoplastic polymers like epoxy resin or unsaturated polyester resins. The fibers on the other hand can be made from various materials but most common are glass-, carbon-, ceramic, or natural fibers. Together the matrix and reinforcement form a composite that may encompass some interesting advantages compared to typical building materials like steel, aluminum, or wood. Depending on the laminate, FRPs can be made very lightweight with a high tensile strength and stiffness for its mass. Carbon fiber-reinforced polymers (CFRP), for instance, can have a very impressive strength-to-weight ratio that outperforms steel and aluminum. For this reason, high performance industries like aeronautics and automotive industry have increased their focus on this material over the past decades. In addition, fiber-reinforced polymers have the advantage of being thermally stable and generally change their shape only very little with the temperature.

What makes FRPs particularly interesting in the context of this research, however, are two main aspects: Firstly, FRPs have very impressive fatigue and bending properties, which enable them to undergo large elastic deformations and cyclical loading. Secondly, they allow for fine-tuning their innermost structure and lay-up, for instance by changing aspects like fiber orientation, fiber density, weave patterns, and selective layering. This allows for highly differentiated local adaptation and tailor-fit material make-up. For example, one can safe a lot of weight and significantly optimize a structural part by determining the strengths and directional paths of acting external forces and placing the stability providing fibers according to the lines of principle stress. This way, it is possible to ideally match a part to its structural and functional needs and to balance between weight, safety, and performance.

6.5.4. Prototyping of the Flectofin®

To emphasize the significance of this novel possibility for designing a material and structural part from the inside out, the Flectofin® principle was built with fiber-reinforced polymers (Lienhard et al., 2011). This research was done in a large team effort between the Plant Biomechanics Group (PBG) at the Albert-Ludwigs-University of Freiburg, the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart, the Institute of Textile Technology and Process Engineering (ITV) in Denkendorf as well as with the industrial partner clauss markisen Projekt GmbH.

After a comparison of different high modulus composites, glass fiber-reinforced polymers (GFRP) were selected for the fabrication of the Flectofin® lamella because glass fibers are less costly than carbon fibers, more translucent, and have a better weather resistance than aramid fibers for example. A series of glass fiber woven fabrics, which differed in fiber lay-up and area weight, were tested for their stiffness, resistance against wind-induced vibration, and the targeted 90° bending requirements near the beam profile of the Flectofin®.

With the help of several prototypes, a perfect setting was found for the production of a 2 m long Flectofin® lamella (Fig. 6.24). The desired high strength and low stiffness properties were achieved by laminating very thin plain-woven fabrics with an area weight of 80 g/m^2 in a set of layers. The special feature of this laminate is that the stiffness varies along its width. It is stiffer near the beam profile and softer towards to outer edge of the lamella. This gradient in stiffness was made possible by reducing the thickness of the GFRP laminate and decreasing the number of layers from 8 to 4. Being stiffer in the location where the Flectofin® has to bend the most

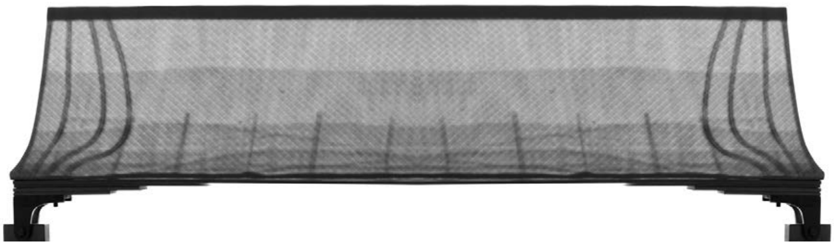


Figure 6.24: The Flectofin® was laminated out of GFRP with gradient stiffness properties. It is stiffer near the backbone beam and gets softer towards the edge of the lamella. Additional rovings support the lamella locally and help avoiding critical notch stresses.

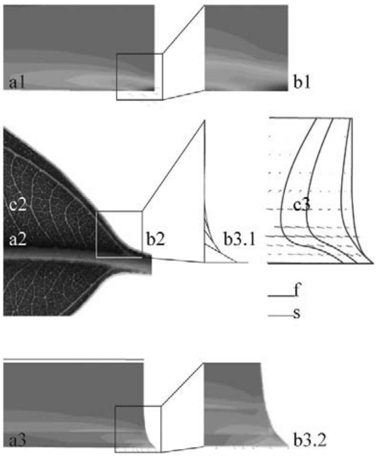


Figure 6.25: The *Eucalyptus* leaf inspired the placement of additional rovings, which helped reducing stress concentrations.

brings the advantage of distributing the acting forces over a wider area while avoiding local stress concentrations. In order to further reduce tension forces in the Flectofin®, especially where the lamella touches the beam profile, glass fiber rovings were spread out along the direction of forces. Interestingly, the solution to this specific technical problem, how to best combine a softer lamina with a stiffer beam element, was found by using reverse biomimetics as a method and by searching for biological role models with a similar structural configuration. Here, the inspiration came from *Eucalyptus* leaves, which reduce stress peaks through a combination of optimized contour lines and fiber orientation (Fig. 6.25) (Lienhard et al., 2011). The optimized shape of the *Eucalyptus* leaf can be explained and reproduced with the method of tension triangles (Mattheck, 1997). With these changes to the contour geometry of the Flectofin® lamella, the maximum notch stresses could be reduced by approximately 60% of the permissible stresses for standard GFRP. For the matrix, an ultra-flexible epoxy resin was chosen and treated with several dyestuffs to satisfy specific optical demands. In order to achieve the essential high quality of the laminate, the Flectofin® was fabricated in two parts and then joined together. While the beam element is only an off-the shelf extrusion profile, the lamella was custom-made by researchers of the ITV Denkendorf using a so-called Vacuum Assisted Process VAP®. Here, a special layer of air-permeable foil is used during the fabrication process in order to avoid that disruptive air bubbles might get trapped inside of the laminate. This enhances the quality of the only 2 mm thick laminate significantly and makes it a lot less sensitive to fatigue.

Since fatigue performance is one of the key issues for elastic kinetic structures in general, the researcher team built a full-scale facade mock-up to test the actual bending behavior of the Flectofin® (Fig. 6.26-6.27). This prototype was built in collaboration with the industrial partner clauss markisen Projekt GmbH. The mock-up featured multiple linear motors that where individually controllable and allowed for cyclical loading tests and various motion scenarios of up to five lamellas. The tested Flectofins® were 2 m in length, 0.25 m width, and 50 mm thickness in the beam profile and 2 mm thickness of the lamella. They required a support displacement of only 30 mm in order to be fully triggered and flipped by 90°.

Figure 6.26: Mock-up facade clad with three Double Flectofins®.

6.5.5. Scaling of the Flectofin®

In addition to the selection of an appropriate material, another central question for the manufacturing of bio-inspired compliant mechanisms is whether these systems can be scaled up significantly to match architectural dimensions. Since this question is of great importance for the applicability of bio-inspired compliant mechanisms for large-scale constructions, one member of the Flectofin® team, Julian Lienhard, has examined the structural potentials and limitations that are related to scaling of these mechanisms more closely (Lienhard & Knippers, 2013; Schleicher et al., 2013; Lienhard, 2014).

Figure 6.27: Flectofin® facade can open and close the *Strelitzia*-inspired lamellas and thus provide shading on demand.

Based on this research, one can say that scaling compliant mechanisms is in principle possible on the condition that one has to conciliate the system's geometrical and elastic stiffness. While the geometrical stiffness results from global curvature and the relationship of multiple constraint members, the elastic stiffness is defined by individual material properties and geometrical characteristics. Scaling a mechanism like the Flectofin® is possible. It was prototypically validated for 3-D printed models of about 0.2 m length and the 2 m long GFRP lamellas. Furthermore, the Flectofin® team has made a feasibility study for lamellas with a length of 14 m.

As shown by the comparison of multiple slender profiles with varying dimensions, Lienhard and Knippers (2013) revealed that scaling of elastic systems is highly dependent on the influence of dead load and stability. The decisive role for a system's structural integrity is played hereby by its resistance to snap-through buckling failure. Compared to other structural systems, stability in flexible structures cannot simply be achieved by increasing elastic stiffness, since the element thickness is limited by material strength and bending curvature. However, there are ways to influence the stability of a structure. One way to increase a structure's stability it through tension stresses because they, unlike residual compression stresses can generate a self-stiffening effect. The Flectofin® lamella, for example, shows an increase in stability in its deflected state due to the predominance of tension stresses within.

During the course of these investigations it was noticeable that the up-scaling of a compliant mechanism like the Flectofin® seems to be much easier than scaling it down. This is due to the fact that the bending radii scale proportionally to the geometry and consequently cause smaller local stresses. The constant dimensions of the fibers, independent of the component size, usually give another reason. So while a 2 m long lamella was built with a thickness of 2 mm, a significantly larger 14 m long lamella only required a thickness of 8 mm. It is very likely that this thickness can even be reduced further when fine-tuning the laminate's anisotropy and local stiffness distribution to the extreme. In the end, however, scaling and material optimization cannot continue endlessly. Normally, a limit is reached when the dead load of a structure becomes the predominant factor in the system and overshadows every other positive scaling effect.

6.6. Outlook - Thematic Pavilion EXPO 2012

An opportunity to actually implement compliant mechanisms and flexible materials on a larger scale architectural project has opened up during the EXPO 2012 in Yeosu, South Korea. For this grand international festival, the architecture office "soma" from Vienna has envisioned a theme pavilion with the name "Ocean One" as an eco-friendly landmark and trend-setting example for this future-oriented exhibition. Following the EXPO theme "The Living Ocean and Coast," this permanent building was planned as the core facility during the time of the exhibition as well as museum and showroom for the time thereafter.

A very special highlight of this building is its kinetic facade with 108 individually controllable lamellas (Fig. 6.30). What looks a little like shark gills, is in fact an adaptive building system that controls the solar exposure of the facade in the daytime and provides striking animated lighting patterns during the night. The office "Knippers Helbig Advanced Engineering" did the technical concept and structural planning for this facade. The facade has a total length of 140 m and is designed to withstand very high wind loads of up to 35 m/s at the Korean coast.

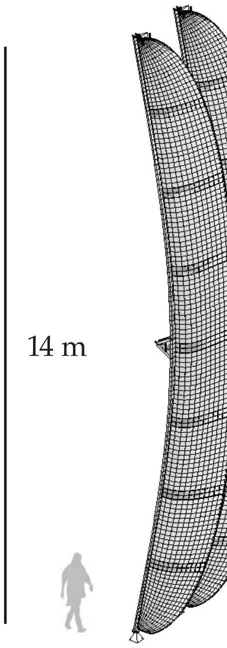
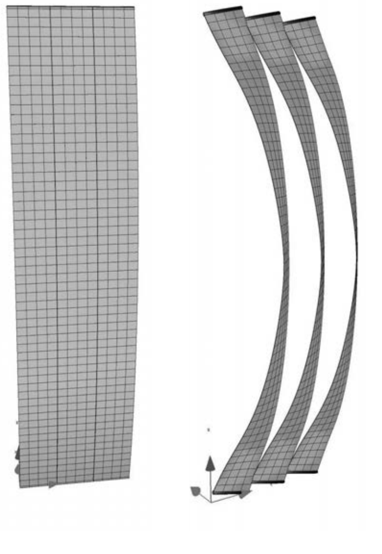


Figure 6.28: A feasibility study tested a significantly scaled-up version of the Flectofin® that reached a length of 14 m.

During the early planning phase of this project, the architects and engineers considered the implementation of the Flectofin® for this facade. They asked the Flectofin® team for consultation and feasibility studies. Even though technically possible, the Flectofin® did not meet all structural and aesthetic requirements and was therefore not pursued any further. However, inspired by the research on plant movements, another kinetic system was developed by Knippers Helbig, which is also based on elastic deformation triggered by the failure mode of shell buckling (Knippers et al. 2012). The final lamella concept is made of slightly curved plates, which are supported by two hinged corners at the top and the bottom. In the adjacent corners, two servomotors apply a compressive force in the plane of the lamellas, which leads to a linear displacement of the corner points and a controlled buckling deformation (Fig. 6.29). This compliant mechanism shows locally smaller strains than the Flectofin®, but has the disadvantage of not being able to open the facade completely. The achieved aesthetics and freedom of motion, however, matched perfectly the initial design intentions of the architects and offered a more favorable ratio of structural stability and actuation energy than the Flectofin®.

Figure 6.29: Kinetic structure based on shell buckling. Servomotors at two corners of each lamella trigger a controlled buckling deformation.



The final kinetic facade was built in collaboration with Hyundai Engineering & Construction Co. Ltd. The 108 elastically deformable lamellas were hand-laminated out of GFRP and ranged in length between 3 m and 14 m. Apart from a stiffener at the edge that has to bend less, the lamellas only needed a thickness of only 9 mm to comply the high static needs. The resulting kinetic facade has a fascinating structural behavior. In the open configuration where the lamellas are fully deflected, for example, the curved geometry and the residual stress state result in a very rigid system that deforms only a few millimeters under high wind loads (Fig. 6.31). In the closed configuration on the other hand, the adjacent lamellas begin to touch each other and can even be clamped together by using the servomotors in reverse to pull on them. This way the facade can withstand even the strongest storms without damage (Fig. 6.32).

6.7. Summary

In summary it can be said that both the kinetic facade of the Thematic Pavilion at the EXPO as well as the Flectofin® mock-ups have been made possible as a result of the functionalization of elastic deformations. These deformations are exactly the kinds of non-desirable cases of stability failure, which in classical engineering would need to be avoided at all costs, by using sophisticated nonlinear analyses and complicated bracings. Even though the Yeosu facade does not follow the abstraction of the plant movement directly, prior analyses of these biological concept generators led to a deeper understanding of the biomimetic potential. This encouraged the team to look for solutions outside of traditional designing and constructing methods and to go beyond preconceptions, such as avoiding disproportionate deformations and stability failure modes. The examples of the Flectofin® and the EXPO facade show that a linear understanding of biomimetics may only be sufficient if the focus is on the abstraction of single functions as is the case in technical products such as the Flectofin® lamella. In architectural tasks, however, differing requirements between the aesthetics and functionality have to be met in a given set of defined boundary conditions. In the context of architecture a linear abstraction process is, therefore, difficult to maintain. Instead, an expanded definition of biomimetics is required. This work has shown that the analysis of natural forms and motion principles have the potential to inspire architects and engineers in such a way that they use fundamentally new strategies in architectural design and follow new approaches to implement these ideas in technical constructions.

Figure 6.30: Ocean One pavilion at the Expo 2012 in Yeosu features a kinetic facade with 108 bendable lamellas that allow for controlled light exposure of the facade.

Figure 6.31-6.32: The up to 14 m high lamellas can be opened and closed individually and thus enable an impressive transformation of the building envelope.

7. RESEARCH CONTRIBUTIONS AND FUTURE OUTLOOK

'TRANS-Disciplinary: Seemingly contrasting fields, when brought together, inform each other through the collision of ideas, transform into a new dimension greater than each alone, and transmute beyond any preconceived expectations.'

- Hiroshi Ishii (Keynote at NIME2014 on 7/2 in London)

7.1. Overview - What has been achieved and what could be next?

The final chapter reviews the theoretical, methodological, and technological contributions of this thesis and tries to envision potential research topics, which it might initiate in the near future. This overall analysis will not only summarize the individual implications of this thesis to the obviously related fields of mechanical engineering, basic biological research, and architectural design but also reflect on how the thesis was able to bind the different research lines together into one coherent narrative. In order to better promote this transdisciplinary working process, this chapter will recall the core approach and ideas that enabled this biomimetic knowledge transfer between the disciplines.

It is the hope of the author that this summary will provide helpful orientation in a complex and multi-faceted problem set on the one hand, and be an invitation for further research of this fascinating field on the other. This final chapter should be read as source of inspiration, which might spark new ideas and encourage the next generation of researchers to contribute in their own way.

The following summary is structured according to the different chapters of this thesis. This summary will also take the opportunity to point out all those unresolved issues that could be interesting starting points for future research while emphasizing the significant wider context of this thesis. The reflections on the theoretical contributions of this thesis refer to the first chapters with their analysis and association between *Kinetic Structures in Design* and *Kinetic Structures in Biology*. The reflections on the methodological contributions are related to the fourth chapter on *Methodology* and its attempt to clarify a suitable biomimetic working process that acts as framework for this thesis. Finally, the technical contributions of this thesis reference the chapters on *Case Studies* and *Implementations* with their exemplary analysis of biological role models and their transfer of underlying motion principles to flexible devices in architecture.

7.2. Kinetic Structures in Design

Following a general introduction, the second chapter on *Kinetic Structures in Design* is of particular importance for the further course of this thesis because it provides a theoretical background in the common approach to mechanical design. By recalling the innovative leap of the Industrial Revolution, this chapter raises the awareness how one specific era has shaped the mindset for generations of engineers until today. The theories, methods, and conceptions that were developed during that time gave birth to the scientific treatment of mechanics that we now refer to as classical mechanics. It is because of this profound legacy that the Industrial Revolution is still affecting the present paradigm in engineering.

The first key finding of this chapter is that engineers still tend to apply a traditional way of thinking to their design of kinetic structures, which prioritizes rigid-body mechanics. Typically for this approach, machines consist of multiple rigid elements that are linked together with distinct hinges and gain their movability mainly by a clever use of mechanisms that provide a mechanical advantage. These so-called simple machines are the essential building blocks in mechanical engineering and their range of classification and possibility of combining defines the achievable design space.

The second key contribution of this chapter is that it draws the readers attention to the topic of flexures and compliant mechanisms. Having emerged out of the necessity to design kinetic structures in an application scale that is considered to be too small for rigid-body mechanics, this alternative construction principle distinguishes itself from the previous one by functionalizing flexibility. Compliant mechanisms deliberately take the flexibility of their members into account and move by means of large deformations. This clever use of elastic material behavior and structural instabilities is usually only known from biological systems, which makes compliant mechanisms a highly suitable bridge to the next chapter on kinetics structures in biology.

One aspect that remained open at the end of the chapter and may be worth following up upon is whether compliant mechanisms could be classified analogously to the simple machines in classical mechanics. It would require intensive efforts to investigate whether it is possible to reduce flexures down to essential building blocks that provide a unique mechanical benefit. If this is possible, however, it would probably allow ignition of a similar creative process to the one started by Franz Reuleaux. It would open the door to the design of even more complex flexible systems just by stringing and recombining these basic building blocks together.

7.3. Kinetic Structures in Biology

The third chapter on *Kinetic Structures in Biology* provides the second part of the theoretical background to this thesis. It presents a radically different approach to the challenge of designing movable structures by looking into nature as source of inspiration. The aim is to offer an interesting counterpart to the rigid-body mechanics of the previous chapter by taking a detailed look at the flexible and adaptive motion behavior found in plant movements. In this context, plants are particularly fascinating because their movements don't rely on the presence of rigid links and distinct hinges but are mainly due to material properties such as high elasticity and resilience against failure. With these characteristics, plants seem especially well suited to be discussed in comparison to the compliant mechanisms of the previous chapter, even though, of course, plants are much more complex in their composition and buildup.

By offering an unusual perspective on the topic of kinetic structures, this chapter plays an important role for the narrative of this thesis. It contributes greatly to the topic by giving a good overview of the differentiating features, which are used in the classification of plant movements. With a closer look at taxes, tropisms, and nastic movements, this chapter shows that plants are far from being static but instead have a whole spectrum of motion principles available to react and respond to their environment. This chapter also pays attention to the special role of motors and mechanisms that drive and gear the plants' motion behaviors. This includes, for instance, the reaction to external loads, internal growth and hydraulic mechanisms, or elastic instabilities such as snap-buckling and other clever failure types that are capable of amplifying a motion to gain a benefit. Finally, this chapter ends with a review of why plant movements have the potential to become role models for technical kinetic systems and supports this statement with a table showing a contrasting yet revealing juxtaposition of rigid-body mechanisms, compliant mechanisms, and flexible plant movements.

Again, this chapter also scratches only the surface of a much more profound research direction, which provides many opportunities for deeper investigation and actions. From a biological perspective, for example, one may wish to further refine the classification system of plant movements based on the cross-linked systemic relationships between sensors, actuators, and the means for their control and regulation. Another possible contribution to the topic might be to expand the source of inspiration and to consider other biological role models as well. An extended screening could, for instance, include motion principles of ferns, mosses, fungi, and other symbiotic organisms like lichens. From a technical point of view, one might be interested in questioning the categories and weighting of the classification. A different approach could filter the screening, for instance, based on the technical reachability of the observed motion principle. Plant movements that are driven by a simple, locally applied force may be emulated much easier by technical means than motion principles that require multiple complex cellular interactions at different places of the moving organ. Finally, another selection criteria could reevaluate the screening in favor of the used energy source that triggers the motion. From a technical point of view this can make a big difference since the types of stimulation may render different implementations. Motion principles that are based on changes of humidity or temperature, for example, might be better suited for the development of passive and decentralized adaptive systems while other movements that are evoked by inherent chemical signals, changing action potentials, or locally applied forces may be better role models for the development of smart materials or centrally controlled kinetic structures.

7.4. Methodology

The fourth chapter supports this thesis with a methodological background. It envisions a novel transdisciplinary working process, which could act as a framework and guide the further course of the study. Moreover, the chapter establishes two focus areas. A general reflection on the emerging science of biomimetics and its overarching ideas on the one hand, and a road map how biomimetics could be applied, in particular in the context of this thesis, on the other. The main goal is to offer more than just an abstract discussion of a topic that currently hits the zeitgeist. Instead it is also an attempt to suggest a step-by-step instruction for its use.

The first part of the chapter offers an exploration of the biomimetic approach. By initially defining its terms and clarifying its motives and objectives, it is possible to further contemplate about the general and specific challenges, which this newly developing field is facing. The second part of this chapter is based on the author's personal experience. Based on these impressions, the second part aims to map repeating themes and emerging trends in biomimetics as they relate to the conducted research in this thesis. This section describes a gradual knowledge transfer, which usually starts with a screening of biological role models. This is followed by the disclosure of the motion principles involved and the remodeling of the bio-inspired mechanism with technical means. The final step of this road map suggests the use of gained knowledge to inform a possible application development, such as the conceptualization of novel flexible components. for the field of architecture.

Despite its well-intentioned attempt, this chapter remains the most vague and unresolved, which is not particularly surprising. With biomimetics, a field was chosen that is not yet recognized as scientific discipline precisely because it lacks a better understanding of its general theories, methods, and working processes. Finding a common language is a challenging task and requires more work in that area. Also the proposed road map is at most only a subjective suggestion that will probably look very different for other projects and research lines. Future researchers could in turn compare the map with the process sequences in their own projects and based on that expand or restructure the map.

7.5. Case Studies

The fifth chapter is called *Case Studies*. It is the most substantive and targeted chapter and deepens the technical aspects of this thesis. The main contribution of this chapter is the practical implementation of the previously envisioned biomimetic working process. By using seven plant movements as example, this chapter demonstrates how the plants' underlying motion principles can be revealed, understood, and abstracted into bio-inspired compliant mechanisms. In doing so, the technological transfer procedure follows a certain sequence of steps, which starts with a description of the biological role model, its functional morphology, and the observed plant movement. This is followed by the disclosure of the underlying motion principle. The gained knowledge of the mechanism's functional-morphological relationships is then translated into an abstracted bio-inspired compliant mechanism and tested for its mechanical variability and consistency. The first example examined in this way is the opening and closing motion of stomatal pores in plant leaves. This reversible plant movement results from multidirectional changes of two interacting cells. Their volumetric swelling and shrinking affects the pore in its aperture and thereby allows the plant to exchange gases or evaporate water. The second example deals with the leaflet motion of *Oxalis* (Oxalidaceae). This plant movement is also based on multidirectional changes of specific cells but in this case it is the volumetric swelling and shrinking of an entire cell cluster called pulvinus that drives the motion. The third example describes the blooming motion of *Lilium* (Liliaceae). The tepals of this flower undergo unidirectional changes along their edges, which causes a differential expansion at the perimeter of the tepal and results in an opening movement. The fourth example of *Ipomoea* (Convolvulaceae*)* flower has a comparable mechanism yet shows its use in an interestingly different configuration. The fifth example is the trapping mechanism of the Venus flytrap, *Dionaea* (Droseraceae). This plant's trapping leaves move due to a stress differential caused by bidirectional changes in varying surface layers. This initial motion is then further amplified and significantly accelerated by a structural snap-buckling effect that arises from the shell geometry of the trap leaves. The sixth example is the trapping movement of another carnivorous plant, called *Aldrovanda* (Droseraceae). It couples the unidirectional changes of a distinct midrib with bidirectional changes of adjacent surfaces. This example is particularly fascinating since it features a curved-line folding mechanism to accelerate the motion. Finally, the seventh and last example is the pollination movement found in *Strelitzia* (Strelitziaceae). This flower features a mechanism that allows for a reversible movement whenever an external load is applied to the plant at a specific point.

All seven plant movements are fascinating role models for bio-inspired compliant mechanisms and promise a high potential for technical applications. Although favored by the author, these role models are certainly not the only ones. Instead, the plant kingdom offers a whole plethora of movements and complex motion principles to learn from. Future researchers could, therefore, just pick another plant and test the demonstrated transfer process on a different case study. More targeted research might, for example, focus on one distinct motion principle (e.g. differential cell expansion) and compare its use in various plant species or analyze its mechanical characteristics among multiple plants of the same species. Another starting point for further research could be to expand the simulation techniques beyond plates and shells towards more complex solid, porous, or multi-cellular structures. And finally, another valuable contribution to the topic would be the development of better evaluation criteria through quantifiable and measurable aspects, which would help to compare different mechanisms to each other or assess the degree of efficiency.

7.6. Implementations

The sixth chapter of this thesis, called *Implementations*, adds the final part of the technical contributions. It considers a practical use of bio-inspired compliant mechanisms in the field of architecture. What makes this chapter significant is its attempt to lift this study from basic research to the level of early product development. By addressing the problems of a specific area of application, in this case the architectural task of shading double-curved facades, this chapter confronts the newly developed technology with challenging yet generally predictable conditions. In this framework, advantages and disadvantages of flexible kinetic structures can be discussed and possible implementation scenarios can be envisioned. The aim thereby is not only to suggest the replacement of already existing technical solutions but to envision possible new applications as well.

This chapter begins by emphasizing the significance of facade shading systems for the built environment. This is followed by a general explanation of the geometrical and mechanical challenges, which these architectural devices have to match. The chapter, however, also goes one step further and conceptualizes shading devices out of flexible structures. Of course, using compliant mechanisms for double-curved facades may have some severe difficulties but also renders unique opportunities. The chapter illustrates these relationships by designing shading systems for an ellipsoid. This test body is characterized by a complex geometry and its panelization and cladding is anything but simple since it requires the individual scaling and distortion of the flexible components. It is the key contribution of this chapter to show that the previously discovered bio-inspired mechanisms can in fact be adapted to this geometry while remaining fully functional. This potential is demonstrated by means of three exemplary facade systems. The first one is a facade that implements curved-line folding components inspired by *Aldrovanda*. The second facade concept features flexible shingles inspired by *Lilium*. The third facade uses the patented Flectofin® that was inspired by *Strelitzia*. Besides the design, another objective of this chapter is to consider the materialization and prototyping of these structures. This chapter contains a screening of materials through a closer inspection of thermoplastics and 3-D printing technology as well as fiber-reinforced polymers and composites. The prototypical use of these materials is demonstrated on the Flectofin®. Finally, this chapter ends with an outlook to the thematic pavilion on the EXPO 2012, which features a closely related kinetic facade and impressively shows that this technology is ready for implementation.

In practical terms, this final chapter is probably the most interesting one and offers many starting points for future work not only in architecture but also for many other industries as well. The here-implemented bio-inspired mechanisms are universal and could also be used for many other applications. Smart flaps and wings for aviation or adaptive body parts for the automotive industry are only two of many possible fields of application that come immediately to mind. Within the field of architecture at the moment, this study is not more than just a small seed from which various research lines could flourish. Future designers could investigate, for example, how climatic requirements may best transform the shapes and tilling symmetries of these shading systems. Material scientists and engineers could devote themselves to increasing the durability of elastic materials in the most effective way. At the end of this work, the author is left with the good feeling that there are really no creative boundaries for the next generation to build up on this work. So off you go!

APPENDIX

The purpose of this appendix is to clarify the experimental setup used for the simulation of the plant-inspired kinetic models as described in Chapter 5. While the techniques for digital modeling and finite element analysis were previously mentioned only peripherally, this appendix will provide the interested reader with further details. To ensure the longevity of this information, the following data sheets will narrow less on the handling of the used software packages, since their development cycles are so fast, but rather focus on the basic simulation concepts and the used numerical values for the structural elements.

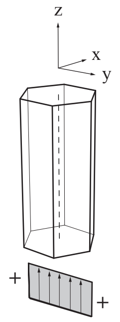
Biological Reference and Experimental Setup
Each data sheet first references the biological role model, the investigated motion type, and the identified mechanism. The further experiments then abstract the motion principles and remodel them in the software packages Rhinoceros, Grasshopper, and SOFiSTiK.

Geometrical Settings and Material Settings
The models' geometrical proportions and material characteristics are provided in the second section. Here, particularly variations in thickness play a key role because they can be manipulated easily and have a great effect on the flexibility of the models.

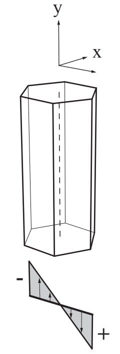
Settings for FEM Simulation
The FEM simulation of all seven case studies was done in SOFiSTiK. This software package allows for nonlinear finite element analysis under consideration of higher order effects like large deformations and rotations. The exact procedure was firstly described in (Lienhard 2014, pp. 126-129) as part of the chapter on "Computational Form-finding." The applied method uses a specially developed incremental-iterative calculation routine. This procedure is based on the application of primary load cases in order to trigger a deformation and actuate the mechanism in a structure. All seven case studies are modelled out of beam and shell elements. The plants' growth effects that cause individual cells to elongate or contract are recreated in SOFiSTiK by different loading scenarios. The application of temperature differences to beam and shell elements, for example, causes a similar expansion and contraction as in the plant cells.

The primary actuation types used are:

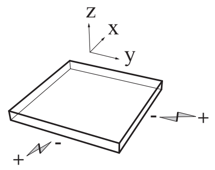
T = Uniform temperature change (beam loading)
DTZ = Temperature difference in local z-direction (beam loading)
DT = Temperature difference (quad loading)
PZ = Load in local z-direction (beam or quad loading)



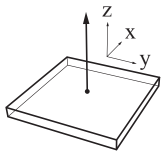
beam loading
(T)



beam loading
(DTZ)



shell loading
(DT)



shell loading
(PZ)

Case Study 1: Stomatal Aperture

Biological Reference

Role model: Leaf stomata
Motion type: Stomata aperture
Mechanism: Multidirectional changes of two cells
Volumetric swelling and shrinking based on changes in turgor pressure

Experimental Setup

Software used: Rhinoceros, Grasshopper, SOFiSTiK
Focus of study: Effect of different geometrical features
Number of models: $n = 4$
Stomata 1: No cables, no inner flanks
Stomata 2: 20 circumferential cables, stiff inner flanks
Stomata 3: 40 circumferential cables, stiff inner flanks
Stomata 4: 8 longitudinal cables, stiff inner flanks

Geometrical Settings (Stomata 2)

Length: $l = 1500$ mm
Width: $w = 800$ mm
Thickness: $t_1 = 1$ mm (membrane element)
Thickness: $t_2 = 2$ mm (inner flanks)
Diameter: $d = 5$ mm (cables)

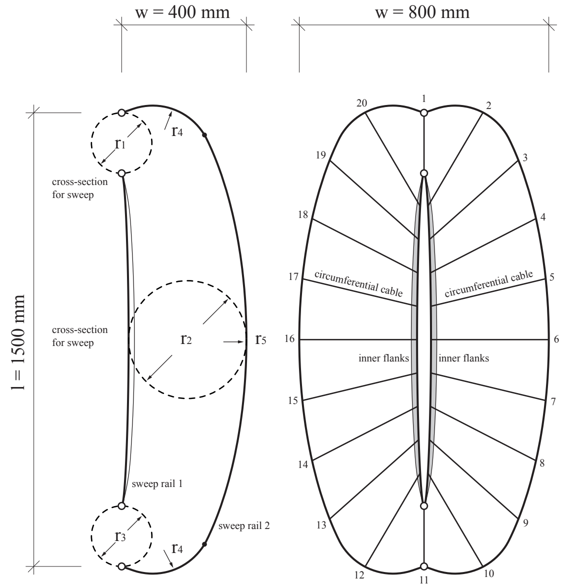
Material Settings (Stomata 2)

Young’s Modulus: $E_1 = 900$ N/mm^2 (membrane element)
Young’s Modulus: $E_2 = 15000$ N/mm^2 (inner flanks)
Young’s Modulus: $E_3 = 130000$ N/mm^2 (cables)

Settings for FEM simulation (Stomata 2)

Abstracted actuation: Inflation by force in normal direction
Actuation location: applied to membrane
Actuation type: PZ (force in local z-direction)
Support condition: 1 x Fixed support (YP = PX + PZ)
1 x Pinned support (PP = PX + PY + PZ)

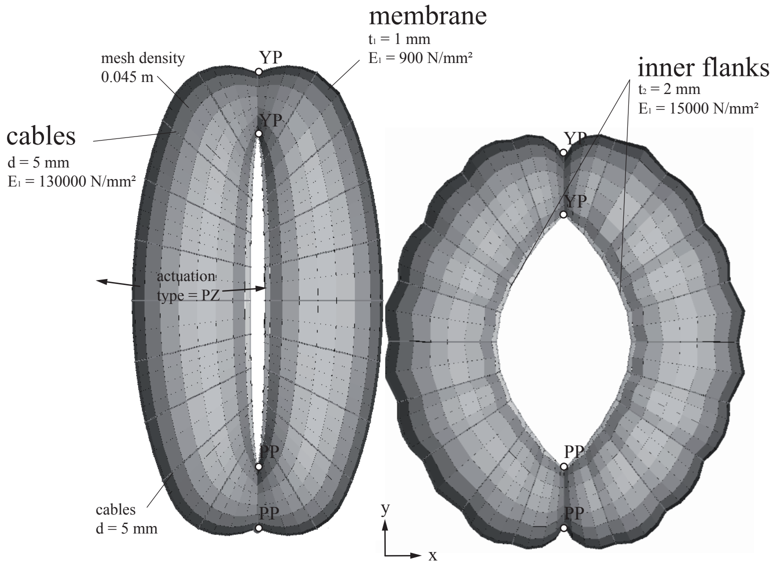
Geometrical Modeling (Stomata 2)



r_1 = 100 mm
r_2 = 100 mm
r_3 = 195 mm
r_4 = 200 mm
r_5 = 1760 mm

20 circumferential cables

Finite Element Simulation (Stomata 2)



LC = 1

LC = 13

Case Study 2: Leaflet Movement of *Oxalis* (Oxalidaceae)

Biological Reference

Role model: *Oxalis* (Oxalidaceae)
Motion type: Leaflet movement
Mechanism: Multidirectional changes of cells clusters
Volumetric swelling and shrinking based on changes in turgor pressure

Experimental Setup

Software used: Rhinoceros, Grasshopper, SOFiSTiK
Focus of study: effect of different geometrical features
Number of models: $n = 2$
Oxalis 1: Pulvinus acts longitudinally
Oxalis 2: Pulvinus acts longitudinally and transversely

Geometrical Settings (Oxalis 2)

Length: $l =$ 2000 mm
Thickness: $t_1 =$ 2 mm (leaflet surface)
Thickness: $t_2 =$ 1 mm (flexure zone)
Diameter: $d_1 =$ 5 mm (edge rod)
Diameter: $d_2 =$ 2 mm (edge rods)

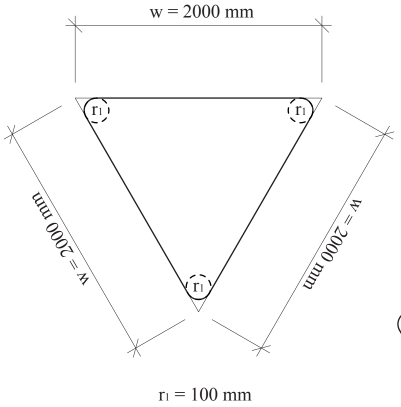
Material Settings (Oxalis 2)

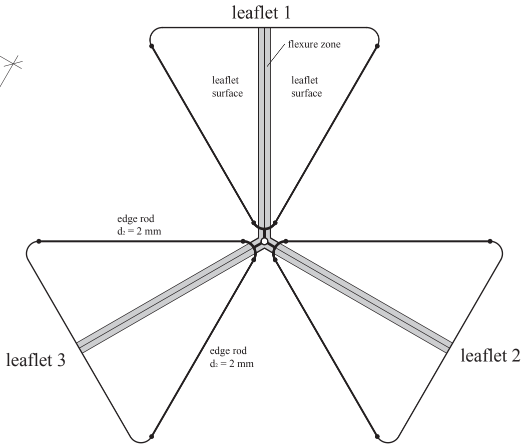
Young's Modulus: $E_1 =$ 15000 N/mm^2 (leaflet surface)
Heat exp. coefficient: $\alpha T_1 =$ 17 x 10-6/K (leaflet surface)
Young's Modulus: $E_2 =$ 3200 N/mm^2 (edge rods)
Heat exp. coefficient: $\alpha T_2 =$ 85 x 10-6/K (edge rods)

Settings for FEM simulation (Stomata 2)

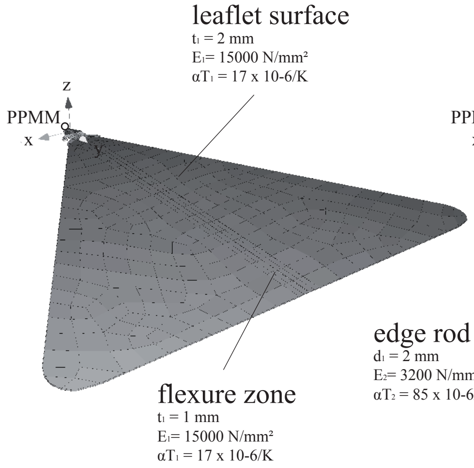
Abstracted actuation: Bending by thermal heat expansion
Actuation location: Edge rod
Actuation type: DTZ (differential heat expansion in the edge rod's upper and lower flanks)
Loop range: $\Delta t = 70°C$
Support condition: 1 x Pinned support (PPMM = PX + PY + PZ + MX + MY + MZ)

Geometrical Modeling (Oxalis 2)

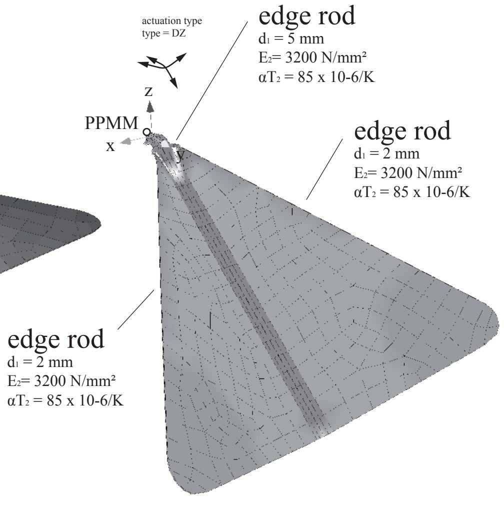




Finite Element Simulation (Oxalis 2)



LC = 1
t = 0°C



LC = 13
t = 70°C

Case Study 3: Flower Opening of *Lilium* (Liliaceae)

Biological Reference

Role model: *Lilium* (Liliaceae)
Motion type: Flower opening
Mechanism: Differential growth along the tepals edges

Experimental Setup

Software used: Rhinoceros, Grasshopper, SOFiSTiK
Focus of study: Effect of geometrical variations
Number of models: n = 25
Tepal 1.1.-5.5.: Models with increasing curvature on the tepals’ ends and center

Geometrical Settings

Length: $l = 2000$ mm
Width: $w = 350$ mm
Thickness: $t_1 = 2$ mm (tepal surface)
Diameter: $d_1 = 13$ mm (edge rods)

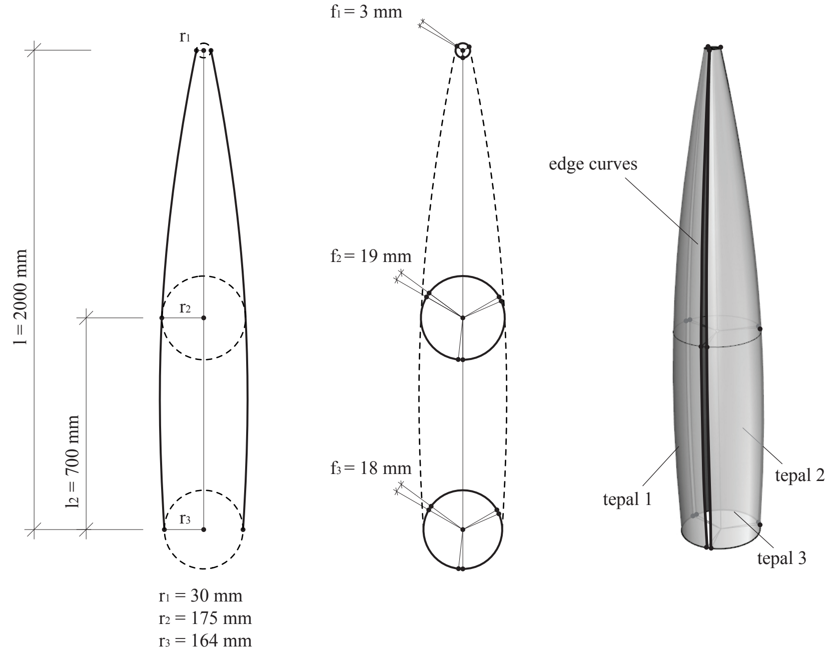
Material Settings (Tepal 5.1.)

Young’s Modulus: $E_1 = 12000$ N/mm^2 (tepal surface)
Heat exp. coefficient: $\alpha T_1 = 17$ x 10-6/K (tepal surface)
Young’s Modulus: $E_2 = 3200$ N/mm^2 (edge rods)
Heat exp. coefficient: $\alpha T_2 = 85$ x 10-6/K (edge rods)

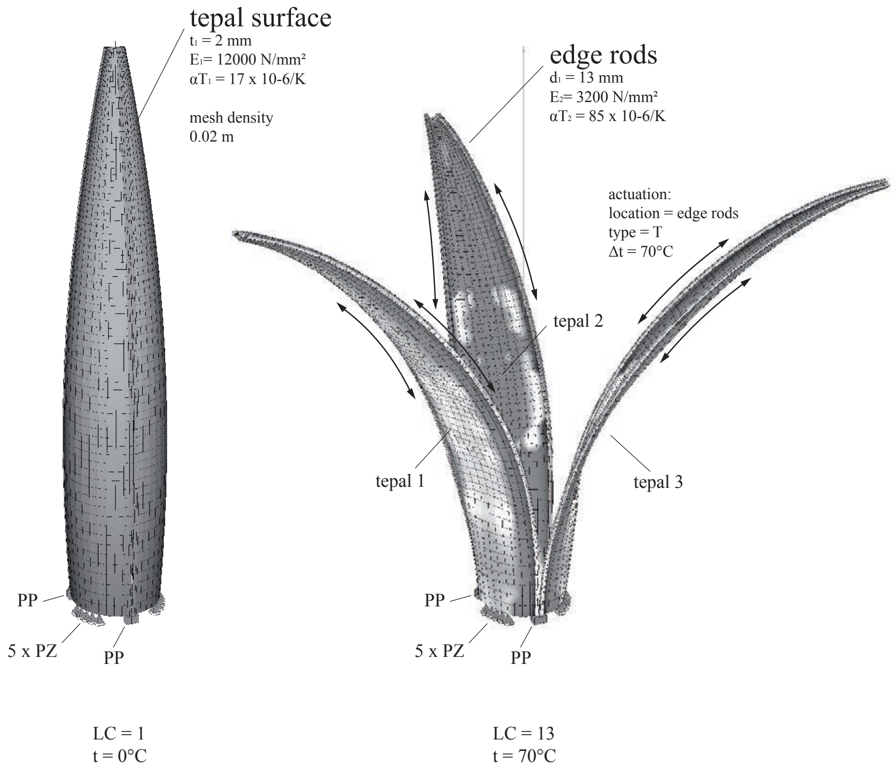
Settings for FEM simulation

Abstracted actuation: Bending by thermal heat expansion
Actuation location: Edge rods (full cross-section)
Actuation type: T (heat expansion in edge rods)
Loop range: $\Delta t = 70$°C
Support condition: 2 x Pinned supports (PP = PX + PY + PZ)
5 x Fixed supports (PZ)

Geometrical Modeling



Finite Element Simulation



Case Study 4: Flower Opening of *Ipomoea* (Convolvulaceae)

Biological Reference

Role model: *Ipomoea* (Convolvulaceae)
Motion type: Flower opening
Mechanism: Differential growth along the tepals edges

Experimental Setup

Software used: Rhinoceros, Grasshopper, SOFiSTiK
Focus of study: Effect of geometrical variations
Number of models: $n = 10$
Ipo 1-5: Different actuation types and locations
Ipo Twist 1-5: Same actuation of different geometries

Geometrical Settings (Ipo 2 with 180° twist)

Length:	$l = 2000$ mm	
Width:	$w_1 = 260$ mm	(bud)
Width:	$w_2 = 185$ mm	(band)
Thickness:	$t_1 = 2$ mm	(band surface)
Diameter:	$d_1 = 25$ mm	(edge rods)

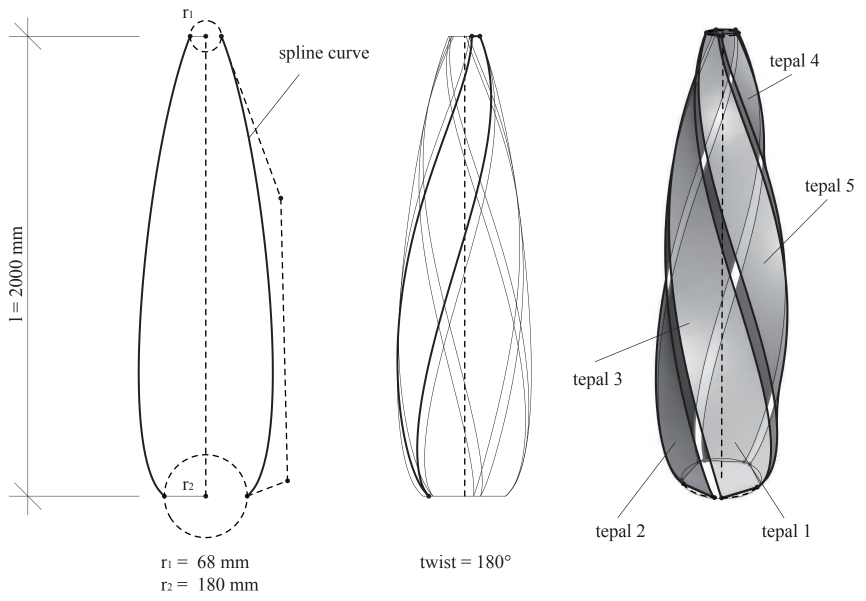
Material Settings (Ipo 2 with 180° twist)

Young's Modulus:	$E_1 = 12000$ N/mm^2	(band surface)
Heat exp. coefficient:	$\alpha T_1 = 17$ x 10-6/K	(band surface)
Young's Modulus:	$E_2 = 3200$ N/mm^2	(edge rods)
Heat exp. coefficient:	$\alpha T_2 = 85$ x 10-6/K	(edge rods)

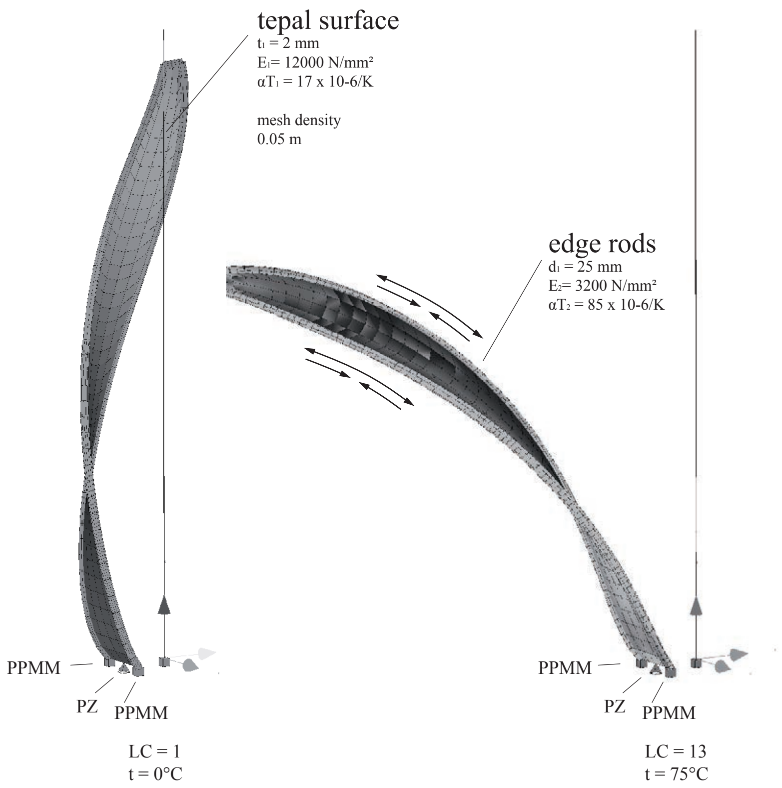
Settings for FEM simulation (Ipo 2 with 180° twist)

Abstracted actuation: Bending by thermal heat expansion
Actuation location: Edge rods
Actuation type: DTZ (differential heat expansion in the edge rod's inner flanks in local z-direction)
Loop range: $\Delta t = 75$°C
Support condition: 1 x Pinned support (PZ)
2 x Fixed support (MM = MX + MY + MZ)

Geometrical Modeling



Finite Element Simulation



Case Study 5: Trapping Movement of *Dionaea* (Droseraceae)

Biological Reference

Role model:	*Dionaea* (Droseraceae)
Motion type:	Trapping mechanism
Mechanism:	Bidirectional changes and snap-buckling

Experimental Setup

Software used:	Rhinoceros, Grasshopper, SOFiSTiK
Focus of study:	Effect of geometrical variations
Number of models:	n = 3
Dionaea 1:	Direct translation of role model
Dionaea 2-3:	Dionaea 1 with additional cuts

Geometrical Settings (Dionaea 1)

Length:	l = 1700 mm	
Width:	w = 1000 mm	
Thickness:	t_1 = 2 mm	(lobe surface)
Diameter:	d_1 = 25 mm	(edge rods)

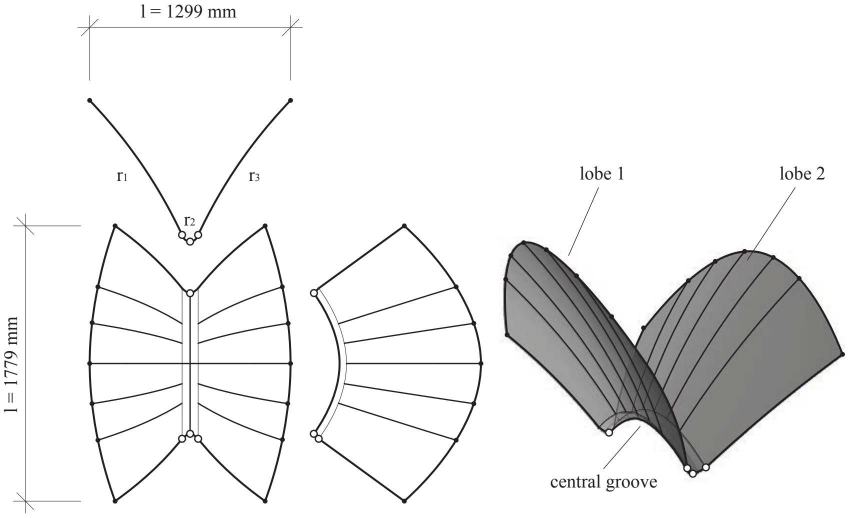
Material Settings (Dionaea 1)

Young's Modulus:	E_1 = 12000 N/mm^2	(lobe surface)
Heat exp. coefficient:	αT_1 = 17 x 10-6/K	(lobe surface)
Young's Modulus:	E_2= 3200 N/mm^2	(lobe rods)
Heat exp. coefficient:	αT_2 = 85 x 10-6/K	(lobe rods)

Settings for FEM simulation (Dionaea 1)

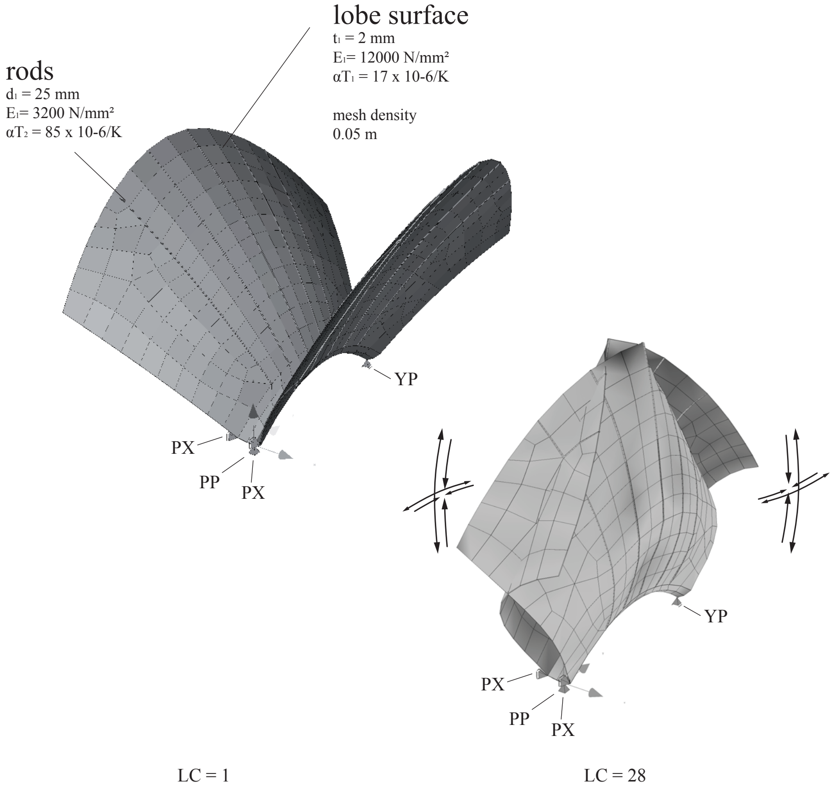
Abstracted actuation:	Bending by thermal heat expansion	
Actuation location:	Lobe surface and lobe rods	
Actuation type:	DT (differential heat expansion in the upper and lower layers of the lobe surface)	
	T (heat expansion in the lobe rods)	
Loop range:	Δt = 75°C	
Support condition:	1 x Fixed support	(YP = PX + PZ)
	2 x Fixed support	(PX)
	1 x Pinned support	(PP = PX + PY + PZ)

Geometrical Modeling



$r_1 =$ 3239 mm
$r_2 =$ 52 mm
$r_3 =$ 3239 mm

Finite Element Simulation



LC = 1 LC = 28

Case Study 6: Trapping Movement of *Aldrovanda* (Droseraceae)

Biological Reference

Role model:	*Aldrovanda* (Droseraceae)
Motion type:	Trapping mechanism
Mechanism:	Unidirectional changes of mid-rib Bidirectional change of lobe surfaces Curved-folding mechanism

Experimental Setup

Software used:	Rhinoceros, Grasshopper, SOFiSTiK
Focus of study:	Effect of geometrical variations
Number of models:	n = 13
Model A1-4:	Tests using Rigid Origami Simulator
Model A5-9:	Differences in thickness of the flexure zone
Model A10-13:	Differences in width of the flexure zone

Geometrical Settings

Length:	$l = 2000$ mm	
Fold radius	$r = 1900$ mm	
Thickness:	$t_1 = 5$ mm	(central portion)
Thickness:	$t_2 = 3$ mm	(lobe surfaces)
Thickness:	$t_3 = 2$ mm	(flexure zone)
Width:	$w_1 = 20$ mm	(flexure zone)
Diameter:	$d_1 = 50$ mm	(midrib)

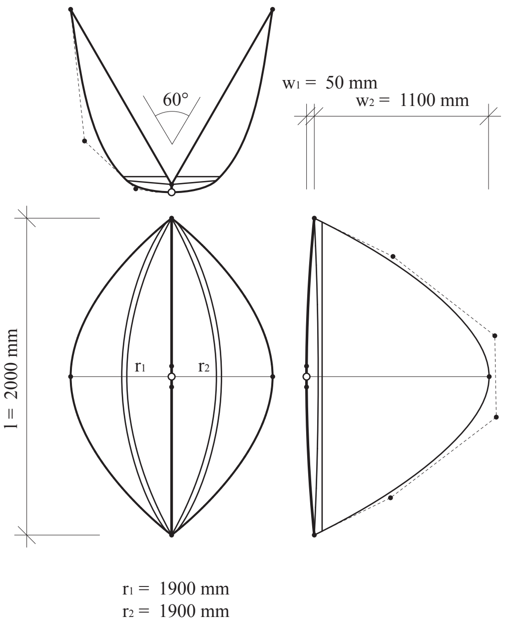
Material Settings

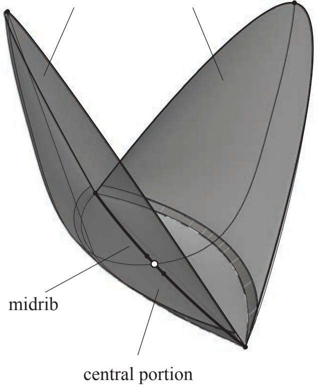
Young's Modulus:	$E_1 = 12000\ N/mm^2$	(lobe surface)
Heat exp. coefficient:	$\alpha T_1 = 17 \times 10\text{-}6/K$	(lobe surface)
Young's Modulus:	$E_2 = 3200\ N/mm^2$	(midrib)
Heat exp. coefficient:	$\alpha T_2 = 85 \times 10\text{-}6/K$	(midrib)

Settings for FEM simulation (Model A10)

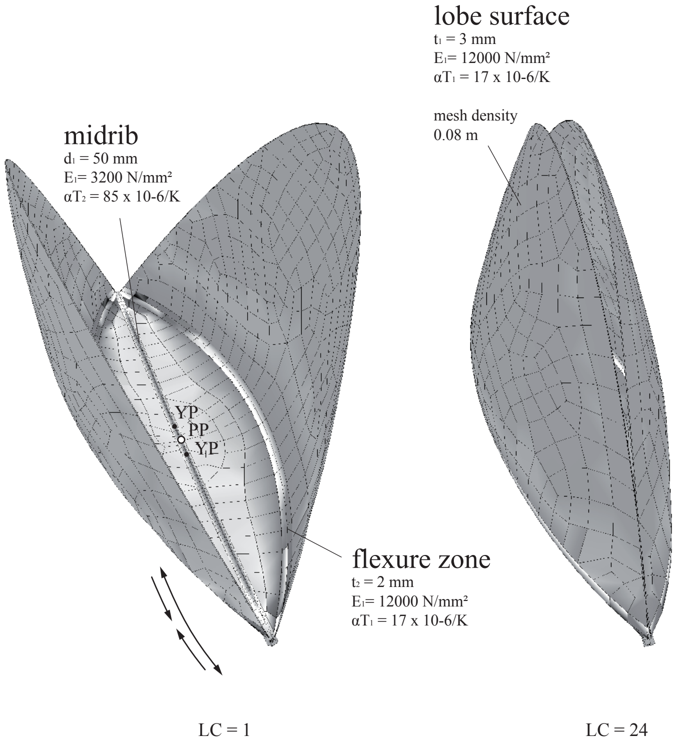
Abstracted actuation:	Bending by thermal heat expansion	
Actuation location:	Midrib	
Actuation type:	DTZ (differential heat expansion)	
Loop range:	$\Delta t = 75°C$	
Support condition:	2 x Fixed support	(YP = PX + PZ)
	1 x Pinned support	(PP = PX + PY + PZ)

Geometrical Modeling





Finite Element Simulation



LC = 1 LC = 24

Case Study 7: Pollination Mechanism of *Strelitzia* (Strelitziaceae)

Biological Reference

Role model: *Strelitzia* (Strelitziaceae)
Motion type: Pollination mechanism
Mechanism: Punctual change by locally applied force
Lateral torsional buckling

Experimental Setup

Software used: Rhinoceros, Grasshopper, SOFiSTiK
Focus of study: Effect of geometrical variations
Number of models: $n = 10$
Model S1-4: Different support conditions
Model S5-10: Different lamina configurations

Geometrical Settings (Model S8)

Length: $l_1 = 2000$ mm (lamina)
Width: $w_1 = 200$ mm (lamina)
Thickness: $t_1 = 2$ mm (lamina)
Length: $l_2 = 2000$ mm (beam)
Width: $w_2 = 40$ mm (beam)
Height: $h_2 = 20$ mm (beam)

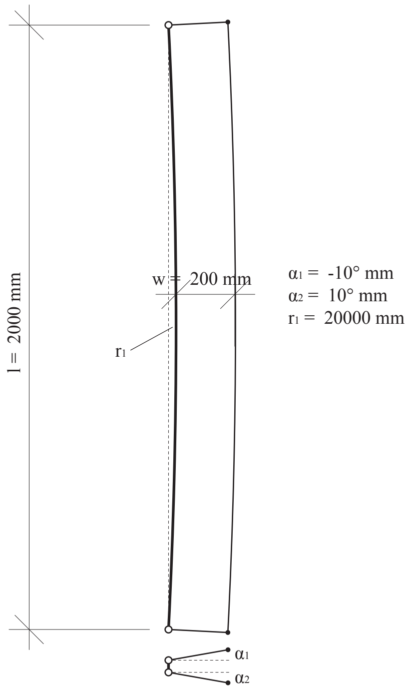
Material Settings (Model S8)

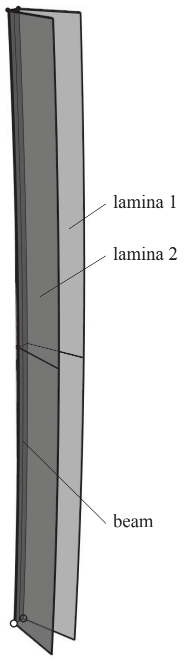
Young's Modulus: $E_1 = 12000$ N/mm^2 (lobe surface)

Settings for FEM simulation (Model S8)

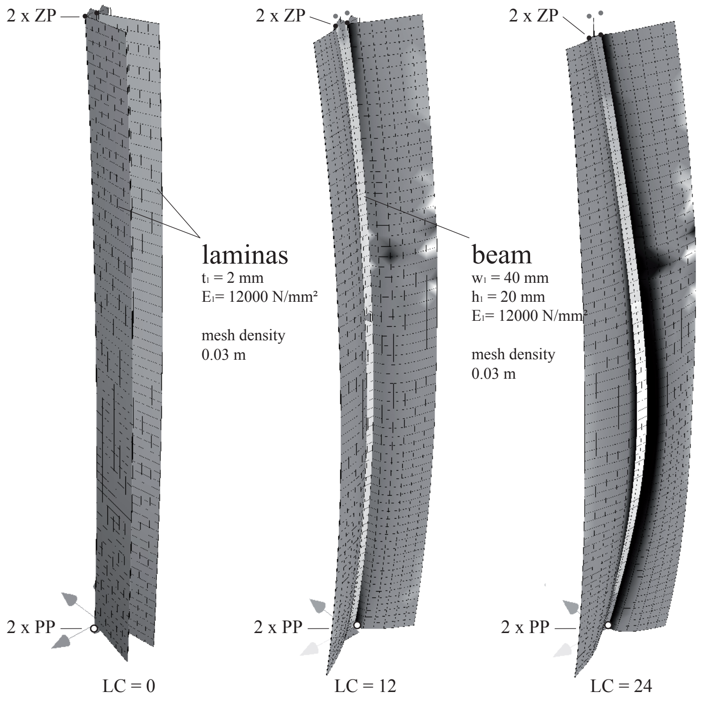
Abstracted actuation: Bending by displacement of support
Actuation location: Support of beam
Actuation type: PZ (loading in z-direction)
Loop range: $\Delta d = 20$ mm
Support condition: 2 x Fixed support (ZP = PX + PY)
2 x Pinned support (PP = PX + PY + PZ)

Geometrical Modeling





Finite Element Simulation



BIBLIOGRAPHY

Ampère, A. M., Sainte-Beuve, C. A., & Littré, É. (1838). *Essai sur la philosophie des sciences*. Bachelier.

Ananthasuresh, G. K., Kota, S., & Kikuchi, N. (1994). Strategies for systematic synthesis of compliant MEMS. In *Proceedings of the 1994 ASME winter annual meeting* (pp. 677-686).

Anderson, W. B. (1914). *Physics for Technical Students in Colleges and Universities*. McGraw-Hill.

Ashida, J. (1934). Studies on the leaf movement of Aldrovanda vesiculosa LI Process and mechanism of the movement. *Mem. Coll. Sci., Kyoto Univ. B*, *9*, 141-244.

Asimov, I. (1988). *Understanding physics* (Vol. 1). Barnes & Noble Publishing.

Aylor, D. E., Parlange, J. Y., & Krikorian, A. D. (1973). Stomatal mechanics. *American Journal of Botany*, 163-171.

Bieleski, R., Elgar, J., & Heyes, J. (2000). Mechanical aspects of rapid flower opening in Asiatic lily. *Annals of Botany*, *86*(6), 1175-1183.

Blanding, D. L. (1999). *Exact constraint: Machine design using kinematic processing.* American Society of Mechanical Engineers.

Borelli, G. A., Bernoulli, J., Elinger, N., & a Jesu, C. J. (1743). *De motu animalium*. Petrum Gosse.

Boronkay, T. G., & Mei, C. (1970). Analysis and design of multiple input flexible link mechanisms. *Journal of mechanisms,* 5(1), 29-40.

Boudaoud, A. (2010). An introduction to the mechanics of morphogenesis for plant biologists. *Trends in plant science*, 15(6), 353-360.

Braam, J. (2005). In touch: plant responses to mechanical stimuli. *New Phytologist*, 165(2), 373-389.

Bresinsky, A., & Strasburger, E. (2008). *Lehrbuch der Botanik*.

Brown, W. H. (1916). The mechanism of movement and the duration of the effect of stimulation in the leaves of Dionaea. *American Journal of Botany*, 68-90.

Buckley, T. N. (2005). The control of stomata by water balance. *New Phytologist*, *168*(2), 275-292.

Bunning, E. (1973). *The physiological clock: circadian rhytms and biological chronometry*. London: english universities Press.

Burgert, I., & Fratzl, P. (2009). Actuation systems in plants as prototypes for bioinspired devices. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *367*(1893), 1541-1557.

Cardwell, D. S. L. (1995). *Wheels, clocks, and rockets: A history of technology*. WW Norton & Company.

Chiu, Y. C. (2010). *An Introduction to the History of Project Management: From the earliest times to AD 1900*. Eburon Uitgeverij BV.

Chow, W. W. (1981). Hinges and Straps.

Christie, J. M., & Murphy, A. S. (2013). Shoot phototropism in higher plants: new light through old concepts. *American journal of botany*, 100(1), 35-46.

Coombs, G., Mitchell, S., & Peter, C. (2007). Pollen as a reward for birds. The unique case of weaver bird pollination in *Strelitzia reginae*. *South African Journal of Botany*, *73*(2), 283.

Copeland, E. B. (1902). The mechanism of stomata. *Annals of Botany*, (2), 327-364.

Cortizo, M., & Laufs, P. (2012). Genetic basis of the “sleeping leaves” revealed. *Proceedings of the National Academy of Sciences*, *109*(29), 11474-11475.

Coxeter, H. S. (1972). M.; Moser, WOI: Generators and Relations for Discrete Groups.

Cronk, Q., & Ojeda, I. (2008). Bird-pollinated flowers in an evolutionary and molecular context. *Journal of Experimental Botany*, *59*(4), 715-727.

da Vinci, L. ca. 1500. *Codex Atlanticus*.

Darwin, C. (1876). *The effects of cross and self fertilisation in the vegetable kingdom*. John Murray.

Darwin, C., & Darwin, F. (1880). *The power of movement in plants*. John Murray.

Darwin, C., & Darwin, F. (1888). *Insectivorous plants*. J. Murray.

Derderian, J. M., Howell, L. L., Murphy, M. D., Lyon, S. M., & Pack, S. D. (1996). Compliant parallel-guiding mechanisms. In *Proceedings of the 1996 ASME Mechanisms Conference*.

Douthe, C., Baverel, O., & Caron, J. F. (2007). Gridshell in composite materials: towards wide span shelters. *Journal of the international association for shell and spatial structures*, *48*(3), 175-180.

Dumais, J., & Forterre, Y. (2012). "Vegetable dynamicks": the role of water in plant movements. *Annual Review of Fluid Mechanics*, *44*, 453-478.

Eigensatz, M., Kilian, M., Schiftner, A., Mitra, N. J., Pottmann, H., & Pauly, M. (2010, July). Paneling architectural freeform surfaces. In *ACM Transactions on Graphics (TOG)* (Vol. 29, No. 4, p. 45). ACM.

Endress, P. K. (1994) *Diversity and evolutionary biology of tropical flowers*. Cambridge University Press: Cambridge, pp. 352-358.

Erdman, A. G., & Sandor, G. N. (1997). Mechanism design: analysis and synthesis (Vol. 1).

Estrada, J. (1994). Endress, PK (1994). Diversity and Evolutionary Biology of Tropical Flowers. In *Anales del Jardín Botánico de Madrid* (Vol. 52, No. 2, pp. 257-258). Real Jardín Botánico.

Euler, L. (1765). *Theoria motus corporum solidorum seu rigidorum.* AE Roser.

Euler, L. (1774). Methodus inveniendi lineas curvas maximi minimive proprietate gaudentes (appendix, de curvis elasticis). *Lausanne und Genf, 1744*.

Fenster, C. B., Armbruster, W. S., Wilson, P., Dudash, M. R., & Thomson, J. D. (2004). Pollination syndromes and floral specialization. *Annual Review of Ecology, Evolution, and Systematics*, 375-403.

Ferguson, E. S. (1962). *Kinematics of Mechanisms from the Time of Watt* (Vol. 27). Smithsonian Institution.

Forterre, Y. (2013). Slow, fast and furious: understanding the physics of plant movements. *Journal of experimental botany*, ert230.

Forterre, Y., Skotheim, J. M., Dumais, J., & Mahadevan, L. (2005). How the Venus flytrap snaps. *Nature*, *433*(7024), 421-425.

Frost, S. K., & Frost, P. G. H. (1981). Sunbird pollination of Strelitzia nicolai. *Oecologia*, *49*(3), 379-384.

Galilei, G. (1964). Le meccaniche, 1600. *A. Favaro, Firenze*, 66.

Galston, A. W., & Davies, P. J. (1970). Control mechanisms in plant development. *Control mechanisms in plant development.*

Gibbs-Smith, C. H., & Rees, G. (1978). *The inventions of Leonardo da Vinci.* London: Phaidon.

Gilroy, S., & Masson, P. H. (Eds.). (2008). *Plant tropisms*. Blackwell Pub..

Gruber, P. (2010). *Biomimetics in Architecture*. Springer Wien.

Hanson, A. D., & Kende, H. (1975). Ethylene-enhanced ion and sucrose efflux in morning glory flower tissue. *Plant physiology*, *55*(4), 663-669.

Hart, J. W. (1990). *Plant tropisms: and other growth movements.* Springer.

Hartenberg, R. S., & Denavit, J. (1964). *Kinematic synthesis of linkages*. McGraw-Hill.

Hausladen, G., De Saldanha, M., & Liedl, P. (2006). ClimaSkin. *Konzepte für Gebäudehüllen, die mit weniger Energie mehr leisten. München: Callwey*.

Heywood, V. H., Brummitt, R. K., Culham, A., & Seberg, O. (2007). Flowering Plant Families of the World: Royal Botanic Gardens.

Hill, B. S., & Findlay, G. P. (1981). The power of movement in plants: the role of osmotic machines. *Quarterly reviews of biophysics*, *14*(02), 173-222.

Hodick, D., & Sievers, A. (1988). The action potential of Dionaea muscipula Ellis. *Planta*, *174*(1), 8-18.

Hodick, D., & Sievers, A. (1989). On the mechanism of trap closure of Venus flytrap (Dionaea muscipula Ellis). *Planta*, *179*(1), 32-42.

Holmes, D. P., & Crosby, A. J. (2007). Snapping surfaces. *Advanced Materials*, *19*(21), 3589-3593.

Howell, L. L. (2001). *Compliant mechanisms*. John Wiley & Sons.

Iijima, T., & Sibaoka, T. (1985). Membrane potentials in excitable cells of Aldrovanda vesiculosa trap-lobes. *Plant and cell physiology*, *26*(1), 1-13.

Iijima, T., & Sibaoka, T. (1981). Action potential in the trap-lobes of Aldrovanda vesiculosa. *Plant and cell physiology*, 22(8), 1595-1601.

Jensen, B. D., Howell, L. L., Gunyan, D. B., & Salmon, L. G. (1997). The design and analysis of compliant MEMS using the pseudo-rigid-body model. *ASME-PUBLICATIONS-HTD*, 354, 119-126.

Jost, L., & Gibson, R. J. H. (1907). *Lectures on plant physiology*. Clarendon Press.

Joyeux, M. (2013). Elastic models of the fast traps of carnivorous Dionaea and Aldrovanda. *Physical Review E*, *88*(3), 034701.

Kaihara, S., & Takimoto, A. (1981). Physical Basis of Flower-opening in Pharbitis nil. *Plant and Cell Physiology*, *22*(2), 307-310.

Kaiser, H., & Grams, T. E. (2006). Rapid hydropassive opening and subsequent active stomatal closure follow heat-induced electrical signals in Mimosa pudica. *Journal of experimental botany*, *57*(9), 2087-2092.

Kende, H., & Baumgartner, B. (1974). Regulation of aging in flowers of Ipomoea tricolor by ethylene. *Planta*, *116*(4), 279-289.

Knippers, J., & Speck, T. (2012). Design and construction principles in nature and architecture. *Bioinspiration & biomimetics*, *7*(1), 015002.

Knippers, J., Jungjohann, H., Scheible, F., & Oppe, M. (2013). Bio-inspirierte kinetische Fassade für den Themenpavillon "One Ocean" EXPO 2012 in Yeosu, Korea. *Bautechnik,* 90(6), 341-347.

Kohl, H. (1995) Bundestagsrede vom 1. Juni 1995 zur Geschichte der Vertreibung, Plenarprotokoll 13/41, S.03183.

Koller, D., & Van Volkenburgh, E. (2011). *The restless plant*. Harvard University Press.

Krebs, R. E. (Ed.). (2004). *Groundbreaking scientific experiments, inventions, and discoveries of the Middle Ages and the Renaissance*. Greenwood Publishing Group.

Kronestedt, E., Walles, B. (1986) Anatomy of the *Strelitzia reginae* flower (Strelitziaceae). *Nord. J. Bot.* 6(3), pp. 307-20.

Küppers, U., & Tributsch, H. (2009). *Verpacktes Leben-verpackte Technik: Bionik der Verpackung*. John Wiley & Sons.

Kwok, K., & Pellegrino, S. (2010). Shape Recovery of Viscoelastic Deployable Structures. *& Proceedings*.

Lakshmana Rao, C., Lakshminarasimhan, J., Sethuraman, R., & Sivakumar, S. M. (2004). Engineering mechanics: statics and dynamics.

Lee, H., Xia, C., & Fang, N. X. (2010). First jump of microgel; actuation speed enhancement by elastic instability. *Soft Matter*, *6*(18), 4342-4345.

Liang, H., & Mahadevan, L. (2009). The shape of a long leaf. *Proceedings of the National Academy of Sciences*, *106*(52), 22049-22054.

Liang, H., & Mahadevan, L. (2011). Growth, geometry, and mechanics of a blooming lily. *Proceedings of the National Academy of Sciences*, *108*(14), 5516-5521.

Lienhard, J. (2014). Bending-active structures: form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein.

Lienhard, J., Poppinga, S., Schleicher, S., Masselter, T., Speck, T., & Knippers, J. (2009). Abstraction of plant movements for deployable structures in architecture. In *Proceedings of the 6th Plant Biomechanics Conference* (pp. 389-397).

Lienhard, J., Poppinga, S., Schleicher, S., Speck, T., Knippers, J. (2010) Elastic architecture: nature inspired pliable structures. In: *Design and Nature V* (ed. Brebbia, C. A.). WIT Press: Southampton, pp. 469-477.

Lienhard, J., Schleicher, S., & Knippers, J. (2011). Bending-active Structures–Research Pavilion ICD/ITKE. In *Taller, Longer, Lighter-Meeting Growing Demand with Limited Resources, Proceedings of IABSE-IASS Symposium*.

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: a hingeless flapping mechanism inspired by nature. *Bioinspiration & biomimetics*, 6(4), 045001.

Lobontiu, N. (2010). *Compliant mechanisms: design of flexure hinges*. CRC press.

MacGregor, J. G. (1887). *An elementary treatise on kinematics and dynamics*. Macmillan.

Mahnken, R. (2011). *Lehrbuch der technischen Mechanik-Statik: Grundlagen und Anwendungen*. Springer-Verlag.

Martone, P. T., Boller, M., Burgert, I., Dumais, J., Edwards, J., Mach, K., ... & Speck, T. (2010). Mechanics without muscle: biomechanical inspiration from the plant world. *Integrative and comparative biology*, *50*(5), 888-907.

Matini, M. R. (2007). Biegsame Konstruktionen in der Architektur auf der Basis bionischer Prinzipien.

Mattheck, C., Burkhardt, S. (1990) A new method of structural shape optimization based on biological growth. *Int. J. Fat.* 12, pp. 185-190.

Mattheck, C., Kubler, H. (1995) *Wood - the internal optimization of trees*. Springer Verlag: Berlin.

Mattheck, C. (1998). Design in nature: learning from trees. Springer.

McCarthy, J. M., & Soh, G. S. (2010). *Geometric design of linkages* (Vol. 11). Springer.

McEwen, E., Miller, R. L., & Bergman, C. A. (1991). Early bow design and construction. *Scientific American*, *264*(6), 76-82.

Meckel, T., Gall, L., Semrau, S., Homann, U., & Thiel, G. (2007). Guard cells elongate: relationship of volume and surface area during stomatal movement. *Biophysical journal*, 92(3), 1072-1080.

Meidner, H., & Mansfield, T. A. (1968). Physiology of stomata. *Physiology of stomata.*

Midha, A., Norton, T. W., & Howell, L. L. (1994). On the nomenclature, classification, and abstractions of compliant mechanisms. *Journal of Mechanical Design*, *116*(1), 270-279.

Migliaccio, F., Tassone, P., & Fortunati, A. (2013). Circumnutation as an autonomous root movement in plants. *American journal of botany*, 100(1), 4-13.

Miller, G. R. (1991). An object-oriented approach to structural analysis and design. *Computers & Structures*, *40*(1), 75-82.

Milwich, M., Speck, T., Speck, O., Stegmaier, T., & Planck, H. (2006). Biomimetics and technical textiles: solving engineering problems with the help of nature's wisdom. *American Journal of Botany*, 93(10), 1455-1465.

Mirabet, V., Das, P., Boudaoud, A., & Hamant, O. (2011). The role of mechanical forces in plant morphogenesis. *Annual review of plant biology*, 62, 365-385.

Mohr, H., & Schopfer, P. (1995). Plant physiology. Springer Berlin Heidelberg.

Moon, F. C. (2003). Franz Reuleaux: Contributions to 19th century kinematics and theory of machines. *Applied Mechanics Reviews*, *56*(2), 261-285.

Moran, N. (2007). Osmoregulation of leaf motor cells. *FEBS letters*, *581*(12), 2337-2347 .

Moran, N. (2007). Rhythmic leaf movements: physiological and molecular aspects. In *Rhythms in Plants* (pp. 3-37). Springer.

Morgan, M. H. (1960). Vitruvius. *De Architectura translated by MH Morgan (Vitruvius: The Ten Books on Architecture. 1960 edition (first published 1914). New York*.

Motsinger, R. N. (1964). Flexural devices in measurement systems. *Measurement Engineering*, 1, 383-435.

Moulia, B., & Fournier, M. (2009). The power and control of gravitropic movements in plants: a biomechanical and systems biology view. *Journal of experimental botany*, 60(2), 461-486.

Müller-Haeckel, A. (1975). Endogene Jahresperiodik der Blattbewegungen zweier Oxalis-Arten. *Physiologia Plantarum*, 35(3), 236-242.

Nakanishi, F., Nakazawa, M., & Katayama, N. (2005). Opening and closing of Oxalis leaves in response to light stimuli. *Journal of Biological Education*, *39*(2), 87-91.

Niklas, K. J. (1992). *Plant biomechanics: an engineering approach to plant form and function*. University of Chicago press.

Ostdiek, V. J., & Bord, D. J. (2005). Inquiry Into Physics.

Paros, J. M. and Weisbord, L. (1965). How to design flexure hinges. *Machine Design*, 37, 151-156.

Pascal, B. (1910). *Thoughts* (No. 48). PF Collier & Son.

Paul, A. R., Roy, P., & Mukherjee, S. (2004). *Mechanical sciences: Engineering mechanics and Strength of Materials*. PHI Learning Pvt. Ltd..

Pettigrew, J. B. (1908). *Design in nature*. Longmans, Green & Company.

Philippidis, T. P., & Vassilopoulos, A. P. (1999). Fatigue strength prediction under multiaxial stress. *Journal of Composite Materials*, *33*(17), 1578-1599.

Phillips Jr, H. L., & Kende, H. (1980). Structural changes in flowers of Ipomoea tricolor during flower opening and closing. *Protoplasma*, *102*(3-4), 199-215.

Piker, D. (2013). Kangaroo: form finding with computational physics. *Architectural Design*, *83*(2), 136-137.

Poppinga, S. (2013). *Qualitative und quantitative Analyse des Form-Struktur-Funktions-Zusammenhangs bei verschiedenen Pflanzenbewegungen und deren bionische Umsetzungspotentiale* (Doctoral dissertation).

Poppinga, S., & Joyeux, M. (2011). Different mechanics of snap-trapping in the two closely related carnivorous plants Dionaea muscipula and Aldrovanda vesiculosa. *Physical Review E, 84*(4), 041928.

Poppinga, S., Lienhard, J., Masselter, T., Schleicher, S., Knippers, J., & Speck, T. (2010, January). Biomimetic deployable systems in architecture. In *6th World Congress of Biomechanics (WCB 2010). August 1-6, 2010 Singapore* (pp. 40-43). Springer Berlin Heidelberg.

Poppinga, S., Masselter, T., Lienhard, J., Schleicher, S., Knippers, J., & Speck, T. (2010). Plant movements as concept generators for deployable systems in architecture. *Design and Nature V*, 403-409.

Pottmann, H., & Wallner, J. (2009). *Computational line geometry.* Springer Science & Business.

Pottmann, H., Asperl, A., Hofer, M., & Kilian, A. (2007). *Architectural Geometry*. Bentley Institute Press.

Reith, M., Baumann, G., Claßen-Bockhoff, R., & Speck, T. (2007). New insights into the functional morphology of the lever mechanism of Salvia pratensis (Lamiaceae). *Annals of botany, 100*(2), 393-400.

Reuleaux, F. (2012). *Kinematics of machinery: outlines of a theory of machines*. Courier Dover Publications.

Rowan, M. K. (1974). Bird pollination of Strelitzia. *Ostrich*, *45*, 40.

Ruhland, W. (Ed.). (1967). Handbuch der Pflanzenphysiologie: E*ncyclopedia of plant physiology*. Springer.

Satter, R. L. (1979). Leaf movements and tendril curling. *Encyclopedia of plant physiology*, 7, 442-484.

Satter, R. L., & Galston, A. W. (1981). Mechanisms of control of leaf movements. *Annual Review of Plant Physiology*, *32*(1), 83-110.

Schleicher, S., Lienhard, J., Knippers, J., Poppinga, S., Masselter, T., & Speck, T. (2011). Hingeless, infinitely deformable folding mechanism. *Patent EP2320015.*

Schleicher, S., Lienhard, J., Poppinga, S., Masselter, T., Speck, T., & Knippers, J. (2011). Bio-inspired kinematics of adaptive shading systems for free form facades. In *Proceedings of the IABSE-IASS Symposium, Taller Longer Lighter, London, UK* (Vol. 9).

Schleicher, S., Lienhard, J., Poppinga, S., Speck, T., & Knippers, J. (2010). Abstraction of bio-inspired curved-line folding patterns for elastic foils and membranes in architecture. *Design and Nature V*, 479-90.

Schleicher, S., Lienhard, J., Poppinga, S., Speck, T., & Knippers, J. (2014). A methodology for transferring principles of plant movements to elastic systems in architecture. *Computer-Aided Design*, 60, pp. 105-117.

Schwendener, S. (1882). *Die Schutzscheiden und ihre Verstärkungen*. K. Akademie der Wissenschaften.

Scorza, L. C. T., & Dornelas, M. C. (2011). Plants on the move. *Plant signaling & behavior, 6*(12), 1979-1986.

Sechelmann, S., Rörig, T., & Bobenko, A. I. (2013). *Quasiisothermic Mesh Layout* (pp. 243-258). Springer Vienna.

Shelden, D. R. (2002). *Digital surface representation and the constructibility of Gehry's architecture* (Doctoral dissertation, Massachusetts Institute of Technology).

Simitses, G. J., & Hodges, D. H. (2006). *Fundamentals of structural stability*. Butterworth-Heinemann.

Simons, P. (1994). Die Empfindungswelt der Pflanzen mit Nervenkostüm. In*Pflanzen in Bewegung* (pp. 13-29). Birkhäuser Basel.

Sitte, P., Ziegler, H., Ehrendorfer, F., & Bresinsky, A. (1991). Strasburger. *Lehrbuch der Botanik*, Gustav Fischer Verlag, p. 456-469.

Skead, C. J. (1975). Weaverbird pollination of Strelitzia reginae. *Ostrich*, *46*, 183-185.

Skotheim, J. M., & Mahadevan, L. (2005). Physical limits and design principles for plant and fungal movements. *Science*, *308*(5726), 1308-1310.

Sonnewald, U. (2014). Bewegungsphysiologie. In *Strasburger– Lehrbuch der Pflanzenwissenschaften*. Springer, pp. 447-474.

Speck, T., & Rowe, N. P. (2006). How to become a successful climber - mechanical, anatomical, ultra-structural and biochemical variations during ontogeny in plants with different climbing strategies. In *Proc. 5th Int. Plant Biomechanics Conf* (Vol. 1, pp. 103-8).

Speck, T., Speck, O., Beheshti, N., & McIntosh, A. C. (2008). Process sequences in biomimetic research. *Design and Nature IV*, 3-11.

Standaert, P. (2005). Energy saving and CO2 reduction potential from solar shading systems and shutters in the EU-25. *ES-SO, the European Solar Shading Organization*.

Stebbins, G. L. (1970). Adaptive radiation of reproductive characteristics in angiosperms, I: pollination mechanisms. *Annual Review of Ecology and Systematics*, 307-326.

Stiles, F. G. (1978). Ecological and evolutionary implications of bird pollination. *American Zoologist*, *18*(4), 715-727.

Stuhlman, O. (1948). A physical analysis of the opening and closing movements of the lobes of Venus' fly-trap. *Bulletin of the Torrey Botanical Club*, 22-44.

Suresh, S. (1998). *Fatigue of materials*. Cambridge university press.

Tachi, T. (2009). Simulation of rigid origami. *Origami*, *4*, 175-187.

Taiz, L., & Zeiger, E. (2002). Plant Physiology. 3rd. *Ed. Pub. Sinauer.*

Tamiya, T., Miyazaki, T., Ishikawa, H., Iriguchi, N., Maki, T., Matsumoto, J. J., & Tsuchiya, T. (1988). Movement of water in conjunction with plant movement visualized by NMR imaging. *Journal of biochemistry*, *104*(1), 5-8.

Thompson, D. W. (1942). On growth and form. *On growth and form.*

Timoshenko, S. P., & Young, D. H. (1956). Engineering mechanics.

Toyota, M., & Gilroy, S. (2013). Gravitropism and mechanical signaling in plants. *American journal of botany*, *100*(1), 111-125.

Tuttle, S. B. (1967). How to achieve precise adjustment. *Machine Design*, *39*(4), 227.

Uicker, J. J., Pennock, G. R., & Shigley, J. E. (2011). *Theory of machines and mechanisms* (p. 466). Oxford: Oxford University Press.

Usher, A. P. (1988). *A History of Mechanical Inventions*. Courier Dover Publications.

Usher, A. P. (2013). *A History of Mechanical Inventions: Revised Edition*. Courier Dover Publications.

Vincent, J. F. (2002). Survival of the cheapest. *Materials today, 5*(12), 28-41.

van Doorn, W. G., & van Meeteren, U. (2003). Flower opening and closure: a review. *Journal of Experimental Botany*, *54*(389), 1801-1812.

VDI-Richtlinie 6220 (2012). *Bionik Konzeption und Strategie*. Düsseldorf. VDI-Verlag.

Von Mohl, H. (1856). Welche Ursachen bewirken die Erweiterung und Verengung der Spaltöffnungen. *Botanische Zeitung, 14*, 697-704.

Watanabe, S., & Sibaoka, T. (1973). Site of photo-reception to opening response in Mimosa leaflets. *Plant and cell physiology*, *14*(6), 1221-1224.

Whitney, H. M., & Glover, B. J. (2007). Morphology and development of floral features recognised by pollinators. *Arthropod-Plant Interactions*, *1*(3), 147-158.

Whittaker, E. T. (1988). *A Treatise on the Analytical Dynamics of Particles and Rigid Bodies*. Cambridge University Press.

Williams, S. E., & Bennett, A. B. (1982). Leaf closure in the Venus flytrap: an acid growth response. *Science*, *218*(4577), 1120-1122.

Wolf, L. L., & Stiles, F. G. (1989). Adaptations for the'fail-safe'pollination of specialized ornithophilous flowers. *American Midland Naturalist*, 1-10.

Woods, D. B., & Turner, N. C. (1971). Stomatal response to changing light by four tree species of varying shade tolerance. *New Phytologist*, *70*(1), 77-84.

Wright, T. W. (1898). *Elements of mechanics including kinematics, kinetics and statics, with applications*. D. Van Nostrand Company.

Zentner, L., & Böhm, V. (2008). On the Classification of Compliant Mechanisms. *Proceedings of EUCOMES 08*, 431-438.

Ziegenspeck, H. (1938). *Die Mizellierung der Turgeszenz-und Wachstumsmechanismen der Pflanzen.*

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Fig. 2.18: Thermo Scientific (2014). bscissors_67 [Online image]. Retrieved January 10, 2015, from: http://goo.gl/beIknO

Fig. 2.20-2.21: Joseph O. Jacobsen (2010). Lamina Emergent Mechanisms [Online image]. Retrieved January 10, 2015, from: http://goo.gl/NCbb2o

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Fig. 3.1: Gerald and Buff Corsi (2000). Snow buttercups [Online image]. Retrieved January 10, 2015, from: http://goo.gl/EVbXjE

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Fig. 3.5: Fir0002 (2008). Bee pollinating peach flower [Online image]. Retrieved January 10, 2015, from: http://goo.gl/xvahhQ

Fig. 3.6: Eugene Reimer (2003). Grass-pink (Calopogon tuberosus var tuberosus) [Online image]. Retrieved January 10, 2015, from: http://goo.gl/nmRCdv

Fig. 3.7: Peter Shaw (2013). Swollen petiole base called a pulvinus [Online image]. Retrieved January 10, 2015, from: http://goo.gl/NvU0jr

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Fig. 5.2: Nancy Nehring (2008). Photomicrograph of stomata of leaf [Online image]. Retrieved January 10, 2015, from: http://goo.gl/pYhHv6

Fig. 5.3: Pearson Education, Inc. (2005). Cells turgid stoma open [Online image]. Retrieved January 10, 2015, from: http://goo.gl/PTvJK9

Fig. 5.7: Richard Wheeler (2010). Oxalis Triangularis Timelapse [Online image]. Retrieved January 10, 2015, from: http://goo.gl/VykrCg

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'I'm not trying to imitate nature, I'm trying to find the principles she's using.'
- Buckminster Fuller (qtn in http://goo.gl/rsR2V7)

'While in appearance a machine differs greatly from any of the force- or motion-distributors of nature, yet for the theoretical or pure mechanician no such difference exists, -- or rather it completely disappears on analysis, so that for him the problems of machinery fall into the same class as those of the mechanical phenomena in nature. He sees in both forces and motion existing, and subject to the same great laws which, developed in their most general form, govern and must govern every single case.'
- Franz Reuleaux (Kinematics of Machinery, p. 17)

'A machine is a combination of resistant bodies so arranged that by their means the mechanical forces of nature can be compelled to do work accompanied by certain determinate motions.'
- Franz Reuleaux (Kinematics of Machinery, p. 35)

'In technology, shape is expensive, material is cheap.
In biology, material is expensive, shape is cheap.'
- Julian Vincent (qtn in http://goo.gl/ZIKKFm, p. 8)

'The same thoughts sometimes put forth quite differently in the mind of another than in that of their author: unfruitful in their natural soil, abundant when transplanted.'
- Blaise Pascal (Thoughts, p. 415)

'And thus, in contrast to the mere gaze, which by scanning organisms in their wholeness sees unfolding before it the teeming profusion of their differences, anatomy, by really cutting up bodies into patterns, by dividing them into distinct portions, by fragmenting them in space, discloses the great resemblances that would otherwise have remained invisible; it reconstitutes the unities that underlie the great dispersion of visible differences.'
- Michel Foucault (The Order of Things, p. 293)

'Architecture today is very much a team game. Increasingly designers work as generalists who try to combine the work of specialists to best effect and so explore new territory.'
- Hugh Whitehead (qtn by Jane Burry in http://goo.gl/WiBpv)

'TRANS-Disciplinary: Seemingly contrasting fields, when brought together, inform each other through the collision of ideas, transform into a new dimension greater than each alone, and transmute beyond any preconceived expectations.'
- Hiroshi Ishii (Keynote at NIME2014 on 7/2 in London)

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