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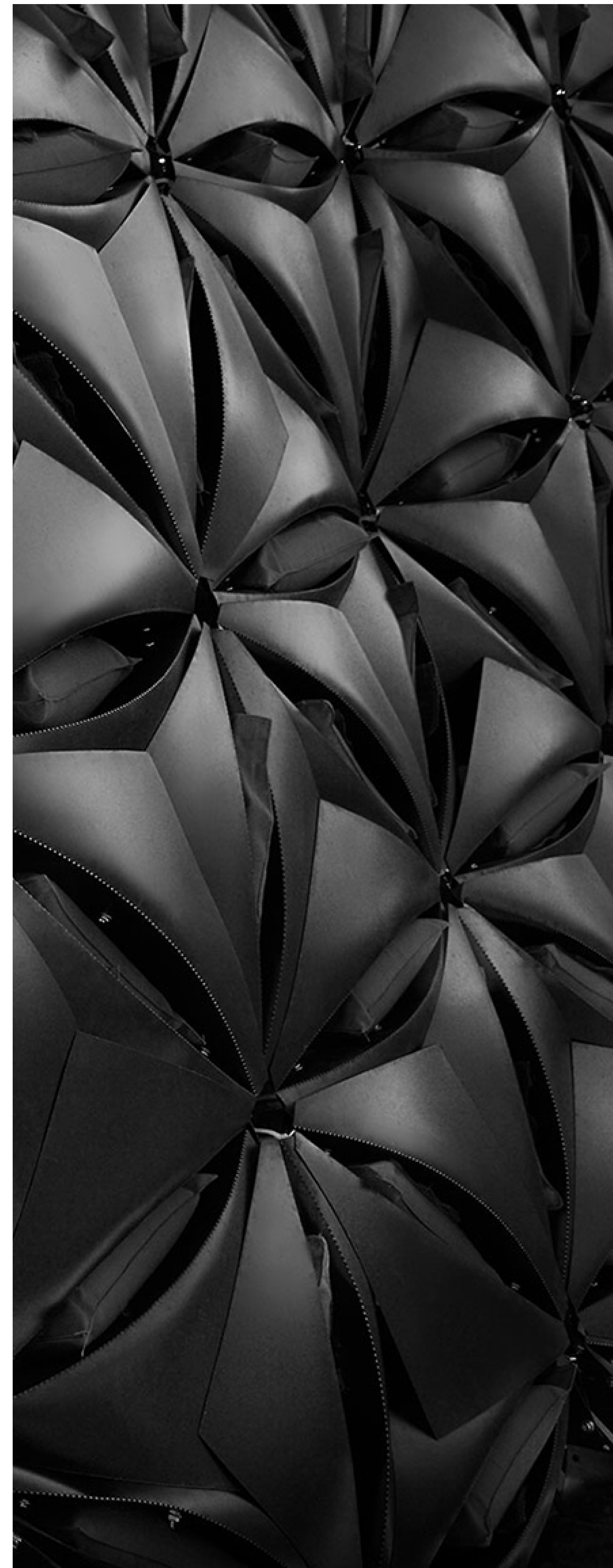

Axel Hannes Körner

Compliant Folding

Design and fabrication methodology
for bio-inspired kinetic folding mechanisms
utilized by distinct flexible hinge zones

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Compliant Folding

Design and fabrication methodology for bio-inspired kinetic folding mechanisms utilized by distinct flexible hinge zones

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

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Zusammenfassung

Situiert im Kontext bio-inspirierter nachgiebiger Mechanismen für architektonische Anwendungen und adaptive Gebäudehüllen setzt sich diese Arbeit das Ziel, ein Rahmenkonzept für Design und Fertigung von bio-inspirierten nachgiebigen Faltmechanismen, die durch flexible Gelenkzonen ermöglicht werden, zu entwickeln. Dies beinhaltet einen methodischen Entwurfsansatz, bestehend aus der Abstraktion und Klassifizierung von biologischen Faltmechanismen, sowie einen sequenziellen Abstraktionsprozess der zugrundeliegenden Wirkprinzipien hinsichtlich deren kinetischen Verhaltens, Materialisierung und Aktuierung. Darüber hinaus wurde die geometrische Anpassungsfähigkeit der untersuchten Faltmechanismen evaluiert, insbesondere in Bezug auf die Anwendbarkeit auf verschiedene Tessellierungen für doppelt gekrümmte Flächen. Die gewonnenen Erkenntnisse bildeten die Grundlage für die Entwicklung einer Reihe von technischen Anwendungen auf Demonstrator-Ebene. Die funktionalen Fallstudien dienen nicht nur als Basis, um das etablierte Rahmenkonzept zu testen und zu evaluieren, sondern auch um verschiedene Fertigungs- und Materialisierungsstrategien, sowie aktiv gesteuerte Aktuierungsprinzipien zu definieren, zu testen und zu bewerten.

Die ersten Kapitel bieten eine Kontextualisierung des Themas innerhalb des größeren Architekturdiskurses und geben einen Überblick über den Hintergrund, der die präsentierte Forschung beeinflusst hat, einschließlich bionischer Architektur, nachgiebiger Mechanismen und geeigneter Materialien. Dieser Teil der Arbeit schließt mit einer Darstellung aktueller Forschungsherausforderungen im Bereich kinetischer und adaptiver Gebäudehüllen und stellt eine Reihe von Projekten nach dem Stand der Technik vor.

Kapitel drei enthält die Veröffentlichungen über die Entwicklung der vier Demonstratorprojekte Flectofold, Flexafold, Arch(k)inetic und den ITECH Forschungsdemonstrator 2018-19, sowie relevante Untersuchungen, welche die Grundlage für diese Arbeit zum Thema bio-inspirierte nachgiebige Faltmechanismen bildeten.

Kapitel vier und fünf schließen die Arbeit mit einer Zusammenfassung und kritischen Reflexion der Ergebnisse sowie der Diskussion möglicher zukünftiger Entwicklungen im Bereich nachgiebiger Mechanismen für adaptive Gebäudehüllen ab.

Abstract

Within the larger context of bio-inspired compliant mechanisms for architectural applications and adaptive building envelopes, this thesis aims for the establishment of a design and fabrication framework for bio-inspired compliant folding mechanisms, utilized by distinct flexible hinge-zones. This includes a methodological design approach, consisting of the abstraction and classification of biological folding mechanisms, as well as a sequential abstraction process of underlying working principles regarding kinetic behaviour, materialisation, and actuation strategies. Furthermore, the geometric adaptability and the design space of the established folding mechanisms has been evaluated, especially related to the applicability to different tessellation patterns for double curved surfaces. The insights built the basis for the development of a series of technical applications on a demonstrator level. The functional case studies serve not only as basis to test and evaluate the established design framework, but also to define, test and assess various fabrication and materialisation strategies, as well as actively controlled actuation principles.

The first chapters provide a contextualisation of the topic within the larger architectural discourse and give an overview of the background which has influenced the presented research, including biomimetic architecture, compliant mechanisms and suitable materials. The section concludes with a presentation of current research challenges within the field of kinetic and adaptive building envelopes and introduces a series of sate of the art projects.

Chapter three contains the publications about the development of the four demonstrator projects Flectofold, Flexafold, Arch(k)inetic and the ITECH Research Demonstrator 2018-19 and relevant investigations which built the basis for this thesis on the topic of bio-inspired compliant folding mechanisms.

Chapter four and five conclude the thesis with a summary and critical reflection of the results, as well as the discussion of potential future developments within the topic of compliant mechanisms for adaptive building envelopes.

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1. Introduction

Most technical movable applications are utilised by so called rigid body mechanisms, where rigid elements are joint by hinges with specified degrees of freedom. In contrast to this clear functional distinction between stiff elements and joints, the investigation of biological systems reveals numerous motion principles which are based on elastic deformation of fibrous materials, known as compliant mechanisms. These compliant mechanisms use the interrelation between form, structure and material – inherent to biological systems – to achieve a great variation of motion possibilities, while keeping the mechanical complexity comparatively low. Besides performative aspects, the investigation of biological compliant mechanisms offers interesting design potentials. Mechanisms based on elastic deformation often only need a small actuation impulse to actuate a complex three-dimensional output motion – not obvious but still plausible to the observer, an aesthetic value of complex biological motion.

1.1 Motivation

Sustainable and conscious handling of resources, as well as reduction of energy consumption are of utmost importance in design and engineering in general and especially in the planning of our future built environment. Here, the distinct design of active adaptation to react to changing external boundary conditions is of special interest, following the premise that adaptive structures can satisfy a higher range of performative demands with less embodied energy. Within this context, climate adaptive façade systems have taken a prominent role, since facades, as the mediators between an external and an internal climate, are one of the main factors for energy exchange between a building and its surrounding.

In contemporary architecture, most movable elements are utilised by rigid body mechanisms, which are mainly guided along straight translation or rotation axes. Especially in the context of adaptive façade elements, this fact leads to mechanical complexity and geometric constraints. The application of common adaptive shading systems on more complex building geometries and double curved facades increases the mechanical complexity significantly and makes them prone to

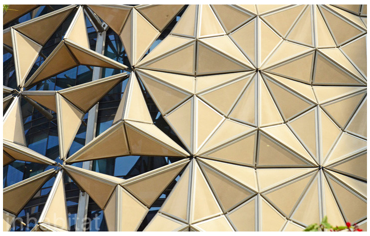

FIG. 1.1

Adaptive Facade Shading Al Bahr Towers by AEDAS

failure. Consequently, such systems often are not applicable, or can only be mounted on the inside, which leads to a drastic loss of efficiency in control of thermal heat gain.

Flexible membranes may offer larger geometric freedom, but such elements are only stable in a stressed and predefined deployed configuration. The transition phase between open and closed configuration is hard to control. Rigid folding mechanisms, such as the adaptive façade shading of Al Bahr Towers by AEDAS in Abu Dhabi (Fig. 1.1) (Fortmeyer and Linn 2014) offer the potential to be applicable to complex and double curved façade geometries. But, again, to the cost of an increased mechanical complexity.

So called compliant mechanisms utilise elastic deformation to transfer an input force to a desired output performance. The motion behaviour is achieved by a combination of functional geometric articulation, accordingly distributed material, and locally defined mechanical properties. They function without rigid body mechanics and offer large potential for geometric adaptations, while at the same time reducing the mechanical complexity significantly.

Although most technical mechanical applications are still realised by rigid body mechanisms, biology reveals a multitude of very robust motion patterns based on the reversible elastic deformation of fibrous materials. Especially folding patterns of surface like elements in plants and arthropods offer a great variety of complex but efficient motion principles with low mechanical complexity.

In addition to quantifiable technical advantages, bio-inspired compliant mechanisms offer a great potential in terms architectural Gestalt. While in most common technical applications rigid components are sliding against each other or rotating along straight axis, in biological compliant mechanism a comparatively small initial actuation impulse leads through motion amplification to a complex three-dimensional deformation. This complex resultant motion behaviour appears to be plausible for the observer but is less obvious than in classical rigid body mechanisms, making it an engaging design feature.

For the design of compliant mechanisms, it is essential to understand geometry, material and functional elastic deformation as an inseparable unit. In contrast to rigid body mechanisms, it is not possible to isolate the motion behaviour from the material itself.

Thus, the investigation of bio-inspired compliant mechanisms has a long history at the University of Stuttgart, especially at the itke. The investigation started with the work of Mohammad-Reza Matini, who set the ground work for this field of research and let to his dissertation “Biegsame Konstruktionen in der Architektur auf der Basis bionischer Prinzipien” (Matini 2007). He identified and classified a series of biological motion patterns and proposed a method to abstract principle kinematic building blocks. Simon Schleicher continued the work and formalised a sequential design and simulation methodology for the abstraction of plant motions to technical application which led to his dissertation on “Bio-inspired Compliant Mechanisms for Architectural Design - Transferring Bending and Folding Principles of Plant Leaves to Flexible Structures” (Schleicher 2016).

In this context, the presented work aims to extend the previous developed methodological approaches for the design of bio-inspired compliant mechanism with the main focus on folding mechanisms, utilised by distinct flexible hinge zones of concentrated compliance. This involves the investigation, abstraction and combination of mechanical and geometrical folding principles and their materialisation as found in nature. Additionally, the work proposes refined and new design and simulation methods with the use of kinematic and kinetic models, which integrate investigations about materialisation, fabrication, and actuation concepts. Eventually, based on the disclosed mechanical and geometrical principles a technical categorisation framework for biological role models is proposed to assist the search for similar mechanical behaviours within role models which are not related in biological terms.

1.2 Research Objectives

The main research objective throughout the presented work is the development of a coherent design framework for bio-inspired compliant folding mechanisms, to provide a systematic approach of how to investigate and abstract biological folding mechanisms.

Therefore, the work is comprised of investigations on varying levels, ranging from an abstract conceptual design methodology, the establishment of geometric and mechanical constraints, to physical application development on a demonstrator level (Fig. 1.2).

The design methodology builds up on previous work done by Mohammad-Reza Matini (Matini 2007) and Simon Schleicher (Schleicher 2016) by refining the process and adding new methods to the existing repertoire. The research includes the methodological approach of abstraction of biological principles on various levels, such as kinematic and mechanical behaviour, materialisation strategies, as well as actuation principles. Furthermore, it aims to refine the established kinematic and kinetic simulation methods with focus on a qualitative study of working principles and form-force relationships, as well as quantitative studies considering detailed materialisation and fabrication methods and actuation. Eventually, a technical classification terminology is proposed to identify similar mechanical principles and various biological role models, to guide the search for biological role models with defined technical descriptions.

The geometric adaptability of kinetic compliant folding mechanisms utilised by distinct elastic hinge zones of concentrated compliance focuses on a local level on the theoretical design space of kinematic principles, as well as the parameterisation of influencing attributes, such as materialisation, actuation and geometric features. The insights on local adaptation possibilities are used to translate specific folding mechanisms to different polygonal tessellation patterns, applicable for the discretisation of synclastic and anticlastic geometries.

The development of physical applications on a demonstrator level has been of main importance throughout the presented research. The guiding research objectives within the field of application development have been questions of materialisation, especially related to material gradients and transitions from high to low stiffness, as well as the associated fabrication complexity. On the actuation level the focus lies on the development of actively controlled pneumatic actuators and their integration into the material system. The control methodology aims for an active control system, which can be integrated in various operating systems and interaction sce-

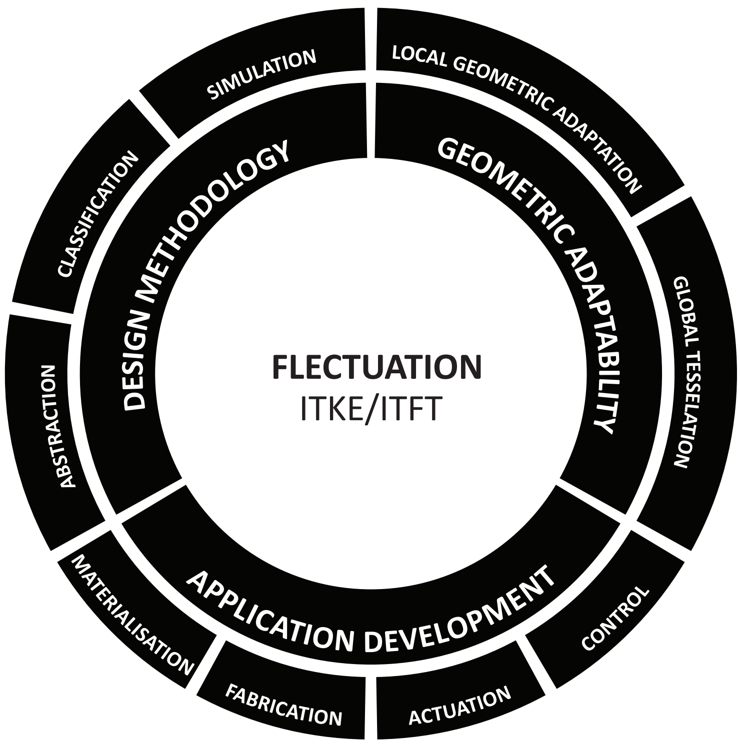

FIG. 1.2

Research objectives

narios. Furthermore, the physical demonstrators can be seen as poof-of-concept for the proposed design framework.

It must be stated that none of the sub-aspects can be considered in isolation. All aspects are part of an integrated design process. Thus, the developed design framework is used to extract, manage, and provide necessary data and information between the relevant steps of development.

1.3 Exclusions

The application as adaptive façade shading device has been the main motivation throughout the process and is clearly reflected in the development of the presented research demonstrators on a very fundamental level. The assessment and evaluation in comparison to existing state of the art façade shading elements has not been part of this research. Furthermore, the active control systems allow for the integration into varying control and interaction scenarios, which has been exemplary proven. The integration into existing building operating systems was not part of the research.

2. Background

The presented work is situated at the intersection of different research fields and disciplines. Thus, the following pages will give a broad overview of the background, which influenced the research. This includes the discussion of biomimetic research as a design methodology, compliant mechanisms, and suitable materials. The chapter concludes with the presentation of current challenges in the field of adaptive facades and the introduction of relevant projects within the overarching topic.

2.1 Biomimetics as a Design Methodology

The word "biomimetics" is a combination of the two Greek words "Bios" (life) and "Mimesis" (to imitate). The direct translation would be "to imitate life" or "to imitate biology". In contrast to this literal translation, the most common scientific definition of biomimetics is not the direct copy of biological role-models into technical applications. Instead, it describes the creative process of transferring knowledge, insights, and ideas between different scientific disciplines, such as biology, engineering, and, in this case, also architecture. Thus, the term bio-inspired is used often in the context of biomimetic research to underline the aim. The German word "Bionik" and the French word "Bionique" combine the words biology and technology, and can be seen as equivalent to biomimetic and emphasise the interdisciplinary approach (Schleicher, 2016; Speck & Speck, 2008).

Thomas and Olga Speck define the biomimetic process more precise as "the realization of technical applications based on insights resulting from fundamental biological research." (Speck & Speck, 2008). Here, the basis of biomimetic research is the exchange of knowledge. A detailed quantitative analysis of biological role-models is used on the one hand to understand biological principles, which can be abstracted, generalized, and eventually transferred to technical applications. On the other hand, the quantitative analysis (often carried out with methods from other disciplines, such as engineering, physics, or chemistry) offers new insights in understanding the biological role-model. (Speck & Speck, 2008) introduced the term of reverse biomimetics for knowledge transfer from other disciplines to biology.

Although, biomimetic research offers great potential to generate new ideas as scientific discipline it is still hard to define. The lack of defined rules for abstraction and translation processes, as well as the interdisciplinary nature, make it difficult to establish a structured and goal-oriented workflow for biomimetic research. Consequently, previous definitions focused primarily on the intention of starting a biomimetic research project, rather than defining its process (Schleicher, 2016).

Thus, many biomimetic design strategies have been developed throughout recent years within various research institutions. (Badarnah & Kadri, 2015) classified them into two main categories (Fig. 2.1):

1. **"Problem-based approach", a top down approach or "technological pull" (Speck & Speck, 2008). This approach starts with a technological problem and searches for solution strategies in nature. In (Badarnah & Kadri, 2015) this approach is structured into three steps: Problem definition, biological explorations, and solution development. The three steps are connected with transition phases, in which knowledge and information between the technical and engineering domain and the biology domain are exchanged.**
2. **"Solution-based approach", a bottom-up approach or "biological push" (Speck & Speck, 2008). Here, the research starts with biological observations, which eventually lead to technical innovation. (Badarnah & Kadri, 2015) structure this approach into the biological domain and the technical domain, connected by one transition phase.**

An often expressed critique on those rather linear biomimetic design approaches (Badarnah, 2012; Knippers & Speck, 2012; Schleicher, 2016) is, that it seems best applicable, if the research focuses on the translation of a specific biological principle into a specific application, such as Velcro (Fig.

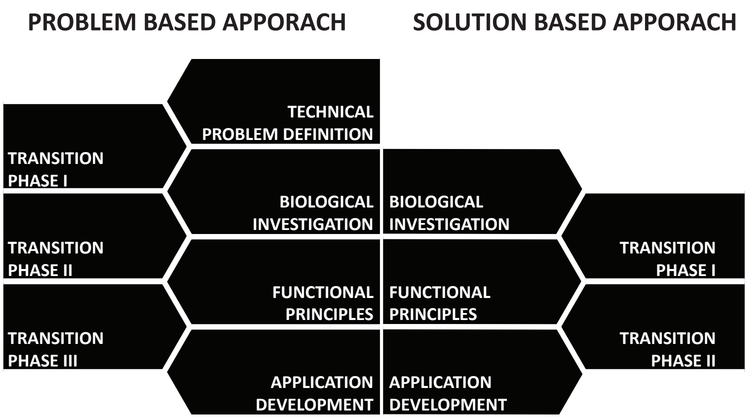

FIG. 2.1

Design sequences for problem based and solution based biomimetic development process

2.2) and flectofin® (Fig. 2.3), or if a very clearly described technical problem needs to be solved. Thus, the methodological approach for biomimetic design strategies has to be extended and the communication process within the various transition phases between technology and biology has to be systemised. The investigation of biological form and function principles should inspire engineers and architects to develop fundamentally new solution strategies, which are not necessarily directly derived from a specific biological role-model (Knippers & Speck, 2012).

Among others, three methodological approaches of biomimetic design and research should be mentioned and highlighted in this context: (1) "A methodology for the generation of biomimetic design concepts" (BioGen) (Badarnah, 2012, 2017; Badarnah & Kadri, 2015), (2) "Biegsame Konstruktionen in der Architektur auf der Basis bionischer Prinzipien" (Matini, 2007) and (3) "Bio-inspired Compliant Mechanisms for Architectural Design" (Schleicher, 2016).

With the development of BioGen Lidia Badarnah focuses on the development of a systematic approach to classify biological principles according to functional performance. Thus, a series of different role-model strategies can be identified, which fulfil the same or similar functional aspects by employing different biological processes (i.e. morphology, anatomy, behaviour, etc.). To describe the classification according to functional attribution, the term functional convergence is introduced as a major communication tool between the domains of biology and engineering. Which should help to guide the search for relevant biological role-models. Thus, in the context of façades, BioGen defines functional aspects needed for performative building envelopes, such as heat gain, air exchange, water transport, or light filtration. Then, biological role-models are identified, which fulfil this functions, and further classified in terms of the underlying principles. This classification and communication method not only assists the search for new biological role-models, but also enables the combination of different principles on different abstraction levels, such as material based and geometry based principles (Badarnah, 2017).

Mohammad-Reza Matini developed a systematic approach for the investigation of motion principles based on compliant mechanisms as found in biology. Thus, he abstracts basic motion principles and transfers them into geometric models, categorized according to underlying motion typologies (i.e. two-dimensional and three-dimensional shape change, change of curvature direction, etc.), which eventually leads to a catalogue of compliant motion principles. By abstracting and combining different motion principles, he pro-

FIG. 2.2

Velcro as an example for a biomimetic product

FIG. 2.3

flectofin® as an example for a bio-inspired compliant mechanism for architectural applications poses a series of technical applications in an architectural context (Matini, 2007).

In collaboration with biologists of the Plant Biomechanics Group in Freiburg, Simon Schleicher developed a methodology for the abstraction and simulation of plant motions by the means of computational models. His methodology includes the simulation of the actual plant motions, the disclosure of underlying principles and their geometric variations, as well as the analysis of the involved forces and energy. To establish a repeatable, sequential method for the abstraction of bio-inspired compliant mechanisms, he divided his approach into three models. The geometrical model can be seen as a static representation of the underlying geometrical principles responsible for the respective motion. Once identified, the geometric model can be parameterised, and a catalogue of topological identical variations can be generated. The kinematic model investigates the actual motion. The geometrical variations can be qualitatively evaluated in terms of their influence on the motion without considering forces. The kinetic model uses nonlinear finite element analysis to simulate large elastic deformations and to evaluate the involved forces. Based on exact physical material properties, it enables the sophisticated comparison of actuation forces and resultant motions for geometric variations, different materialisation strategies and stiffness gradients.

The mentioned design methodologies provide systematic procedure to transfer, abstract and classify technological and biological principles. What is missing is the consistent categorisation of specific principles to describe technical and biological functional principles with the same language, to assist the search for biological role-models with similar functional principles but possible different morphological materialisation principles.

2.2 Compliant mechanisms

A mechanism is defined as a device to transform an input motion, force and energy to an output motion, force or energy (Verein Deutscher Ingenieure, 1993). In contemporary technical constructions this transformation is mainly achieved by so called rigid body mechanisms, where rigid links are joined together with kinematic connections.

In contrast to rigid body mechanisms, so-called compliant mechanisms achieve their functionality by controlled elastic deformation of flexible members (Howell et al., 2013). Those mechanisms can be completely free of typical joints. Thus, compliant mechanisms need less maintenance and the

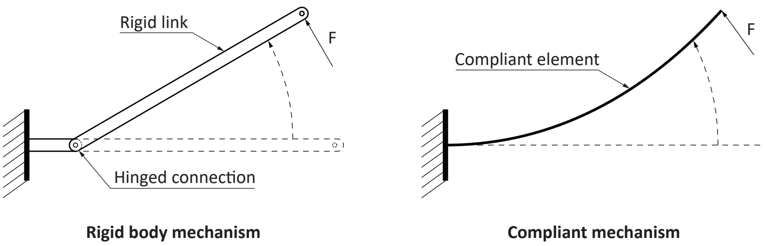

FIG. 2.4

Comparison of rigid body mechanism and compliant mechanism

mechanical complexity is reduced significantly (Fig. 2.4) (Howell et al., 2013).

On a higher level, compliant mechanisms can be classified into two distinctive groups according to the type of flexibility used to achieve the desired mechanical behaviour: Mechanisms with concentrated compliance and mechanisms with distributed compliance.

Mechanisms with concentrated compliance are characterised by limiting the flexible deformation to only a small part or region and not to the whole structure (Albanesi et al., 2010). Such mechanisms are very similar to rigid body mechanisms in their behaviour, where kinematic joints are replaced with distinct flexible hinge zones (Fig. 2.5).

A compliant mechanism with distributed compliance achieves its flexibility by elastic deformation of large areas or the entire structure. Thus, during the motion the deformation and therefore stresses are not concentrated in small areas but are, distributed over the whole element (Albanesi et al., 2010; Poppinga et al., 2016) (Fig. 2.6).

The intentional use of elastic deformation to facilitate a defined function and mechanical purpose is everything but new and can be observed throughout history. Here, the bow must be mentioned as a prominent example for an early human-made machine utilized by compliant mechanisms. Archaeological findings date back to the stone age, with indirect indications as old as 64,000 years (Lombard & Phillipson, 2010; Rosendahl et al., 2006). Also, many compliant mechanisms can be found in the sketches of Leonardo da Vinci (Howell et al., 2013). The use of compliant mechanisms in early machines and many simple applications, such as foldable packaging, key rings, paper clips etc. (Fig. 2.7-2.9) might be due to an intuitive and empirical design approach which contrasts an analytical design approach which is needed for more complex mechanisms. Rigid body mechanisms are comparatively straight forward to design with an analytical approach, due to the fact, that it is easy to isolate different functions to different parts. For compliant mechanisms on the other hand, it is not possible to separate kinematic and kinetic behaviour from functional aspects. Thus, the analytical design of compliant mechanisms becomes more complex. Pseudo rigid body

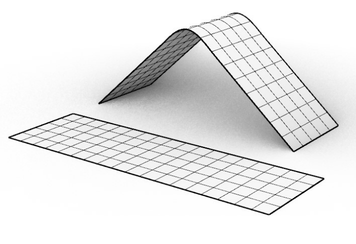

FIG. 2.5

Compliant mechanism with concentrated compliance

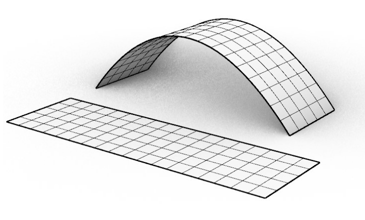

FIG. 2.6

Compliant mechanism with distributed compliance

FIG. 2.7
Keyring

FIG. 2.8
Paper clip

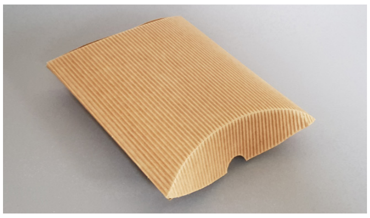

FIG. 2.9
Curved-line folding packaging

mechanisms have been introduced to assist the design. Here, a compliant mechanism is represented by a rigid body mechanism with additional spring elements to estimate the involved forces. On the other hand, compliant mechanisms can reduce the mechanical complexity of the mechanisms itself (Howell et al., 2013). Therefore, the design might be more complex, but the actual mechanism can be simpler and less prone to failure.

Advancements in computational design and simulation tools, combined with new materials and fabrication methods attracted again the interest of many researchers to investigate the possibilities and potentials of compliant mechanisms.

The shift from compliant mechanisms to rigid-body mechanisms, and eventually back to compliant mechanisms, is best illustrated with the examples of the wings of aeroplanes. One of the first aeroplanes developed by the Wright brothers employed wing warping to control the flight (Fig. 2.10). But, due to the complexity of the design, it was soon replaced by rigid plates, connected by kinematic hinges. Nowadays the research trend for flight control investigates once again the wing warping. (Howell et al., 2013; Sinapius et al., 2014).

It can be summarized that compliant mechanisms offer many advantages, but also disadvantages, especially considering the comparatively complex design. Thus, for each specific design task it needs to be carefully evaluated if the advantages outweigh the challenges. A comprehensive review of advantages and challenges associated inherently with compliant mechanisms can be found in (Howell et al., 2013) and (BYU Compliant Mechanisms Research Group, 2020):

2.2.1 Advantages inherent to compliant mechanisms

Compliant mechanisms offer the potential to integrate multiple functions into fewer parts by employing material flexibility instead of kinematic hinges, springs etc. This offers various significant advantages, such as weight reduction and simple fabrication processes, often even in one single fabrication step, such as 3d printing or injection moulding. Many compliant mechanisms (Fig. 2.9) can be produced from flat sheet material, where controlled flexibility within the continuous material can be achieved with subtractive (laser cutting, milling, etc.) or additive (lamination, 3d printing) fabrication techniques.

The advantages mentioned above lead directly to economic advantages, due to reduced fabrication and assembly complexity, as well as shipping costs. Especially the weight reduction is a relevant factor for many industries, such as automobile or aerospace. The reduction (or in some cases even elimination) of wear, backlash and friction increases the performance and accuracy of compliant mechanisms and over-

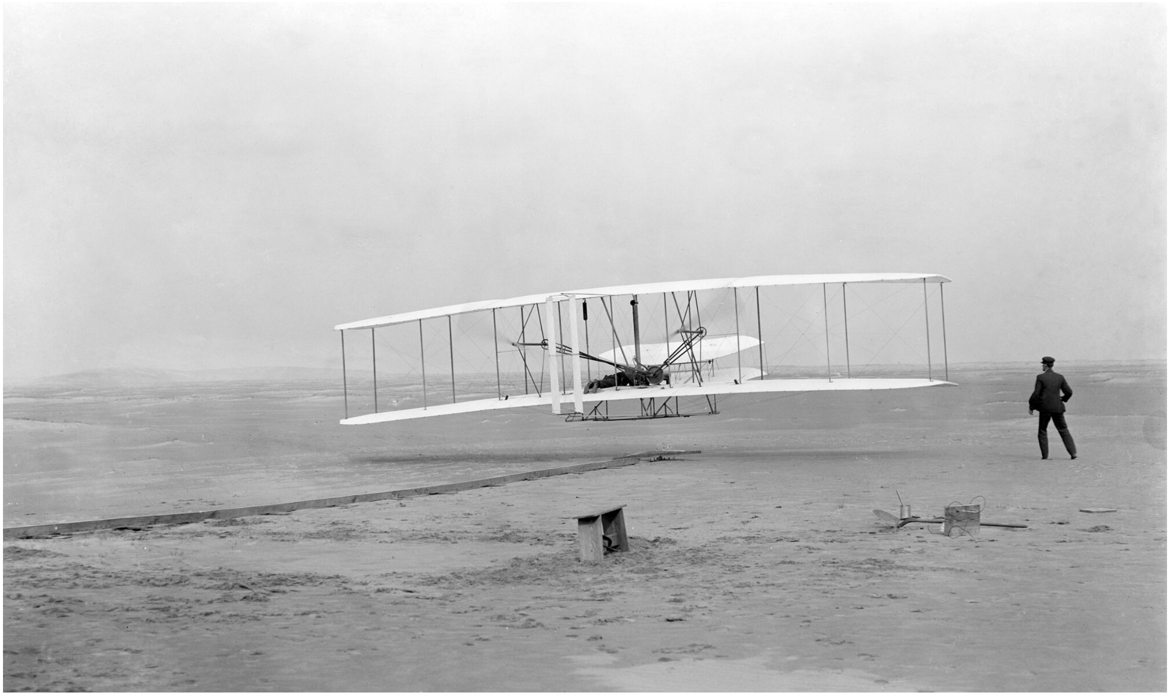

FIG. 2.10

An early aeroplane using wing warping for flight control

come the need of lubrication (Howell et al., 2013) and (BYU Compliant Mechanisms Research Group, 2020).

Compliant mechanisms can store elastic energy within their flexible parts. This elastic energy can be used to restore the zero-energy state after the actuation force is released. Thus, actuation is only needed in one direction. To facilitate a similar behaviour in rigid body mechanisms additional spring elements need to be added. Thus, the number of parts, and, therefore, the mechanical complexity becomes an even more important aspect.

2.2.2 Challenges inherent to compliant mechanisms

Since the motion of compliant mechanism relies on the material flexibility, the range of motion is limited and not all mechanical principles, such as shaft to bearing to facilitate continues infinite revolutions, can be transferred to compliant mechanisms.

Probably the most difficult aspect is the design and analysis of compliant mechanisms due to the fact that it is not possible to separate the design of a specific motion behaviour from the associated elastic material deformation, involved stresses and forces. Consequently, compliant mechanisms cannot be simplified with traditional methods of mechanical engineering.

Thus, the development of historical examples is often based on a trial and error approach, which works very well for simple mechanisms. But to generalise mechanical principles and to develop reliable and complex mechanical systems, a more detailed simulation- and analysis-based methodology is needed. Since compliant mechanisms rely on large deformations, comparatively complex nonlinear simulation models are needed for analysis.

Besides these rather theoretical challenges, the aspect of fatigue needs to be addressed. Repeated load cycles to achieve large deformations might lead to high stress concentrations and, eventually, to damage. It is essential that the fatigue life exceeds the expected load cycles, which requires detailed knowledge about the involved material behaviour. In this context, also creep due to high stresses over longer periods of time and high temperature fluctuations must be considered unconditionally.

2.2.3 Bio-inspired compliant mechanisms

Even though compliant mechanisms attract increasing attention in engineering, the majority of contemporary mechanisms is still realised by rigid body mechanisms. In contrast most motions in biology are realized with compliant mechanisms, such as folding of insect wings, plant motions, cilia, jelly fishes and many more (Matini, 2007). Thus, it is not surprising that many researchers (Charpentier et al., 2017; Pagitz et al., 2014; Pagitz & Bold, 2013) have been investigating natural motion principles to draw inspiration for technical applications.

2.3 Fibre reinforced plastic

The question of the appropriate material is particularly important for the development of compliant mechanisms, especially due to conflicting requirements inherent to flexible structures. On the one hand the material needs to be flexible enough to facilitate the required deformation. This is especially important for foldable elements with distinct elastic hinge zones of concentrated compliance where comparatively small bending radii are needed. On the other hand, the material needs to be stiff enough to withstand loads, such as self weight and wind loads.
Furthermore, the material is required to store elastic energy to reset the mechanism to its zero-energy state after release of the actuation force.

Julian Lienhard (Lienhard, 2014) identified the ratio between Flexural Strength $\sigma_{M,Rk}$ [MPa] and Flexural Young's Modulus E [GPa] as the major aspect for classifying suitable materials and postulates a ratio $\sigma_{M,Rk}$[MPa]/ E [GPa] > 10 as

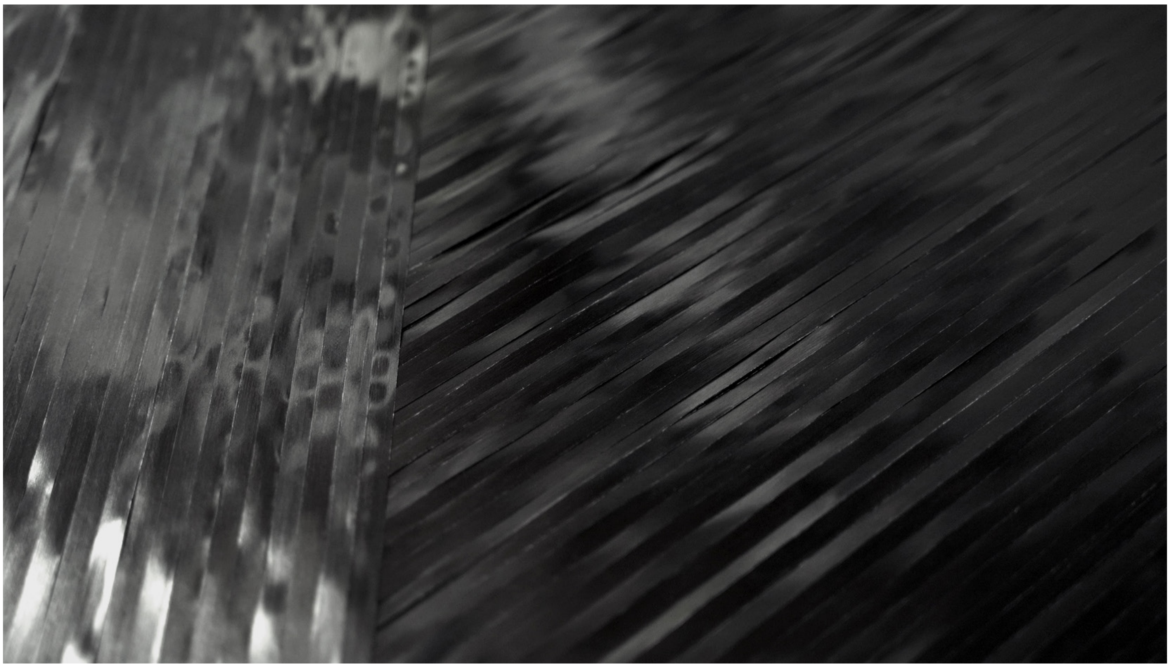

FIG. 2.11

Unidirectional carbon fibre tape in polyamide matrix

suitable for elastic kinetic structures. Furthermore, the long-term fatigue behaviour and long-term creep have to be taken into consideration.

Based on this consideration and the experience of previous kinetic elastic structures, the use of fibre reinforced plastic seems to be promising. In addition to the needed high flexural strength to flexural Young's modulus ratio, fibre reinforced plastics are comparatively lightweight and offer the possibility to calibrate precise local material properties in integral additive fabrication methods.

2.4 Kinetic façade shading

Despite the common perception of our built environment as something static and permanent, architects and engineers have been seeking for reconfiguration and adaptation throughout the history of architecture. This led to many concepts and technical solutions that might facilitate architectural applications to adapt to changing spatial and structural demands, as well as to environmental influences. Thus, portable nomadic shelters can be seen as early examples of transformable architecture, while the retractable velarium of the Roman Colosseum (70-80 AD) (Fig. 2.12) is an impressive example of adaptive sun shading (Asefi, 2010).

Current trends in research related to adaptive architecture argues, that the use of digital tools includes the operation of architectural spaces, which can be perceived as robotic architecture, in contrast to robotic fabrication. Examples range from adaptive spatial installation such as the flexing room (Kilian, 2018), an inhabitable spatial robot and the ITECH Master thesis Self-Choreographing Network by Valentina Soana and Mathias Maierhofer (Maierhofer et al., 2019) (Fig. 2.13), to projects focusing on the performative aspects of autonomous structural adaptation as reaction to sensor feedback (Fig. 2.14) (Senatore et al., 2018; Sobek, 2016).

Within the broad field of adaptive architecture, climate adaptive building skins are of special interest, due to their potential to reduce greenhouse gas emissions. Recent studies suggest that the construction and management of buildings are responsible for about 40% of energy consumption in the European Union. Heating, as well as cooling to keep the internal thermal comfort standards contribute significantly to the high energy consumption of buildings, which can be drastically reduced by the use of external shading devices (Barozzi et al., 2016). Current reports assume that the oil consumption in Europe can be reduced by 10% - a reduction of 111 million tonnes CO2 per year. To set this number in some relation, the complete road traffic in Germany in 2018 was responsible for 155.8 million tonnes CO2 (Fig. 2.15) (BMWi, 2020).

Besides the performative aspects of facades as a mediator between the interior and exterior climate, a façade also has a very important function in terms of communication, design and Gestalt. The discussion of façades remains a prominent topic within the architectural discourse (Velasco et al., 2015), which makes the field of adaptive façades a very important research topic from an engineering as well as a theoretical perspective. Many research institutions are constantly contributing to the topic, such as most recently the COST Action TU 1403 adaptive façade network (Favoino et al., 2018), which

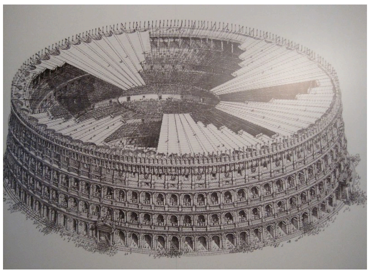

FIG. 2.12

Velarium of the Roman Colosseum

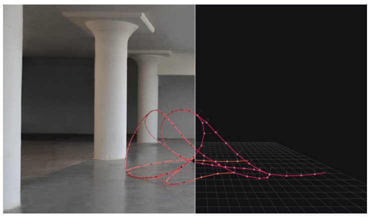

FIG. 2.13

Self-Choreographing Network

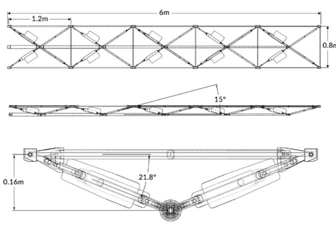

FIG. 2.14

Adaptive truss prototype (Senatore et al., 2018)

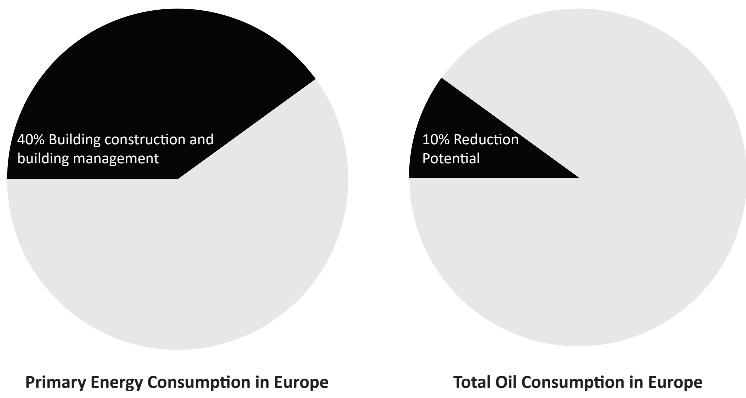

FIG. 2.15

Energy consumption of the building sector and saving potential enabled by the use of adaptive facasd systems aimed for a standardised framework for design, simulation and evaluation of adaptive façades.

Thus, (Attia et al., 2020) categorise future trends and concepts into four main categories:

1. **Dynamic shading summarizes mechanical solutions such as shutters and blinds to obstruct sunlight with the aim to control the interior visual (glair) and thermal comfort level.**
2. **Solar active facades include integrated PV cells, double skin facades, and green facades. Some approaches also fulfil the function of sunlight obstruction and can be combined with dynamic shading elements.**
3. **Chromogenic facades describe glazing, which can change its transparency by active control.**
4. **Active ventilated facades control the ventilation of buildings by actively controlled windows and openings.**

In the context of the presented research mainly dynamic shading systems are of interest. Functional integration of solar active elements, such as PV cells, offers opportunities that will be addressed in future research.

In addition to this typological classification (Attia et al., 2020) propose an analytical framework to categorise promising research topics in the field of adaptive facades:

1. **Human centred design is concerned with human comfort and wellbeing in interior space and psychological acceptance of adaptive facades and the interaction of users with adaptive systems.**
2. **Smart building operating systems, machine learning and artificial intelligence offer the potential to integrate adaptive facades into automated control systems.**
3. **Service driven solutions respond to emerging demands associated with adaptive facades, such as maintenance, user interaction, system integration, technological robustness, system evaluation etc.**
4. **Circularity and materials summarize questions about the materialisation of new adaptive building envelopes. Two main questions are here to mention: the life cycle of used materials and development of lightweight materials.**

Other researchers classified a terminology for kinetic facades based on their system properties. Loonen defines climate adaptive building shells (CABS) as “a system that has the ability to repeatedly and reversibly change its features, functions or behaviour over time in response to changing performance requirements and variable boundary conditions with the aim of improving overall building performance” (Loonen et al., 2013). Furthermore, Loonen classifies CABS into multiple categories:

- **Source of inspiration (i.e. biomimetic, phototropism, heliotropism)**
- **Relevant physics of their interface with the environment (blocking, filtering, converting, collecting)**
- **Time-scales of their operation (seconds, minutes, hours, diurnal, seasons)**
- **Scales of adaptation (micro scale, macro scale)**
- **Control types of actuation (extrinsic, intrinsic)**

Furthermore, kinetic building envelopes can be categorised by types of motions (i.e. rotation, translation), the direction of motion (spherical, circular tangential, radial, pivoting, monoaxial, biaxial, multiaxial) and morphological transformation (i.e. folding grills, telescopic, scissor, folding, folding plates, pneumatic structure etc.) (Velasco et al., 2015). New Move - Architektur in Bewegung - Neue dynamische Komponenten und Bauteile categorises a series of case studies based on the underlying mechanical principles, such as pivoting, rotating, sliding, folding, oscillating, deforming and complex motions (Schumacher et al., 2020).

The following section will present a short overview of relevant projects, which have influenced the development of the presented research. Due to the large amount of existing relevant projects, the overview does not aim for completeness.

2.4.1 flectofin®

The flectofin® (Fig. 2.16) was one the first bio-inspired compliant mechanisms for adaptive façade shading systems, developed at the itke. The investigation of the pollination mechanism of the Bird-of-Paradise flower (*Strelizia reginae*) served as the biological role-model for underlying motion principle. The flower consists of a cantilevering perch with two flower petals connected to it. In case a bird is landing on the perch, this induces bending into the structure, which, eventually actuates a sideways flapping motion of the attached flower petals. Thus, the pollen is exposed and gets attached to the bird, which will carry it to the next flower. After the weight of the bird is removed from the perch, the mechanism resets its zero energy state due to stored elastic energy and the petals close again.

The relevant motion principle for technical application can be represented in simplified way by a rod-like structural element on which thin lamellas are attached. A relatively

FIG. 2.16
flectofin®,
itke - University of Stuttgart

small bending deformation of the central rod leads to amplified deflection of the attached flaps of up to 90°. A phenomenon which is known to the field of structural engineering as lateral torsional buckling and is commonly considered as a failure mode and, therefore, sought to be avoided. In biology on the other hand, this elastic deformation is used to achieve a motion which can be repeated many times.

The actual flectofin® is made of glass fibre reinforced plastic (gfrp). A linear actuation force is applied eccentric on one end of the central gfrp bar to induce the bending, which leads, eventually, to opening of the gfrp flaps. (Julian Lienhard et al., 2011; Julian Lienhard, 2014).

A disadvantage of the underlying mechanical principle is that it requires a comparatively stiff and homogeneous transition zone between the back-rib and attached flaps. This leads not only to relatively high actuation forces and high stress concentration at the connection between flaps and back-rib, but also to an inherent conflict between requirements on motion utilized by elastic deformation (low stiffness preferred) and the capacity to withstand external loads, such as wind (high stiffness preferred).

FIG. 2.17

One Ocean Pavilion
soma architecture and Knippers Helbig Advanced Engineering

2.4.2 One Ocean Pavilion

The analysis of natural motion principles based on compliant mechanisms led to the development of the adaptive and kinetic façade of the One Ocean pavilion (Fig. 2.17) for the Expo 2012 in Yeosu, South Korea. The building has been designed by the Vienna based architecture practice soma, the kinetic façade was developed by Knippers Helbig Advanced engineering. The 140 m long façade consists of 108 flexible lamellas made of glass fibre reinforced plastic. The lamellas range in length between 3 m and 13 m.

Each lamella has a hinged connection on the top and the bottom to an underlying substructure. The two adjacent corners are connected to linear actuators, which apply a compression force on one corner on the upper edge and one corner on the lower edge. This reduces the distance between the two corners and induces an asymmetric bending, combined with a rotational motion of the lemalla – the façade is opening and closing. During the actuation of the 13 m lamella the displacement induced by the actuators is about 450 mm, which leads to an opening angle of 60°. In case of strong wind condition, the lamellas close and lock automatically.

The actuation of each lamella can be controlled individually - not only to control the interior lighting conditions, but also to utilise the kinetic expression of the adaptive façade elements. Thus, different operation modes have been created to animate patterns along the façade (Knippers et al., 2012).

FIG. 2.18

Abu Dhabi Investment Council Headquarters

Aedas Architects and Arup

2.4.3 Abu Dhabi Investment Council Headquarters

The Abu Dhabi Investment Council Headquarters (Fig. 2.18), also known as Al Bahr Towers in Abu Dhabi, consist of two 150m tall glass buildings, with a double curved façade geometry. The building has been designed by Aedas Architects, the kinetic façade elements have been developed by the Arup dynamic structures team and fabricated by the Chinese curtain-wall manufacturer Yuanda. The building complex with its automatically controlled adaptive façade shading system is one of the most sustainable buildings in the gulf region. Worth to mention is the interesting combination of innovative dynamic façade technology and the traditional elements of Arabic shading screen, so called mashrabias.

The kinetic façade consists of 2099 foldable shading elements, made of PTFE coated glass fibre plastic with a translucency of 20%. Thus, even when closed, daylight can still enter the interior. Before construction, the folding elements have been tested in a one to one mock up under artificial sand storm and very hot conditions. The underlying folding pattern is based on triangulated surface tessellation, with an edge length of 4.00 m. Each of the standardised triangular folding elements consists of six plates and are connected to a structurally independent substructure, following the mesh dual of the triangulated tessellation pattern, with the nodes under the central points of the kinetic folding elements, where the fold-lines merge into one point. The substructure is placed 0.60m

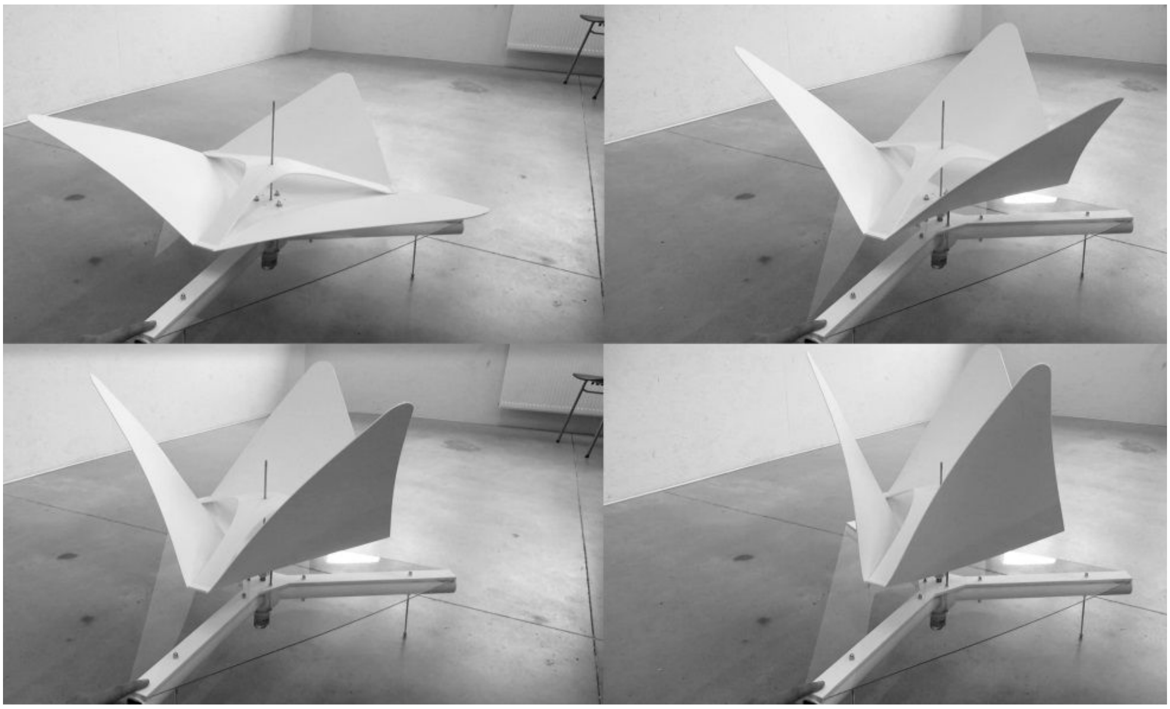

FIG. 2.19

Kinetic curved-line folding elemente

Aline Vergauwen

in front of the actual glass façade and connected by cantilever arms to the curtain wall.

A linear actuator is placed under the central point which pushes the centre outwards to actuate the folding motion. The three folding edges which connect the centre to the three outer vertices are connected with joints, which allow for motion in two distinct directions, to the substructure. The expected life of the actuators is about 15 years and of the motors 10 years, considering operation once a day (Fortmeyer & Linn, 2014; Schumacher et al., 2020)

It is a very impressive kinetic folding façade, applicable to a double curved building geometry. But mechanically very complex.

2.4.4 Pliable shading system, based on curved line folding

Aline Vergauwen explores in her doctoral thesis the potentials of curved line folding for pliable structures in an architectural context. Her investigation resulted in the development of a prototypical kinetic façade shading device, utilized by a curved line folding mechanism (Fig. 2.19).

The underlying folding mechanism is constructed on a triangular basic outline geometry, which makes it suitable for the application to triangular tessellation patterns. It consist of three fold-lines, which always connect to adjacent edges. The apex of all three curved fold-lines directs towards the centre of the underlying triangle. To actuate the folding motion, bending deformation is actively induced into the central region, which leads to opening and closing of the adjacent three flaps. The amount of folding can be precisely controlled by the amount of bending induced into the central region.

The prototypical fully functioning component has been fabricated from a self-reinforced polypropylene material, where polypropylene fibres are embedded into a polypropylene matrix, which leads to five time higher strength than in common polypropylene, and, thus, to a comparatively high strength to bending stiffness ratio, suitable for bending active systems and compliant mechanisms, which rely on large elastic deformation. The use of self-reinforced polypropylene allowed for the use of relatively simple fabrication tools, such as laser cutters. Thus, the flexible fold-lines could be easily engraved into the sheet material.

As mentioned, the actuation is facilitated by actively induced bending into the central region. In order to do so, the central region consists of two layers, with a linear actuator in between. By adjusting the distance between the two layers, the bending, and, eventually, the folding motion can be controlled. By introducing the second layer, the mechanism overcomes the need of secondary structural parts such as a substructure (Vergauwen, 2016; Vergauwen et al., 2016).

The work clearly indicates the relevance and applicability of foldable mechanisms in the context of adaptive façade shading devices. But question related to fabrication, materialisation and control integration remain mainly open.

3. Publications

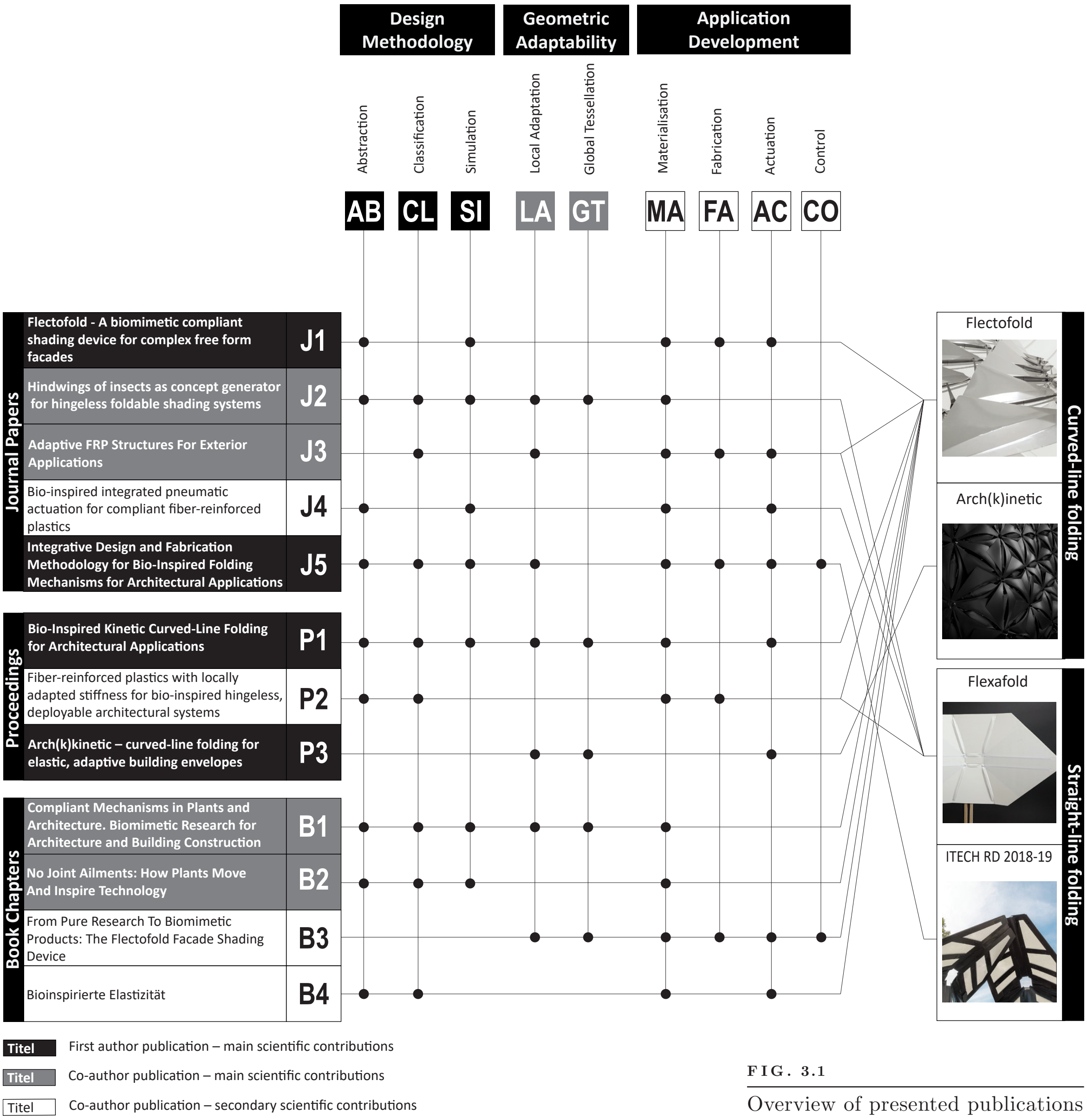

FIG. 3.1

Overview of presented publications

The following chapter presents the publications as originally published on the topic of bio-inspired compliant folding mechanism with main focus on the development of the four demonstrator projects Flectofold, Flexafold, Arch(k)inetic and the ITECH Research Demonstrator 2018-19. The publications are structured into journal papers, conference proceedings and book chapters. Within each section the contributions are listed chronologically. The thematic association of the contribution is illustrated in (Fig. 3.1).

3.1 Journal Papers

3.1.1 Flectofold - A biomimetic compliant shading device for complex free form facades

J1

3.1.2 Hindwings of insects as concept generator for hingeless foldable shading systems

J2

3.1.3 Adaptive FRP Structures For Exterior Applications

J3

3.1.4 Bio-inspired integrated pneumatic actuation for compliant fiber-reinforced plastics

J4

3.1.5 Integrative Design and Fabrication Methodology for Bio-Inspired Folding Mechanisms for Architectural Applications

J5

3.1.1 Flectofold - A biomimetic compliant shading device for complex free form facades

J1

Year: 2018

Authors: Körner, A., Born, L., Mader, A., Sachse, R., Saffarian, S., Westermeier, A. S., Poppinga, S., Bischoff, M., Gresser, G. T., Milwich, M., Speck, T., Knippers, J.

In: Smart Materials and Structures, Volume 27 (1)
https://iopscience.iop.org/article/10.1088/1361-665X/aa9c2f

The article describes the technical development of Flectofold, a compliant curved-line folding element made of glass fibre reinforced plastic, based on the biological role model *Aldrovanda vesiculosa*. The main focus of the presented work, contributed by the author, lies on the investigation of relations between fold line geometry, actuation principles, motion behaviour and stress concentration.

Thus, different fold-line radii have been investigated regarding their influence on the relation between folding angle to actuation pressure, curvature in the different parts and displacement of the support points due to the bending deformation. A larger radius leads to less curvature, which results in less geometric stiffness and higher actuation pressure is needed compared to smaller fold-line radii. On the other hand, less bending of the midrib is needed, which leads to less displacement of the support points. Furthermore, the simulations revealed high stress concentrations at the end points of the hinges. Here, the bending happens only at the inner edge of the hinge zone and does not utilise the full width of the hinge zone. This effect could also be observed in physical models which tend to fail at this point. Thus, a second series of kinetic simulations has been performed to investigate how different actuation principles influence the actual folding motion and the resultant stress distribution within the elastic hinge zones. Three types of actuation principles have been simulated: (1) uniformly distributed pressure was applied on the midrib to resemble a pneumatic cushion between the midrib and a stiff substructure, (2) a pneumatic piston acting locally in the centre of the midrib has been abstracted to a line load applied in the transversal axis of the midrib, and (3) a series of pneumatic cushions acting in tension which are connected to the midrib have been simulated with tension cables, connected to the midrib with beam elements. All three versions are actuated until a folding angle 90° has been reached. The resultant folding geometry of the kinematic model has been compared with idealised geometry from the kinematic model and the stress concentration within the hinge zones have been evaluated.

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3.1.2 Hindwings of insects as concept generator for hingeless foldable shading systems

J2

Year: 2017

Authors: Schieber, G., Born, L., Bergmann, P., Körner, A., Mader, A., Saffarian, S., Betz, O., Milwich, M., Gresser, G. T., Knippers, J.

In: Bioinspiration & Biomimetics, 13(1), Article 1
https://iopscience.iop.org/article/10.1088/1748-3190/aa979c

The article describes the development of the bio-inspired kinetic straight-line folding mechanism Flexafold, based on the wing folding of the biological role model *Graphosoma lineatum italicum*. Thus, it describes in depth the biological investigation of the geometric folding patterns in the insect wings, as well as the gradual transition between the folding plates and distinct hinge zones of higher flexibility.Many folding patterns as found in insect wings can be mathematically abstracted into flexagons, a folding pattern in which four fold lines meet in one central vertex.

For the folding process it is essential that the folding pattern contains three convex and one concave (or vice versa) fold lines. The angles between all four fold lines add up to 360° and two non-adjacent angles add up to 180°. These geometric rules have been the basis or the kinematic behaviour of the Flexafold.To gain more detailed understanding of the relation between fold line geometry, actuation and motion behaviour, a series of kinetic simulations have been performed on a variation of single flexagons and combinations of two flexagons. The folding pattern leads to motion amplification, where a comparatively small initial angle change in the actuated hinge zone leads to an amplified folding motion. Also the materialisation of a folding mechanisms with distinct flexible hinge zones have been inspired by the material gradient in the insect wings. The most relevant aspects have been: (1) Continuous layered structure throughout the folding mechanism; (2) Reduced material thickness within the hinge zone to reduce bending stiffness while keeping the ability to store elastic potential energy; (3) the formation of a gradual transition zone between the stiff plate and the flexible hinge zone; (4) fibre orientation adapted to bending direction within in the hinge zones. These materialisation principles have been successfully implemented in physical demonstrators for the Flexafold, as we as the Flectofold.

The author contributed significantly in the biomimetic abstraction process of the folding mechanism and conceptually to the materialisation aspects. Furthermore, the author contributed significantly in the development of the Flexafold.

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3.1.3 Adaptive FRP Structures for Exterior Applications

J3

Year: 2019

Authors: Born, L., Körner, A., Mader, A., Schieber, G., Milwich, M., Knippers, J., & Gresser, G. T..

In: Advanced Materials Letters, 10(12), 913–918.
https://www.vbripress.com/aml/pdf/1452

The article describes the development of the bio-inspired kinetic straight line folding mechanism Flexafold made of fibre reinforced plastic. It achieves its flexibility by utilising elastic deformation of load-bearing distinct flexible hinge zones with integrated pneumatic actuators. By integrating several actuated hinge zones in one consistent surface like element, it has been possible to fabricate a demonstrator with ten actuated hinge zones.

In the introduction the article gives a broader overview of the state of the art regarding compliant mechanisms with concentrated compliance, especially regarding the use of fibre reinforced hinge-zones. It is stated, that for the intended use as adaptive façade shading device for exterior applications the robustness and capability to carry loads (self-weight, wind load etc.) are of special importance. A detailed evaluation of the Flectofold indicates the starting point in terms of materialisation of load-bearing distinct elastic hinge zones for curved-line folding mechanisms. Even though a load-bearing flexible hinge-zone has been achieved, some disadvantages have been revealed, associated with the transition between the convex to concave faces within a discrete elastic hinge zone. Since this would lead Gaussian curvature during folding, which is not possible with the used material combination, the bending accumulates within a thin line and does not utilise the full width of the hinge zone. To overcome this geometric problem, a methodology has been introduced to translate curved-line folding patterns in corresponding discretised straight-line folding patterns. Furthermore, the external pneumatic actuator, as used for the Flectofold, is described, with the conclusion, that the external actuation is susceptible to malfunctions. Thus, the integration of the cushion into the composite material increases the protection against external influences.

The author contributed significantly to development of the folding pattern and the translation methodology from curved-line to straight-line folding patterns. Furthermore, the author contributed conceptually to the aspects of materialisation, actuation and fabrication.

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3.1.4 Bio-inspired integrated pneumatic actuation for compliant fiber-reinforced plastics

J4

Year: 2019

Authors: Mader, A., Born, L., Körner, A., Masset, P.-A., Milwich, M., Gresser, G. T., & Knippers, J.

In: Composite Structures, 233, Article 111558.
https://doi.org/10.1016/j.compstruct.2019.111558

The work presented in this journal article describes the development of a pneumatic actuation that is fully integrated into the laminate setup of a fibre reinforced plastic, suitable for large-scale and load-bearing compliant mechanisms. While earlier developed demonstrators have been actuated with external pneumatic actuators, the integration of the cushions leads to protection from environmental influences and minimizes their visual impact. Furthermore, the fabrication complexity can be reduced significantly. Thus, the functional principle of the integrated actuator is based on its asymmetric placement within the laminate, where one adjacent side is of higher stiffness than the other side. Upon inflation, the side with lower stiffness exhibits larger elastic deformation, which leads to a rotational motion towards the less stiff side. The actuation principle has been inspired by the investigation of folding insect wings. It has been revealed, that various species such as *Dorcus titanus platymelus* use an increase of pressure within the veins in the wings to accelerate the unfolding process. In addition to the functional principle, also the materialisation has been inspired by the materiality of the insect wings. The veins are hollow cross sections, consisting of a sclerotized exocuticle and a soft resilin-based inner layer of endocuticle. This material set ups has been transferred into the combination of woven glass fibre fabric, pre-impregnated with an epoxy matrix and elastomer layers on both sides of the integrated pneumatic cushion. Thus, stress concentrations in the brittle glass fibre reinforced plastic are reduced to prevent delamination during the actuation, while keeping the material stiff enough to store elastic energy to restore the zero energy state after releasing the actuation pressure.

In addition to advantages regarding the protection and reduction of fabrication complexity, the integrated actuation principle offers the potential to actuate folding and bending of initially flat configuration. Thus, no pre-fold or pre-bent state is needed to actuate the desired motion.

The contributions of the author include the conceptual investigation of the biological role-model and the abstraction of the actuation principle. Furthermore, the author has been part in the design of the presented demonstrators.

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3.1.5 Integrative Design and Fabrication Methodology for Bio-Inspired Folding Mechanisms for Architectural Applications

J5

Year: 2020
Authors: Körner, A., Born, L., Bucklin, O., Suzuki, S., Vasey, L., Gresser, G. T., Menges, A., Knippers, J.
In: Computer-Aided Design, 133, 102988.
https://doi.org/10.1016/j.cad.2020.102988

The work presented in this article continues the research on bio-inspired straight-line folding mechanisms, utilized by distinct elastic hinge zone with integrated pneumatic actuators. This includes the development and integration of methodological approaches for design and simulation, automated fabrication strategies, as well as actuation, control of and interaction with adaptive compliant folding mechanisms.

The findings and their integration into a coherent design framework built the basis for the ITECH Research Demonstrator 2018-19 which has been inspired by the foldable hind wings of *Coleoptera coccinellidae* and *Titanus platymelus*, in terms of the underlying geometric, materialisation and actuation principles. The flexibility in the elastic hinge zone is achieved through local adaptation of material properties. Some beetle species increase fluidic pressure in the veins along the hinge lines to increase the speed of unfolding. For technical applications, pneumatic cushions integrated into the hinge zones are used to actively actuate the folding motion. An integrative workflow for modelling and simulation has been developed for the design of compliant folding mechanisms with distinct elastic hinge zones. The design workflow consists of a parameterised model for generating the basic two-dimensional component and fold line geometries. Under consideration of fabrication and structural constraints, discretisation and reinforcement lines are generated in the two-dimensional model. To translate the basic design geometries into a three-dimensional kinematic model, a kinematic skeleton of the underlying folding mechanism has been developed. The kinematic description of the folding pattern is based on a particle system which allows for asymmetric actuation patterns. Thus, it increases the design space in terms of fold line geometries as well as possible folding behaviour. The demonstrator was manufactured by a robotic tape-laying process of carbon fibre tapes, pre-impregnated with a thermoplastic polyamide matrix, a suitable material for elastic hinge zones with integrated pneumatic actuators.

The author contributed significantly to all mentioned aspects.

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3.2 Conference proceedings

3.2.1 Bio-Inspired Kinetic Curved-Line Folding for Architectural Applications

P1

3.2.2 Fiber-reinforced plastics with locally adapted stiffness for bio-inspired hingeless, deployable architectural systems

P2

3.2.3 Arch(k)kinetic – curved-line folding for elastic, adaptive building envelopes

P3

3.2.1 Bio-Inspired Kinetic Curved-Line Folding for Architectural Applications

P1

Year: 2016
Authors: Körner, A., Mader, A., Saffarian, S., Knippers, J.
In: Acadia 2016 Posthuman Frontiers: Data, Designers, and Cognitive Machines, 270–279.
Editors: Velikov, K., Manninger, S., del Campo, M., Ahlquist, S., Thün, G.
http://papers.cumincad.org/data/works/att/acadia16_270.pdf

This paper describes the development of the bio-inspired kinetic curved-line folding mechanism Felctofold, based on the biological role model *Aldrovanda vesiculosa*. Thus, it describes the systematic process of biological investigations and abstraction process of relevant geometric and physical parameters as found in the plant organism, and, eventually, the development of a physical demonstrator.

This includes the development of a novel kinematic modelling approach of curved-line folding mechanisms, based on the method of reflection (Mitani and Igarashi 2011). This geometry based kinematic model allows for a seamless integration of the kinematic model into the design process with low computational cost. This allows not only for the visualisation of aggregations of folding mechanisms, but also it provides insights in the relation between fold-line geometry and folding motion in a qualitative manner. To gain deeper quantitative understanding of the relation between fold-line geometry, actuation force, displacement of support points, folding angle and respective bending deformation within the folding elements, the kinematic model has been translated into a kinetic model, with the use of the finite element modelling software SOFiSTiK, taking the actual material properties of glass fibre reinforced plastic and actuation pressure into account, as it was also used for the development of the physical demonstrator. Furthermore, the impact of geometric stiffening due to the elastic deformation upon folding has been investigated and how it improves the capacity to withstand external loads.

To visualise the curved-line folding mechanism on double curved building geometries, an algorithmic approach has been developed which subdivides a given synclastic or anticlastic surface into quadrilateral patches of similar anticlastic curvature. With the use of the Reflection Plane Method (Mitani and Igarashi 2011) it is possible to translate the quadrilateral patches into curved-line folding mechanisms.

The author contributed significantly to all mentioned aspects.

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3.2.2 Fiber-reinforced plastics with locally adapted stiffness for bio-inspired hingeless, deployable architectural systems.

P2

Year: 2017
Authors: Born, L., Körner, A., Schieber, G., Westermeier, A. S., Poppinga, S., Sachse, R., Bergmann, P., Betz, O., Bischoff, M., Speck, T., Knippers, J., Milwich, M., Gresser, G. T., & Herrmann, A.
In: Key Engineering Materials, vol. 742, pp. 689–696.
https://doi.org/10.4028/www.scientific.net/KEM.742.689

The article summarizes the biomimetic research and development process of two kinetic folding mechanisms made of fibre reinforced plastic, based on the investigation of two biological role models, the *Aldrovanda vesiculosa*, and the *Graphosoma italicum*. The flexibility is achieved by utilising distinct elastic hinge zones of reduced stiffness.

The motion principle of the *Aldrovanda vesiculosa* has been abstracted to a curved line folding mechanism, where two flaps are connected to a lens shaped middle part by two distinct elastic hinge zones. The curved line folding mechanisms is especially promising for adaptive façade shading systems due to its large motion amplification.

The basic folding principles of many insect wings, such as the *Graphosoma italicum* can be mathematically described as combinations of so called flexagons, a simple straight-line folding mechanisms, consisting of four plates, connected by four hinge distinct hinge zones, which converge on one central point.

The two abstracted folding mechanisms lead to the successful technical implementation and the development of the Flectofold (based on the curved-line folding mechanism as found in *Aldrovanda vesiculosa*) and the Flexafold (based on the straight-line folding mechanism as found in *Graphosoma italicum*). Beside the geometric and kinetic principles, the materialisation principles of the biological role models, especially the distinct hinge zones in *Graphosoma italicum*, were transferred into material set-ups for the fabrication of glass fibre reinforced plastic with distinct elastic hinge zones.

The author contributed significantly to the abstraction of geometric and kinematic principles and the transfer to folding mechanism as used for the technical demonstrators. Furthermore, the author contributed conceptually to the investigation of the biological role models by framing the research aim. The contribution regarding the materialisation and fabrication of the two presented demonstrators have been on a conceptual level.

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3.2.3 Arch(k)inetic – Curved-line folding for elastic, adaptive building envelopes

Year: 2018

Authors: Körner, A., Eshraghi, V., Zolfaghari, A., Haghighi, L. A., Kalantari, M., Knippers, J.

In: Proceedings of the IASS Annual Symposium 2018 –

Editors: Mueller, C. Adriaenssens, S.
https://www.ingentaconnect.com/content/iass/piass/2018/00002018/00000010/art00013

This paper presents the outcome of the research-oriented and experiment-based Arch(k)inetik workshop in Tehran, led by the author. The underlying research question builds upon two specific problems regarding the previously developed Flectofold, a pneumatically actuated kinetic façade shading device, utilized by a curved-line folding mechanism: (1) Geometric adaptability. The Flectofold module is applicable to a quad based tessellation pattern of synclastic and anticlastic surface geometries. But, to provide a certain pre-fold, specific geometric alterations of the initial design are needed. (2) Integration of actuation and substructure. The Flectofold has been actuated by a pneumatic cushion, located between the folding element and a stiff substructure. The connection to the substructure must allow for the shortening due to bending deformation. Thus, the connection details become rather complex.

To improve the geometric applicability to surface geometries of positive and negative Gaussian curvature, an edge-based curved-line folding element has been developed, where each edge of an underlying mesh can be transferred into a kinetic folding element. To apply this element to an arbitrary tessellation pattern, a procedural method has been developed to translate mesh edges under consideration of geometric parameters of the adjacent faces into curved-line folding elements. For each adjacent mesh face one folding element is created, leading to two folding elements in manifold mesh edges.

The integration of pneumatic actuators by placing the cushions between two edge elements obviates the need of a secondary substructure. To compensate the shorting effect of the edge elements during the folding motion, the folding elements are connected by compliant adaptive joints. Thus, no sliding or rotating joints have been needed. The development led to the construction of a physical demonstrator of the kinetic curved-line folding module. The folding elements have been made of polypropylene, the edges and compliant joints have been materialised with spring steel.

The author contributed significantly to all mentioned aspects.

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3.3 Book Chapters

3.3.1 Compliant Mechanisms in Plants and Architecture. Biomimetic Research for Architecture and Building Construction **B1**

3.3.2 No Joint Ailments: How Plants Move And Inspire Technology **B2**

3.3.3 From Pure Research To Biomimetic Products: The Flectofold Facade Shading Device **B3**

3.1.4 Bioinspirierte Elastizität **B4**

3.3.1 Compliant Mechanisms in Plants and Architecture

B1

Year: 2016

Authors: Poppinga, S., Körner, A., Sachse, R., Born, L., Westermeier, A., Hesse, L., Knippers, J., Bischoff, M., Gresser, G. T., & Speck, T.

In: Biomimetic Research for Architecture and Building Construction (Vol. 8, pp. 169–193). Springer

Editors: Knippers J., Nickel, K. G., Speck, T.
https://link.springer.com/chapter/10.1007%2F978-3-319-46374-2_9

This chapter describes the biomimetic and reverse biomimetic research on the trap mechanisms of two closely related carnivorous plants: The underwater plant *Aldrovanda vesiculosa* (waterwheel plant) and *Dionaea muscipula* (venus flytrap), which lives on land.

The motion behaviour of both plants has been simulated on the one hand based on a very detailed model of the actual plant to verify theories about the actual plant motion. On the other hand, kinematic and kinetic models have been developed with the purpose of disclosing and abstracting the underlying motion principles to technical applications.

Thus, the motion behaviour of *Aldrovanda vesiculosa* has been transferred into the kinetic curved-line folding mechanism Flectofold, utilised by flexible hinge zones of concentrated compliance, made of glass fibre reinforced plastic. The flexible hinge zones are enabled by a reduced number of glass fibre layers and specified fibre orientation. The actuation of the folding is carried out by a pneumatic cushion, located between the central mid rib and a stiff substructure.

The contributions of the author included the development of the conceptional framework and definition of technological questions, as well as the development of a kinematic curved line folding model, based on the method of reflection (Mitani and Igarashi 2011), which enables a computationally fast approximation of the folding motion of large aggregations of curved-line folding elements. Furthermore, the author built a refined kinetic model, taking into account fabrication constraints and actuation principles, which eventually lead to the proposed lamination setup and actuation of the presented Flectofold.

Related to the studies of the Venus Flytrap, the author contributed a qualitative analysis of the relation between snap-through behaviour, geometry of the mechanisms and material gradients.

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3.3.2 No Joint Ailments: How Plants Move and Inspire Technology

Year: 2019
Authors: Westermeier, A., Poppinga, S., Körner, A., Born, L., Sachse. R, Saffarian, S., Knippers, J., Bischoff, M., Gresser, G. T., Speck, T.
In: Biomimetics for Architecture: Learning from Nature, pp. 32–41. Birkhäuser
Editors: Knippers J., Schmid U., Speck, T.
https://doi.org/10.1515/9783035617917-006

The book chapter provides an overview to a broader public about the research field related to bio-inspired compliant mechanisms, especially based on the motion behaviour of plants. Thus, it introduces different kinematic and motion amplification principles within the biological context.

Furthermore, the development of the Flectofold from the investigation of the *Aldrovanda vesiculosa* to the abstraction of kinematic principles and the fabrication of first working physical demonstrators is described in depth, to explain the biomimetic research project to a non-scientific audience.

Thus, it describes the abstraction process of the plant motion into computational kinematic and kinetic models, as well as the parameterisation of underlying geometric principles and their influence on the motion behaviour. It provides a short introduction into the field of fibre reinforced plastics and explains the basic materialisation strategy of flexible hinge zones.

The author contributed significantly to the development process of the Flectofold.

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3.3.3 From Pure Research to Biomimetic Products: The Flectofold Facade Shading Device

Year: 2019
Authors: Saffarian, S., Born, L., Körner, A., Mader, A., Westermeier, A., Poppinga, S., Milwich, M., Gresser, G. T., Speck, T., Knippers, J.
In: Biomimetics for Architecture: Learning from Nature, pp. 42–51. Birkhäuser
Editors: Knippers J., Schmid U., Speck, T.
https://doi.org/10.1515/9783035617917-007

This chapter presents to a broader public the detailed development of a large-scale demonstrator of the bio-inspired adaptive folding mechanisms Flectofold in the Rosenstein Museum in Stuttgart. It describes the materialisation strategies for large-scale compliant mechanisms with distinct elastic hinge zones, capable of carrying external loads. Furthermore the geometric adaptability, to make the façade shading device applicable to complex building envelopes has been an important aspect. Thus, the integration into a design methodology which translates surface tessellation patterns into the geometric representations of the Flectofold have been of importance during the development.

The presented large-scale demonstrator consisted of 36 individually actuated and actively controlled Flectofold modules. In addition to the purely scientific value, the public display of the demonstrator indicates the architectural potential of this innovative technology.

The author contributed significantly to the development of the Flectofold module and the development and integration of the design methodology. Furthermore, the author contributed conceptually the design of the large scale demonstrator.

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3.3.4 Bio-Inspired Elasticity

Year: 2019
Authors: Knippers, J., Körner, A.
In: New MOVE: Architecture in Motion - New Dynamic Components and Elements, pp. 28-29
Birkhäuser
Editors: Schumacher M., Vogt M.-M., Cordón Krumme L. A.
https://doi.org/10.1515/9783035617917-008

Based on the description of the bio-inspired façade shading devices flectofin®, One Ocean Pavilion and Flectofold this book chapter intends to introduce the advantages of compliant mechanisms for architectural application to broader public.

It explains the geometrical limitations and mechanical challenges of common rigid body mechanisms and introduces the principle of compliant mechanisms. Due to the fact that in biology many mechanical systems make use of compliant mechanisms, the investigation of biological role models offers many principles which can lead to technical applications. In addition to this pure technical advantages, compliant mechanisms offer new possibilities for architectural Gestalt. Many bio-inspired compliant mechanisms only need a comparatively small actuation impulse, which leads to large amplified resultant motion and shape change, which is not obvious to the viewer but nevertheless plausible.

In addition to significant contributions to the development of the Flectofold, the author was responsible in summarizing the presented case studies and providing the broad introduction into bio-inspired complaint mechanisms for architectural applications to a non-scientific audience.

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4. Results

The overarching aim of the presented research has been the development of a methodological design framework for bio-inspired compliant folding mechanisms, utilized by distinct flexible hinge-zones. Thus, it has been essential to implement a systematic structure to the investigations and results respectively. Therefore, the research has been categorised into three main trajectories:

1. **The conceptual design methodology includes the investigation of biological role models and the abstraction process of functional principles. The specific aim here is the identification of basic functional building blocks, which can be combined for varying technical applications. Eventually, this leads to a categorization of bio-inspired functional categories, and, therefore, to a technical categorization of biological role models to assist future research to identify suitable role models, which might offer solutions for specific technical challenges. Also kinematic and kinetic simulation methods, which are needed for qualitative evaluation of the design space of specific working principles, qualitative studies of form-force relationships and quantitative studies of materialisation and actuation principles are discussed and summarised.**
2. **The second research trajectory investigates the geometric adaptability of the disclosed principles, their variations and combinations. This includes the evaluation of the design space of variations and combinations of the basic kinetic building blocks on a local level (local geometric adaptation), as well as the applicability to different tessellation patterns, applicable to free-form geometries (global tessellation).**
3. **The third research trajectory focuses on the development of technical applications, based on the bio-inspired building blocks and under consideration of geometric adaptability. This includes the development of materialisation and fabrication strategies and their evaluation in terms of complexity and potential automation. Furthermore, actuation principles, mainly based on the use of pneumatic pressure and their active control are aspects, which have to be considered for the development.**

The following chapter provides a short summary of the main findings according to the described research objective.

4.1 Conceptual Design Methodology

The first main research trajectory is focusing on the development of a theoretical abstraction and design methodology for bio-inspired compliant mechanisms.

4.1.1 Abstraction of biological principles

During the presented research, biological principles on three different levels have been successfully abstracted and transferred to technical implementations, which led in different combinations to the presented demonstrator components.

Geometry level

The biological investigation on a geometric level disclosed two distinct folding principles as suitable for the kinetic applications.

J1 J2 J5 P1 B1 B2 B4

The investigation of the trap mechanisms of the carnivorous underwater plant *Aldrovanda vesiculosa* can be abstracted to a curved line folding mechanism. As described in **J1**, **P1**, **B1**, **B2** and **B4** the trap consist of two lobes, which are connected by curved hinge zones to central rib. While the lobes and central rib are comparatively stiff, the hinge zones are more flexible. After being triggered by prey, change in turgor pressure leads to slight change in curvature – small initial geometric change as input – of the central rib, which is amplified by a curved-line folding mechanism and leads to the complete closure of the trap – larger geometric change as output.

The second promising folding mechanism was found during the investigation of the folding patterns in the hind wings of flying beetles, as described in **J2** and **J5**. Many insects cover their fragile hind wings with more robust fore wings (Elytra). To be able to pack them compactly, the hind wings exhibit complex folding patterns along distinct elastic hinge zones. Based on the investigation of many folding patterns found in insect wings, Haas (Haas 1994; Frantsevich 2011) identified the flexagon as mathematical description of a basic straight-line folding mechanism, which often occurs in insect wings.

Thus, on a geometric level the biological investigations revealed curved-line folding and straight-line folding utilized by distinct elastic hinge zones.

Material level

Especially the investigation of the folding patterns in insect wings offered several materialisation principles for distinct elastic hinge zones. Thus, six fundamental structural principles (**J2**) can be abstracted from the wing structure. (1) The wings consist of a continuous layered structure of chitin fibres within a protein matrix. (2) Reduced material thickness leads to reduced stiffness within the elastic hinge zones. (3) The multiple layer of chitin fibres within the wing structure change their orientation between each layer by a small angle. Thus, fibres run in almost any direction, the material is therefore quasi isotropic, an advantage to take loads in varying direction. Furthermore, within the hinge zones only few fibre layers are oriented perpendicular to the folding direction, which would lead to higher bending stresses. (4) In addition to fibre orientation and material thickness different consistencies of the protein matrix lead to variations of material stiffness within the continuous wing structure. Thus, within the hinge zones a higher level of resilin enhanced matrix can be observed. (5) The transition zone between the flexible hinge zone and the stiffer plates are not abrupt but characterized by gradual transition zones. (6) Regions of thicker material (so called false veins) can be found adjacent to the elastic hinge zones. This reinforcing structural element serves as guidance for the folding motion. Therefore, the actual plates of the wing can be thinner and lighter, an important property for flying insects.

J2 J3 J5 P2 B1 B2 B4

Actuation level

In terms of active actuation, two principle strategies have been abstracted from the study of *Aldrovanda vesiculosa* and folding behaviour of insect wings. In both cases an active actuation is needed only in one direction, since the elastic hinge zones (straight-line folding mechanisms), or elastic hinge zones and elastically bent faces (curved-line folding) store elastic energy which enables rapid restoring of the zero energy state. In case of the curved-line folding mechanism as disclosed in *Aldrovanda vesiculosa* the folding motion is actuated by actively induced bending deformation within the central midrib, which leads to the large amplified folding motion. The crucial motion in insect wings is the rapid unfolding of the hind wings in case of approaching danger. While in most beetle species this motion is purely facilitated by the stored elastic energy, some species of *Coleoptera* (Sun et al. 2014) use active regulation of hydraulic pressure within the wing-veins to accelerate the unfolding process.

J4 J5

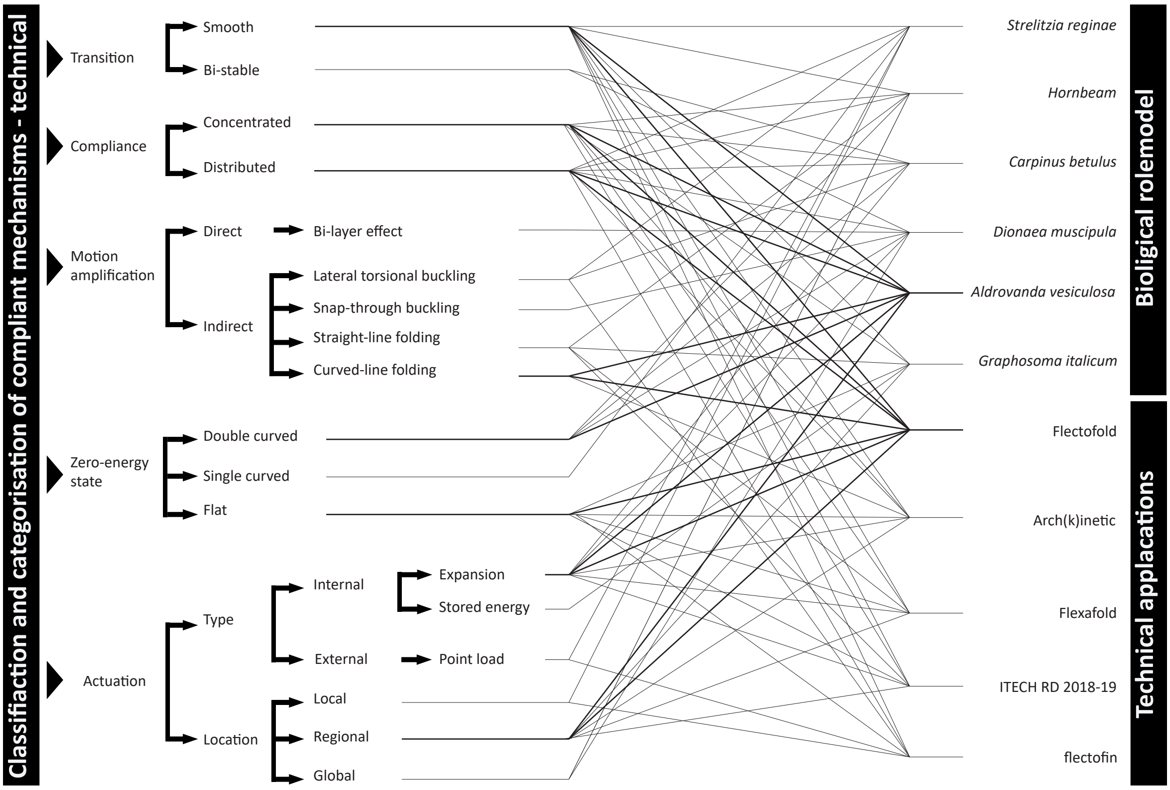

FIG. 4.1

Classification of biological and technical compliant mechanisms

Classification

Based on the abstraction of functional principles and biomimetic building blocks, the research proposes a technical terminology to categorise and classify potential biological role-models and technical applications. This developed common descriptive language aims to assist the communication between technical domain and biological domain.

J1

J2

J5

P1

P2

B1

B2

B4

Within the development of bio-inspired compliant mechanisms a specific set technical classifications and categories has been proposed. This includes a description of the transition phase between distinct geometric states, the type of compliance which enables a specific mechanism, as well as possibilities of motion amplifications and the geometric articulation of the zero-energy state. Furthermore, actuation principles are classified in internal and external actuation impulses, as well as localisation and distribution of the actuation. Thus, the categorisation of biological role-models in a technical terminology enables the identification of biological role-models to provide new solution strategies for actual technological challenges which current technical developments are facing. Furthermore, the common terminology can be used to link different role-models and solution strategies, as well as to combine functional principles for technical applications. In addition to the technological aspects, the categorisation also helps to identify common mechanical features in different biological organisms, which serve a variety of purposes by employing common functional principles (Fig. 4.1).

4.1.2 Simulation

Kinematic and kinetic models with different degrees of detailing and accuracy have facilitated the simulation and analysis of geometric, material and actuation principles and parameters.

Kinematic model

J2 J5 P1 B1

Kinematic models are used to qualitatively assess the influence of geometric parameters and dependencies on the folding motion. In addition to this, the integration of kinematic models within a computationally fast design workflow for visualisation as well as assessments of performative aspects is crucial.

In the course of the presented research two principle approaches of kinematic models have been developed: a purely geometric model, based on the reflection plane method (Mitani and Igarashi 2011) as described in **J2**, **P1** and **B1**, and a particle model using constraint-based dynamics, as described in **J5**.

The kinematic model based on the reflection plane method is computationally fast, which makes it very suitable for visualisation and performative assessment purposes of large aggregations, especially regarding façade shading applications. A disadvantage of this geometry-based method is the fact that it only works for very regular folding patterns, where the curved-fold line remains on one plane during the entire folding motion, or for symmetric flexagon based straight-line folding patterns where always pairs of two non-adjacent fold lines remain on one plane during folding. Furthermore, the assessment and visualisation of asymmetric and irregular actuation has not been possible with the reflection plane method.

To overcome these disadvantages, a second method for kinematic models has been developed, based on a particle model and constraint-based methods. Thus, it is possible to approximate the motion behaviour of irregular straight-line folding patterns, as well differentiated actuation. To minimise the computational effort, the particle model is used to generate a simplified kinematic skeleton of the specific folding component. In a secondary step, the actual component geometry can be mapped on the kinematic skeleton for visualisation purposes and to evaluate performative aspects. While this method overcomes geometric constraints in terms of fold-

J1 J2 J4 J5 P1 B1 B2

ing pattern, as well as anticipated actuation principles, the computational effort and modelling complexity is considerably higher, compared to the geometry-based reflection plane method.

Kinetic model

The Kinetic model uses nonlinear finite element analysis to simulate the motion behaviour taking actual material properties, actuation forces and associated stresses within the simulated mechanisms into account. The established kinematic models can be differentiated into two distinct categories which have been used to develop suitable materialisation and fabrication strategies. Thus, information exchange between the kinetic models and development of physical tests has been crucial. (1) A first kinetic model investigates form-force relationships of a specific mechanism. The model is used to establish a framework of mechanical properties, range of material thickness and gradients in which the specific mechanism is functional, and the needed actuation force is within an acceptable range. Furthermore, this model can be used to determine on a qualitative level how specific geometric variations influence the structural performance under external loading conditions. (2) The second kinetic model takes the actual materialisation and fabrication into account. Thus, the material properties and distributions, as well as actuation principles are precisely modelled according actual to fabrication possibilities. The detailed simulations provide a qualitative study and detailed information about how specific material properties and actuation principles influence the kinetic behaviour, stress concentrations and actuation forces.

4.2 Geometric adaptability

The second main aspect during the presented research has been the question of geometric adaptability of the disclosed basic bio-inspired folding mechanism and how they can be varied, especially in relation to the application as façade shading elements for double curved building geometries. Thus, the research aspect of geometric adaptability has been investigated from two perspectives.

4.2.1 Local adaptability

After identification of the basic mechanical principles based on folding, a variety of geometric variations have been investigated to establish a geometric design space in which the curved-line folding and flexagon based straight-line folding mechanisms are functional.

J2 J3 J5 P1 P3 B1 B3

As presented in **P1**, **P3**, **B1** and **B3**, regarding the curved line folding mechanism different folding patterns with varying number of curved-fold lines have been investigated and proved to be functional. Furthermore, the influence of geometric variations on the kinematic and kinetic behaviour has been evaluated. Variations and combinations of straight-line folding patterns and mechanisms are discussed in **J2** and **J5**. The investigation of the kinematic behaviour of the curved-line and straight-line folding mechanisms revealed advantages and disadvantages for both, straight-line and curved-line mechanisms. To be able to evaluate and assess the advantages and disadvantages in specific cases for specific folding patterns, a methodology has been introduced to translate curved line folding patterns into flexagon-based straight-line folding patterns and vice versa, as described in **J3**.

4.2.2 Global tessellation

J2 P1 P3 B1 B3

Since one of the main guiding questions throughout the development has been the application as an bio-inspired adaptive façade shading device especially in the context of complex, double-curved building geometries, it has been paramount to develop tessellation patterns, which can be translated into curved-line and straight line folding mechanisms. Different strategies have been developed and categorised in terms of the tessellation and translation method. Thus, it has been differentiated between triangular, quad and polygonal tessellation and face or edge-based tessellations. A variation of quad and polygonal tessellation and face based translation methods have been described in **J2**, **P1**, **B1** and **B3**. A triangular tessellation with edge based translation has been discussed in **P3**. Here, it has to be mentioned, that the edge-based translation method is independent of the underlying tessellation, since only the edge and adjacent face centre are needed for the translation process.

4.3 Application development

The results of the previous aspects have been used inform the development of physical demonstrators, which, in return, have been used to verify and evaluate the theoretical investigations. Thus, the developments and refinements of the physical applications in terms of materialisation and fabrication, as well as actuation have been in constant dialogue with aspects of basic mechanisms, simulation and geometric adaptability.

4.3.1 Materialisation and fabrication

J1 J2 J3 J4 J5 P1 P2 B1 B2 B3 B4

Aspects of materialisation and fabrication have been developed together with Larissa Born (ITFT) in coordination with itke and the author. Three different materialisation strategies have been tested successfully.

For curved-line folding mechanisms in a comparatively small scale of up to 420 x 520 mm the VAP® (Vacuum Assisted Process) of woven glass-fibre fabric in epoxy matrix has been proven to be a successful method. The stiffness gradient between stiff faces and hinge zones has been achieved through adjustments of material thickness (number of layers of glass fibre fabric), as well as fibre orientation. An additional layer of PVC foil made the used material setup of glass fibres and epoxy resin less brittle and, thus, enabled the very small bending radii, as needed within in the hinge zone (**J1**, **P1**, **P2**, **B1**).

For curved-line and straight-line folding mechanisms of a larger scale (850 x 720 mm) a material set-up consisting of elastomer foil, woven glass fibre fabric pre-impregnated with epoxy matrix and a covering PVC foil proved to be promising for fabrication of distinct elastic hinge zones with vacuum assisted hot pressing process. This material setup was also used to investigate the graded transition zone between the flexible hinge zones and stiffer plates (**J1**, **J3**, **B3**).

For the fabrication of large scale straight-line folding mechanisms, a materialisation method has been developed with the use unidirectional carbon and glass fibre tape in thermoplastic polyamide matrix. Thus, the brittle and energy-elastic deformation behaviour of the previously used thermoset epoxy matrix could be replaced with the almost entropy elastic deformation behaviour of the thermoplastic polyamide matrix. This makes the use of the elastomer layer obsolete, leading to a simplified and less complex lamination set-up. The possibility of heat forming has been used to form beam-like reinforcements along the hinge zones, which increased the overall structural performance significantly without adding materiel and, therefore, weight to the system (**J5**).

All of the proposed materialisation concepts have advantages and disadvantages which need to be evaluated for any specific application scenario.

4.3.2 Actuation

For the realisation of physical demonstrators, two types of pneumatic actuators have been developed. The first one has been developed for the Flectofold demonstrator. Here, a pneumatic cushion has been placed between the midrib (as one of the curved-line folding faces) and a stiff substructure. Inflation leads to a small bending deformation of the midrib, which actuated the folding. A similar method has been realised for the Arch(k)inetic demonstrator, where a cushion has been placed between to bending plates to actuate the folding motion (**J1**, **P1**, **P2**, **P3**, **B1**, **B2**, **B3**, **B4**).

To minimize the mechanical complexity, visual impact and the exposure to environmental influences, pneumatic actuators which are integrated within the material lay-up of fibre-reinforced plastics have been proposed. Therefore, pneumatic cushions are placed asymmetrically within the composite set-up, where the composite on one side is considerably stiffer than on the other side. Thus, the inflation actuates an asymmetric bending motion around the hinge-zone into the direction of the layer with less stiffness. Due to the relative low width of the hinge-zone compared to the adjacent plates, the bending motion can be compared with a rotary motion. The integrated pneumatic cushion has been successfully tested with the materialisation setup based on the use of glass fibre epoxy prepreg with elastomer. Here, the elastomer covers the cushion on both sides to prevent delamination upon actuation. Furthermore, the pneumatic cushions have been successfully integrated on the material setup based on carbon and glass fibre prepreg tapes on polyamide matrix. Here, the necessary interlaminar adhesion can be achieved without an additional elastomer layer. The saving of the elastomer layers results in a lower laminate weight and overall lighter constructions (**J3**, **J4**, **J5**).

In addition to those two realised actuation principles, a series of possible actuation strategies has been discussed and studied on a theoretical level in **J1**.

J1
J3
J4
J5
P1
P2
P3
B3
B4

5. Conclusions and outlook

The presented research reveals the potential of bio-inspired kinetic folding mechanisms for architectural applications. Based on the development of the four functional demonstrator projects Flectofold, Flexafold, Arch(k)inetic and the ITECH Research Demonstrator 2018-19 a consistent design and fabrication methodology for kinetic folding mechanisms utilized by distinct flexible hinge zones has been introduced. This includes contributions on various levels, ranging from theoretical and methodological definitions to the development of technical applications on a demonstrator level.

The logical next step is from functional demonstrator projects towards prototypical applications as external façade shading device. Thus, questions of fabrication, automation and reducing of material complexity have to be taken into consideration, as well as the performative functionality in relation to state of the art sun shading devices.

Furthermore, the use of fibre reinforced plastics offers the potential of integrating functionality into the material setup. Therefore, sensors can be integrated to identify the current geometric configuration of compliant kinetic folding mechanisms and active control based on the current and desired target geometric configuration. This geometry-based control approach also enables the detection of unforeseen loading conditions, such as strong wind loads, and the folding devices can react by transforming into a safety state.

Since an adaptive sun shading device ideally follows the sun path, the integration of flexible PV cells within the laminate is of particular interest, since the gained solar energy can be used for the active actuation, making the adaptive folding elements independent from external energy supply, an often expressed critique on actively controlled adaptive sun shading devices.

The focus of the presented research has been the development of adaptive suns shading devises in an architectural context. Nevertheless, compliant folding mechanisms with distinct flexible hinge-zones offer potential in other fields of applications, such as the automobile and aerospace industries as well, where the geometric adaptation as a reaction to aerodynamic demands is a crucial factor.

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