BRIDGING EXTERIOR AND INTERIOR CLIMATE

Interdisciplinary Design of a Dual-Functional Adaptive Kinetic Façade

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Abstract. Building facades serve as the interface between their interior and exterior environments. With climate change necessitating adaptive solutions, the development of adaptive facades for a sustainable operational energy cycle for buildings has been prompted. This study delves into the design and prototyping of KineticSKIN, an Adaptive Kinetic Façade (AKF) system. The system leverages kinetic mechanisms to achieve dual objectives: strategically redistributing incident solar energy and enhancing internal user comfort. This paper outlines the comprehensive schematic design phase, integrating performative architectural design through daylighting simulations and mechanical kinematic schemes with an interdisciplinary research approach bridging architecture and mechanical engineering domains. Furthermore, it provides detailed insights into the evolutionary progression of transformable joints and cable-driven actuation systems for practical solutions to the kinetic façade system.

Keywords. Adaptive Kinetic Façade, Interdisciplinary Approach, Cable-driven actuation, Dual-Functional, Performative Design

1. Introduction

Effectively harnessing solar radiation incidents on building facades is essential for a sustainable building operational energy cycle (Alva et al., 2020). This research explores the advantages gained from strategic design and deployment of façade modules in high-rise buildings. In this context, KineticSKIN, an innovative dual-functional adaptive façade system, is introduced to seamlessly adapt to both external environmental conditions (performance) and the needs of indoor occupants (user).

The energy consumption in lighting and HVAC (Heating, Ventilation and Air Conditioning) systems in buildings is significantly affected by seasonal variations.

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During the summer, the high solar altitude causes the UHI (Urban Heat Island) effect leading to overheating in urban areas. Conversely, in winter, the low sun altitude, while providing ample sunlight, causes glare disturbances. Beyond these external factors, user preferences are subjective depending on diverse needs and purposes. Hence, providing user control over lighting levels, views, and other parameters is essential for ensuring a comfortable user experience.

To achieve dual-functionality, three components are considered throughout the process: Morphology, Kinematics, and Construction (Figure 1). Based on a performative design methodology (Oxman, 2008; Soudian and Berardi, 2020), daylighting simulation results were integrated into the morphology design. Through these simulations, the effectiveness of seasonal countermeasures and the impact of user controllability has been assessed and verified.

Literature reviews of kinetic facades emphasize that their successful implementation in buildings depends on kinematics, reliability, and durability (Sharaidin and Salim, 2012). Thus, the challenges in prototyping lie in achieving durability, ease of installation, and maintenance without compromising architectural value. In response, an interdisciplinary approach was adopted by leveraging mechanical engineering expertise, specifically in the field of system dynamics, to ensure the reliability and controllability of the kinetic system.

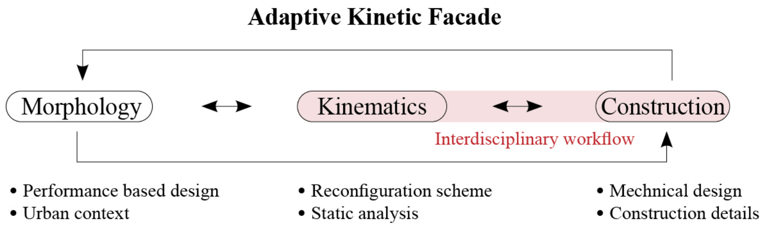


Figure 1. KineticSKIN design process with interdisciplinary workflow

This paper comprehensively details the evolution of KineticSKIN, encompassing the design, simulation, exploration of transformable joints, and actuation principles.

2. KineticSKIN - Adaptive Kinetic Façade (AKF)

In the preceding phase of research, illuminance and solar radiation simulations have been conducted with various facade typologies. The outcome highlighted the advantages of incorporating a kinetic feature that adapts to given conditions while using the same amount of material (Jeong et al., 2022). However, the optimal configuration in relation to the sun's position may not always be compatible with the user's preferences. Hence, with an emphasis on reconciling the inherent trade-offs between system performance and user experience, this section elaborates the overall design concept, simulation-based verification, and materialization scheme of KineticSKIN.

2.1. DESIGN CONCEPT

The concept started from a foldable bifurcated module, featuring upper and lower wings. The upper wing primarily contributes to the global energy cycle, particularly within urban context by redistributing the solar energy. In summer, it dynamically changes the folding angle to track the sun to mitigate solar heat gain or harvesting solar energy over time. During winter, when solar altitudes are lower, the upper wings reorient solar energy towards indoor ceilings, maximizing interior natural lighting while minimizing sun glare (Figure 2). Complementing the upper wings, the lower wings are user-controlled, allowing occupants to customize indoor conditions to meet specific requirements, considering various usage scenarios such as illuminance, view and ventilation.

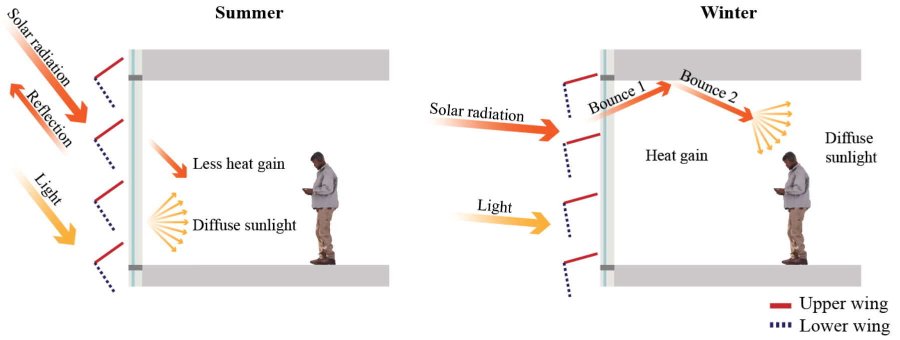
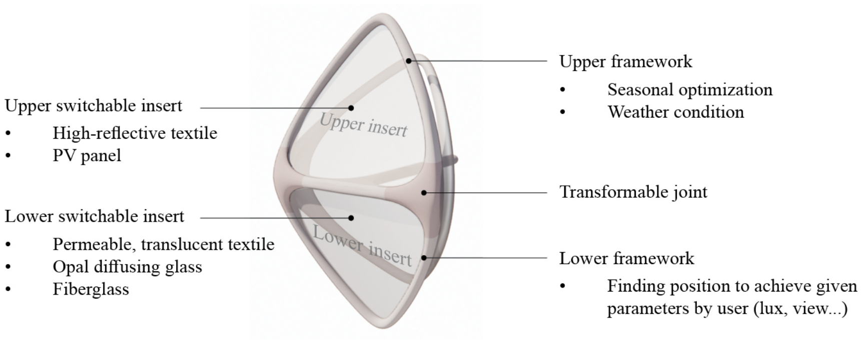


Figure 2. Seasonal countermeasure with respective role of each wing

The hardware system is designed as a framework to accommodate interchangeable inserts, such as PV panels or high-reflective textiles, based on the roles of the wing. This design allows for versatility in serving a wide range of purposes (Figure 3).

Prior to investigating the specifics of the kinematic system, an assessment of the durability and folding capacity required determining the maximum and minimum folding angles of the facade modules. The findings (based on typical office hour, from 8 to 18 in Stuttgart) suggest that a maximum folding angle of 65° is sufficient for optimal performance. However, a visual study (Figure 4) revealed that pushing the maximum folding angle to 85° significantly enhances flexibility, particularly for

Figure 3. Framework and material concept of KineticSKIN



internal user views and extreme weather cases.

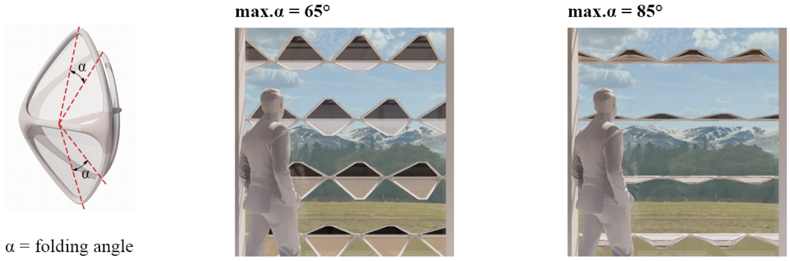


Figure 4. Visual study of maximum folding angles

2.2. ILLUMINANCE & RAY-TRACING SIMULATIONS

To assess the dual goals of user comfort and performance, ClimateStudio (Solemma LLC, 2020) and Ladybug (Roudsari and Subramaniam, 2016) were used for illuminance and ray-tracing simulations. As a parameter, the folding angles of the wings are adjusted to meet the needs of the user as well as to correspond with the position of the sun. To analyse seasonal usage, Simulations are conducted at noon on the summer solstice and winter solstice in an office environment based on Stuttgart, Germany, measuring 10m in depth and 6m wide, with south-facing windows.

To find the optimal folding angle of the upper wings, ray tracing simulations are preceded, providing a visual representation of the reflection of solar rays. Subsequently, the defined angle is used as input for illuminance simulations.

As a result, in summer, the folding angle of the upper wing is set to align its normal vector with the sun ray's altitude, reflecting direct sunlight to the external environment and facilitating effective capture for energy generation. This feature also demonstrates significant potential in alleviating Urban Heat Island (UHI) effects caused by conventional high-reflective curtain wall façades. In contrast, during winter, the folding angle is set to almost fully open angle to redirect incident solar energy toward the indoor ceiling. This promotes the deep penetration of diffuse sunlight into the interior environment (Figure 5) in an equivalent manner to light shelves.

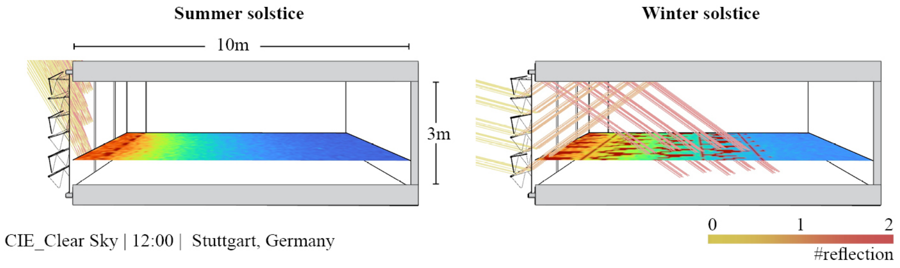


Figure 5. Ray-tracing visualization of direct sunlight

Illuminance simulations were conducted while maintaining the upper wing at angles derived from ray tracing simulations. To assess the user's control over indoor lighting levels and views, the folding angle of the lower wing was tested at both fully open and closed cases. Simulations were conducted using the glazing (U-value = 1.05) and aluminium (white, high reflective) for the frames and inserts. Additionally, simulations of the glass-only case are conducted as a benchmark (Figure 6).

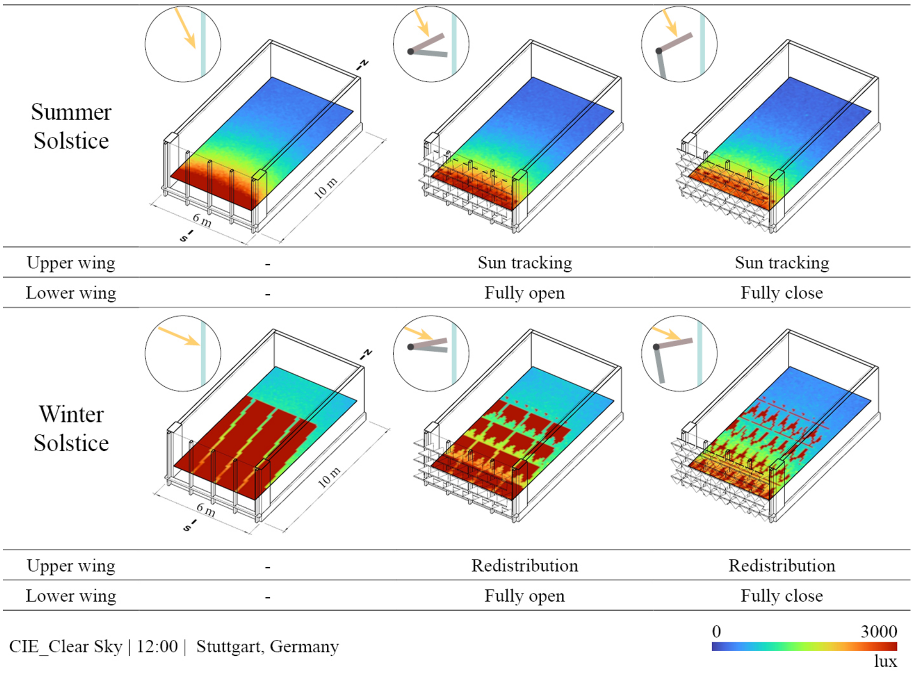


Figure 6. Illuminance simulation results based on seasonal adaptive countermeasures

3. Development of Kinetic Mechanism

With the aim of installing a full-scale prototype in an outdoor setting, an interdisciplinary team developed the kinetic mechanism design. This section offers a comprehensive overview of the development process, with a focus on enhancing durability of folding frameworks, incorporating wind load factors, and minimizing the number of actuators.

3.1. HINGE DEVELOPMENT

Iterative development considered various materials, actuation principles, and hinge mechanisms, striking a balance between manufacturing ease, maintenance, functional requirements, and aesthetics with lightweight construction principles. Four sequential alternatives are elaborated in this section.

3.1.1. Compliant Mechanism Hinge

As the starting point, the first prototype (Figure 7) featured a monolithic structure with elastic TPU elements —acting as springs and hinges—and backside actuation cables. TPU elements compensate for wind loads through their elasticity offering following advantages: Reduced mechanical components (joints, springs, etc.), minimized friction, and no need for lubrication. Despite its advantages, the prototype proved unsuitable for the final solution due to factors like scalability and wind resistance requirements at higher elevations.

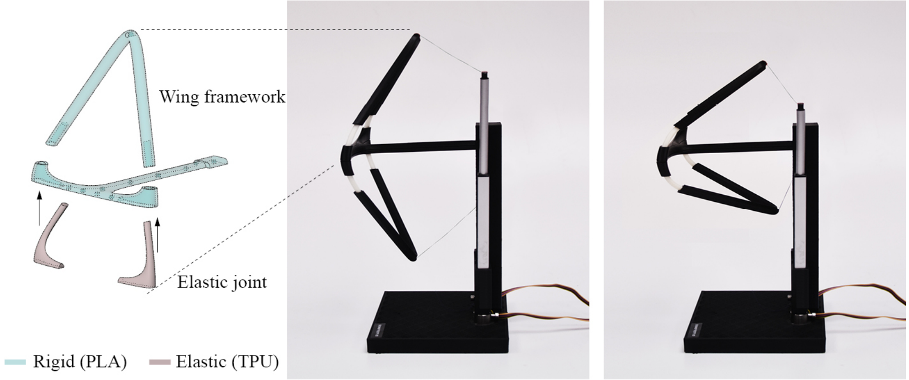


Figure 7. Compliant hinge joint with cable mechanism and 3D printed prototype in 1:5 scale

3.1.2. Elastomeric Layered Panel

Alternatively, elastomeric layered panel by employing stainless steel spring sheet has been explored. It is easy to assemble, ideal for integration of various insert panels including PV panel and provides the sufficient stiffness against wind loads. However, due to the required length of the spring sheet, limitations in the folding angle (as discussed in Section 2.1) and effective surface have been arose which prevented it from further development.

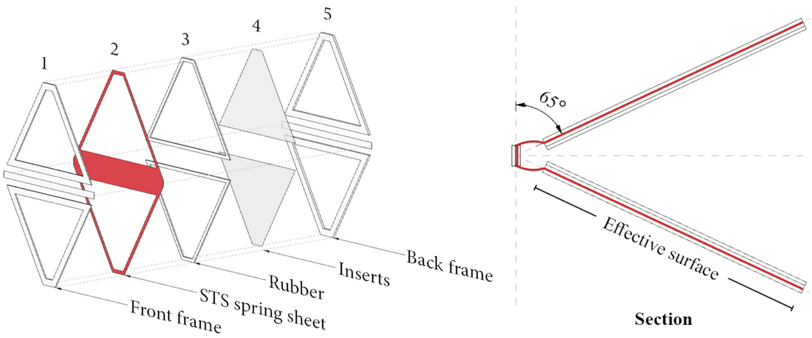


Figure 8. Elastomeric layered panel with Spring metal sheet exploded drawing & section

3.1.3. Torsion Spring Hinge

Further considerations prompted the use of torsion springs to bear wind loads (Figure 9). By integrating a rotating shaft and suspension subframe, the joint part was minimized, ensuring maximized effective surface area. However, scaling challenges have emerged, particularly at higher elevations, resulting in the requirement of larger springs, which is inconsistent with the principle of minimum joint parts.

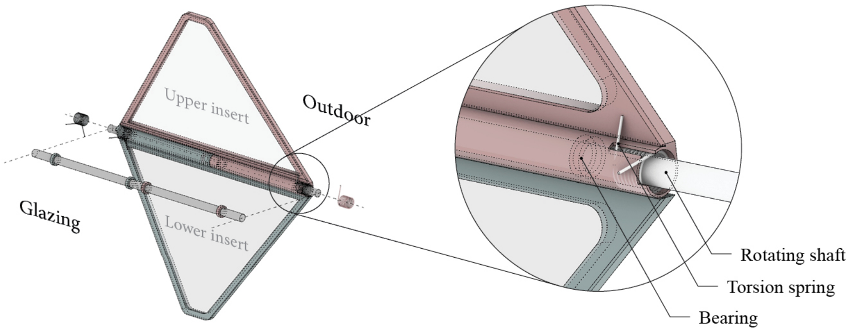


Figure 9. Torsion spring hinge concept

3.1.4. Dual-cable driven Mechanism

The spring-loaded system transitioned to a dual-cable system, featuring cables on both the back (inside) and front (outside), see Figure 10. The constant opposing tensions in these cables ensure stability during dynamic movements and sustain a static position for certain periods. These tension forces maintain equilibrium, facilitating controlled adjustments and positional stability. These features make the dual-cable driven mechanism suitable to the façade system that requires precision and durability.

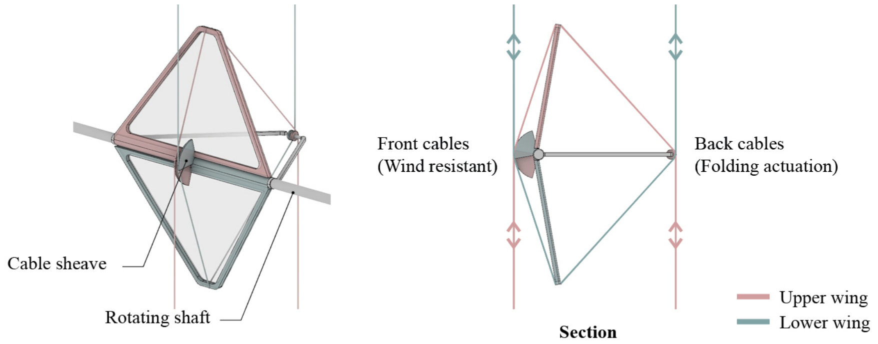


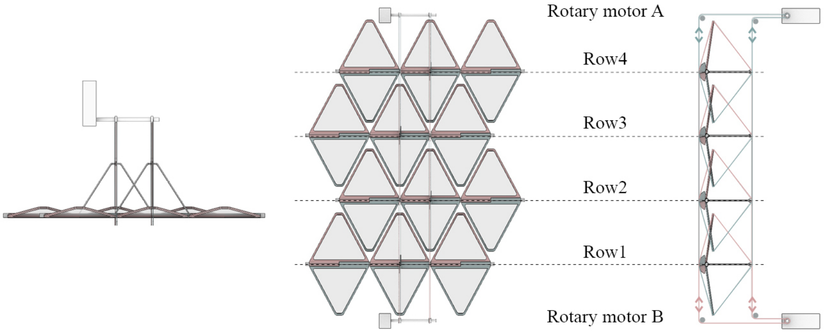
Figure 10. Dual cable system concept

In the meantime, kinematic design iterations were reflected in morphology design. Besides the integrated hinge from Section 3.1.3, an arc-component is added to the surface of each wing to guide the cables on the outside. The arc-components allow only one rotary motor for both cables by making similar dynamic variations in their lengths.

3.2. MOTORIZED CLUSTER

The primary advantage of cable-driven actuation lies in the ability to connect numerous modules to a single actuator, achieving mechanical linkage with minimal visual impact and thereby reducing the overall number of actuators. This enables the grouping of modules, where multiple units share a motor, facilitating efficient cable actuation.

Each upper and lower wing is linked to pulleys on the rotating shaft of an electric worm gear motor via steel wires. The folding motion is controlled by winding the front and back cables in different directions on separate pulleys, allowing for controlled retraction and extension based on the rotary direction of the motor. For a single mullion span about 2m, a cluster of 12 modules is managed by two motors—one for the upper wings and another for the lower wings. The rotary motor B, situated on the floor, operates the 12 upper wings, while the rotary motor A, mounted on the ceiling, drives the lower wings (Figure 11).



Top **Elevation** **Section**

Figure 11. Motorized cluster and layout

4. Result and Discussion

Four sequential developments of transformable joints are presented, with a focus on their mechanical properties and flexibility. This study provided insight into how these joints can be reconfigured for facade applications that require a minimum number of actuators, durability, precision, and flexibility.

The simulation results with the façade system revealed significantly improved illumination levels during both summer and winter solstices compared to glazing alone. In summer, the concentrated incident near the glazing led to extremely high illuminance level, which is mitigated by 30-40% depending on the lower wing's position. During winter, the upper wing effectively redirected low-altitude sunlight to the interior ceiling. As shown in Figure 6, the reflected diffuse light illuminated the interior, providing adequate brightness into the deeper area. The role of the lower wing in both seasons is encouraging, showing that the lower wing alone can provide 10% of indoor illuminance control in summer and 30% in winter. The difference between mean and median lux values is notably reduced by approximately 10% compared to without façade module (Figure 12). This improvement indicates enhanced uniformity in daylighting, particularly attributed to the diffuse light.

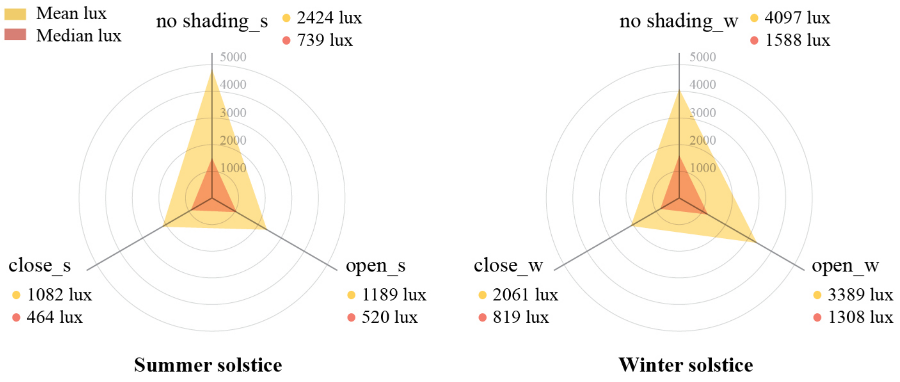


Figure 12. Comparison between mean and median lux level

In the near future, KineticSKIN will be showcased on a 6m wide and 3m in height glazed façade—a full-scale prototype (Figure 13). There will be three clusters of 12 modules each, covering a span of 2m with only two actuators. Next steps involve verifying the kinematic design through a 1:2 prototype and detailed manufacturing of the façade modules. This phase will validate kinematics at a larger scale and explore the feasibility of interchanging insert materials.

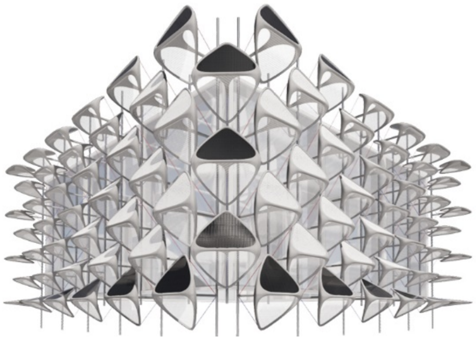


Figure 13. Vision of KineticSKIN

5. Conclusion

AKFs have been studied extensively for their potential in sustainable building energy cycles (Barozzi et al., 2016). Despite their recognized benefits, practical challenges, including installation and maintenance complexities, limit their widespread use. This paper addresses these challenges by presenting an integrated design and development process for an AKF that not only preserves architectural value and functionality but is also practical for implementation.

The outcome is a versatile façade system featuring adaptive design elements, informed by seasonal daylighting simulation results. Employing an interdisciplinary approach, various kinematic design options were rigorously analysed and developed. The result is a cable-driven actuation system that enables folding motions with high resolution while ensuring wind stability through cable interconnection, minimizing the number of required actuators.

This research distinguishes itself by emphasizing a harmonious balance between technical and architectural considerations. By adopting a continuous feedback loop and iterative processes within an interdisciplinary workflow, this integrated approach not only optimizes the entire system for functionality but also streamlines its implementation.

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