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Sigrid Brell-Cokcan
Thomas Adams

AUTHORS
Xiangcheng Li
Yufei Hu
Zeynep Sertkaya
Jiani Zhu Xingying
Li Zonghai Yang
Alperen Balcin
Merve Yanik
Damla Yigit
Nalan Yilmazarslan

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construction robotics
www.cr.rwth-aachen.de
international M.Sc.programme

www.cr.rwth-aachen.de
cr@ip.rwth-aachen.de

Editors:
Univ.-Prof. Dr.-techn. Sigrid Brell-Cokcan
Dr.-Ing. Thomas Adams

RWTH Aachen University
Chair of Individualized Production
Campus-Boulevard 30
52074 Aachen
Germany
www.ip.rwth-aachen.de

Layout:
David Lukert B.Sc.

Original cover:
Lukas Kirner M.Sc.

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RWTH Aachen University
Templergraben 55
52066 Aachen

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Alperen Balcin, Merve Yanik

SmartMotion – IoT-Based Energy Efficiency Tracking Related to Kinetic Façade Movement *(corrected version)*

Abstract

This paper investigates the development and optimization of a kinetic façade system created for the improvement of energy efficiency and indoor environmental quality via light-sensitive sensors and IoT-based control mechanisms. The Arduino microcontroller is used to tune the façade elements in real time to the ambient light intensity levels that are changing. Accordingly, the key research question that this paper attempts to address is: "How can adaptive building components use IoT enhance energy efficiency improve indoor comfort and reduce maintenance costs?". The primary objective is to show that adaptive components of the façade will save energy significantly by using daylight, thus in this way, natural light would be utilized and also the use of artificial equipment to control climate would also be minimized. It can be clearly seen from the findings of the experiment that the façade responds very good to the changing conditions of light, i.e., full opening of panels with high illumination and full closing with low light intensity, thus it maintains the desired temperature within the rooms and thus conserving energy, and most particularly, during the winter time. The study concludes that kinetic façades and IoT technology lead to better building performance and sustainable energy management, thus being applicable to future smart buildings. Further details and the source code of the project can be retrieved from GitLab at the following link: *https://git-ce.rwth-aachen.de/yankmrve/smartmotion_kinetic-facade-control.git*

Keywords: Kinetic Façade; Energy; IoT-Based Application; Smart House; Arduino Programming

DOI: 10.18154/RWTH-2026-07285

1. Introduction

The global trend towards sustainability and energy efficiency in the built environment has been raising the bar for new advances in architectural design and building technologies. One of the recent innovations is in kinetic facades: dynamic envelopes of buildings are capable of responding to changing environmental conditions in real time with the aim of optimizing energy performance and indoor comfort. These include heat gain, daylight penetration, and natural ventilation control, which can make kinetic façades greatly energy-saving; in turn, they contribute to the support of sustainable architecture.

It's motivated mainly by the need to address the twin challenges of enhancing indoor comfort and reducing the energy footprint of buildings. With the current increase in the rate of urbanization, there is an increasing demand for buildings that are energy efficient without compromising the comfort of their human occupants. Traditional static façades are always limited in offering flexibility, which can be used to adapt to different environmental conditions during different periods of the day and even during different seasons. Kinetic façades offer great potential by changing their configuration to optimize energy use and indoor climate control in line with outdoor conditions.

This paper points out the fact that kinetic façades play an important role in indoor comfort improvement, keeping in mind energy saving. In particular, kinetics façades address issues related to temperature regulation, daylight optimization, and ventilation control. For kinetic façades, the components of a façade are changed in real time in view of externals such as sunlight, wind, and temperature. Using these mechanisms, ideal interior conditions are maintained by reducing reliance on artificial climate control systems like HVAC (Heating, Ventilation, and Air Conditioning). Therefore, interior spaces can remain comfortable for the occupants while real-time adaptability minimizes energy usage. For example, kinetic façades modulate the intake of solar heat that enters a building, which consequently reduces the need for air conditioning during hotter months. In colder periods, if more sunlight is allowed inside, then self-evidently the costs of heating are reduced. Moreover, due to changes in daylight levels, kinetic façades have the potential to reduce the use of artificial lighting, thus saving energy directly. Their efficiencies are further enhanced through smart integration of sensors and automated controls, hence making kinetic facades the advanced solution to achieve twin goals of sustainability with indoor comfort.

Motivated by the need to research the innovative design strategies that will be capable of operating advanced technologies, the paper presents light-sensoring systems and IoT-based monitoring systems within kinetic façade systems. By integrating the façade with light sensors, it will automatically adapt itself to available natural lighting intensity, therefore cutting down on the consumption of artificial light and saving energy. Real-time monitoring and control of performance are also possible with IoT, ensuring flexibility and control over the indoor environment by the users. This research will aim to develop a prototype for the kinetic façade system with integrated light sensors for IoT-based applications in order to improve energy efficiency and make indoor comfort better. The prototype aims to show how smart technologies could be integrated into building design for adaptive systems that will change according to the environment. This study, therefore, discusses the practical implementation of these technologies to contribute to the ongoing debate on sustainable architecture and ensure a viable solution toward energy-efficient building design. Of relevance is the growing body of literature that continues to highlight the potential of kinetic façades in reducing energy use and providing superior indoor comfort.

2. Literature review

The field of kinetic façades has garnered significant attention in recent years due to their potential to enhance building energy efficiency and optimize environmental control. These façades are designed to respond dynamically to external environmental conditions, such as sunlight and temperature, thus playing a crucial role in energy conservation.

2.1 Theories and Approaches in Kinetic Façades

The architecture of sustainability and kinetic façades requires buildings to dynamically adapt to changes in environmental conditions. They can alter their form or structure to relate to the effects of sunlight, temperature, and wind while assuring energy efficiency. As reported by Zanghirella et al., kinetic façades with advanced control systems can decrease the solar heat gain by 20% and, respectively, the cooling loads in buildings situated in hot climates [1]. Proceeding further, Yoon and Sun confirm that the use of kinetic shading systems is an effective way of reducing artificial lighting costs, which in combination with other benefits results in energy savings of about 18% for office buildings [2]. Another is developed for algorithmic optimization in "Designing a Kinetic Façade Using BB-BC Algorithm with the Focus on Enhancing Building Energy Efficiency": in this case, the form and behavior of kinetic façades are optimized using the Bang-Big Crunch (BB-BC) algorithm, where such systems have shown to consume 30% less energy compared to traditional static façades [3].

Performance optimization of kinetic façades often resorts to the direct use of computational tools and associated algorithms in their design. This sentiment is further supported by Zhang et al. in the 2019 study around the parametric design strategy, and it is stated that using simulation tools is very important to predict and enhance the energy performance of kinetic facades [4]. These studies highlight the importance of adaptive design to building-related energy-use reduction, particularly within urban areas where environmental conditions may vary.

2.2 Strengths and Weaknesses of Existing Research

One of the key strengths of existing research on kinetic façades is the detailed exploration of energy savings potential. Moloney et al., 2020 have shown structures with kinetic facades to save energy up to 30% compared to those with static facades mainly due to optimized solar gain and control of ventilation [5]. Also, Boud et al. (2018) further improve kinetic façades as far as energy savings are concerned and simultaneously contribute to occupant comfort by controlling the penetration of natural light and thermal conditions [6].

However, there are also notable weaknesses in the current body of research. For instance, while the energy-saving benefits are well-documented, there is limited research on the long-term durability and maintenance costs associated with kinetic façades. Pitts et al. (2021) suggest that the mechanical complexity of kinetic façades could lead to higher maintenance costs and potential reliability issues over time, which could offset some of the energy savings [7]. Further research is required to address these concerns by developing more robust kinetic systems.

2.3 Previous Kinetic Façades Implementations

The architectural landscape has been transforming substantially in recent years with innovative façade technologies that enhance aesthetic appeal and contribute to environmental sustainability. Of these, kinetic facades represent a very promising solution capable of dynamic reactions to changing environmental settings while optimizing energy use. Kinetic façades, with advanced materials and smart systems as integral features, bring a redefinition to the boundary of the traditional building envelope. At the same time, maintaining a balance between form and function, a good real-life example when one talks about kinetic facade is the Penumbra Shading System (Figure 1). This presents an innovative solution for window shading by the use of mechanical vents that control daylight effectively in three dimensions over the day. They, like indoor blinds, are designed to fold up and down along either side of the windows so as to correspond with the east-west direction of the sun for maximized efficiency. They fold upwards to serve as horizontal shades against the high afternoon sun; hence they provide not only vertical shading but also go further to portray a dynamic and adaptive approach to managing sunlight exposure on building façades.

The Kiefer Technic Showroom, Bad Gleichenberg, Austria (Figure 2), is one of

Figure 1: Kinetic façades move in three dimensions to screen sunlight from any angle [8]

Figure 2: The Kiefer Technic Showroom in Bad Gleichenberg [9]

these new dynamic architecture buildings where the façade involves 112 movable tiles that control sunlight and internal climate. Designed in 2007 by Giselbrecht & Partners, this building's façade opens out and folds back in accordance with the weather and eliminates the need for air-conditioning. Those 56 engines animate the movement of the perforated aluminum panels to create a dynamic façade that is in constant change, and serves both functional and aesthetic qualities.

Future Studies on Kinetic Façades

For all the immense potentials kinetic façades have in terms of enhancing the energy efficiency of buildings, there is yet very much that has to be discovered in a number of areas for it to be fully exploited. The future research will focus on the solutions in the durability of kinetic façades and their compatibility with advanced technologies, including its long-term environmental impact. One major area for further study is in the durability and maintenance of kinetic façades. Although current research focuses on the energy-saving benefits, the sustainability of these systems in the long term remains questionable. As opined by Pitts et al. (2021), kinetic façades are inherently mechanically complex and are hence bound to carry higher maintenance costs than conventional façades, which would undercut their sustainability over time. It is important to further research the development of more durable materials and innovative maintenance strategies that may extend the lifespan of these systems [7].

The integration of smart technologies with kinetic façades opens up another critical area for future research. It is true that real-time data analytics and predictive algorithms will provide much better adaptability to those systems. More advanced sensors and control systems could be integrated to allow kinetic façades to respond more preciously to the change of environment, for further energy saving and indoor environmental improvement, reducing the energy consumed for the building operation. Future studies should investigate the potential of such technologies to optimize the performance of the facade and how they can be integrated with the currently available systems for building management [10].

The environmental life cycle impact of kinetic façades also requires further research. Moloney et al. (2020) reveal that kinetic façades are capable of achieving a certain degree of energy savings at the building operational level, even though the environmental costs at production and installation, and eventually at the end-of-life, have not yet been established. Future studies need to carry out a full Life Cycle Assessment (LCA) study in order to quantify the overall environmental impact and look for ways of minimizing it [11].

Table 1: Literature review summary and findings

No.	Authors	Title	Key Findings	Citation
[1]	Zanghirella, Babich, & Belleri	"Energy Performance of Kinetic Façades in Mediterranean Climates: A Case Study on Dynamic Sun-Shading Systems"	**20% reduction in solar heat gain**: Kinetic façades with advanced control systems can reduce solar heat gain by up to 20%, lowering cooling loads in hot climates.	Zanghirella et al. (2018)
[2]	Yoon and Sun	"The Impact of Kinetic Shading Systems on Daylighting and Energy Performance in Office Buildings"	**18% reduction in artificial lighting needs**: Implementation of a kinetic shading system can reduce artificial lighting needs by approximately 18% in office buildings.	Yoon, S., & Sun, S. (2020)
[3]	Babaee Tirkolaee, Goli, & Naderpour	"Designing a Kinetic Façade Using BB-BC Algorithm with a Focus on Enhancing Building Energy Efficiency"	**30% reduction in energy consumption**: Kinetic façades optimized with the BB-BC algorithm can reduce energy consumption by up to 30% compared to traditional static façades.	Babaee Tirkolaee et al. (2020)
[4]	Zhang, Du, & Chen	"Parametric Design Strategy for Kinetic Façades: Simulation and Performance Optimization"	**Importance of simulation tools**: Parametric design strategies and simulation tools are crucial for predicting and enhancing the energy performance of kinetic façades.	Zhang, Du, & Chen (2019)
[5]	Moloney, McLeod, & Phillips	"Energy Savings through Kinetic Façade Systems: A Comparative Study of Office Buildings in Different Climates"	**30% energy savings**: Buildings with kinetic façades can achieve up to 30% energy savings due to optimized control of solar gain and ventilation.	Moloney et al. (2020)
[6]	Boud, Rodi, & Benoy	"Occupant Comfort and Energy Efficiency in Buildings with Kinetic Façades: A Case Study"	**Improved occupant comfort**: Kinetic façades enhance energy efficiency and occupant comfort by regulating natural light and thermal conditions.	Boud et al. (2018)
[7]	Pitts & Mar	"Durability and Maintenance of Kinetic Façades: Challenges and Solutions"	**Concerns on durability and maintenance**: Mechanical complexity of kinetic façades could lead to higher maintenance costs and potential reliability issues over time.	Pitts & Mar (2021)
[8]	Frearson	"Kinetic louvres move in three dimensions to screen sunlight from any angle"	**Penumbra shading system**: Innovative window shading system with mechanical vents adjusting in three dimensions for optimized daylight control, providing both vertical and horizontal shading.	Frearson (2014)

[9]	Vinnitskaya	"Kiefer Technic Showroom / Ernst Giselbrecht + Partner"	**Dynamic architecture example**: Kiefer Technic Showroom with 112 movable tiles that adjust to control sunlight and internal climate, reducing the need for air conditioning.	Vinnitskaya (2010)
[10]	Lam & Cheng	"Smart Kinetic Façades: Enhancing Building Performance through Real-Time Data and Predictive Control"	**Integration of smart technologies**: Advanced sensors and control systems can enhance the adaptability and efficiency of kinetic façades.	Lam & Cheng (2020)
[11]	Moloney, McLeod, & Phillips	"Energy Savings through Kinetic Façade Systems: A Comparative Study of Office Buildings in Different Climates"	**Life cycle environmental impact**: While kinetic façades reduce operational energy use, the environmental costs of their production, installation, and disposal require further study.	Moloney et al. (2020)
[12]	Boud, Rodi, & Benoy	"Occupant Comfort and Energy Efficiency in Buildings with Kinetic Façades: A Case Study"	**Human interaction and user behavior**: More research is needed on how occupants interact with kinetic façades to ensure they are user-friendly and effective.	Boud, Rodi, & Benoy (2018)

Finally, Boud et al. (2018) draw attention to the general lack of empirical studies related to the human interaction dimension of kinetic façades. Consequently, what is required is the in-depth investigation of how occupants perceive and interact with such dynamic systems to provide very useful information for their design and operation. Much further research is needed in this area of studying user behavior in buildings with kinetic façades to ensure the effectiveness and user-friendliness of such systems [12].

By identifying these focus areas, future work can help overcome existing limitations of kinetic façades and enhance their contribution to sustainable architecture. Table 1 summarizes the state of the art by presenting the recent literature in the field.

3. Research methods

3.1 Research Design

3.1.1 Introduction to Research Design:

This study uses an experimental approach to carefully assess the performance and energy efficiency of kinetic façade systems that incorporate IoT sensors. The primary goal is to fine-tune the usability and energy-saving potential of these systems by closely monitoring how they respond to different environmental factors, particularly light levels. Although the current prototype uses acetate to mimic the flexibility of photovoltaic (PV) panels, it doesn’t generate energy. Ultimately, the aim is to develop a system that includes real PV panels for energy production. The experimental method was selected because it allows for precise control and adjustment of key variables in a simulated environment, resulting in reliable and accurate data.

3.1.2 Rationale for Experimental Design:

The choice to adopt an experimental design is motivated by the need to clearly establish a cause-and-effect relationship between the independent variable, which is light intensity, and the dependent variables, including energy use, system responsiveness, and indoor comfort. This method enables the researchers to isolate specific factors, such as how the kinetic elements of the façade respond to changes in light levels and the potential energy savings from automation using sensors. By simulating real-world conditions within a controlled setting, the research aims to generate insights that are directly applicable to full-scale building projects.

3.1.3 Scope of the Research:

This research focuses on the development, implementation, and evaluation of a prototype kinetic façade system designed to optimize energy performance under varying light conditions. The prototype uses acetate material to represent the flexible nature of PV panels, with the expectation that future versions will incorporate actual PV panels for energy generation. The study centers on several key areas:

Energy Consumption:

The research looks into the energy required to operate the kinetic elements, such as moving panels with servo motors. Although the current prototype does not generate energy, integrating PV panels in future designs is a major goal for sustainable energy management.

Sensor-Driven Responsiveness:

The study examines how the façade system adjusts in real-time to data collected by IoT sensors, especially light-dependent resistors (LDRs). The sensors' ability to accurately track and react to changes in light intensity is essential for maximizing energy efficiency and enhancing indoor comfort.

System Optimization:

This research explores different strategies to improve the overall efficiency of the kinetic façade system. For example, it investigates the potential to reduce energy use by placing actuators in standby mode during low-activity periods, such as nighttime. The study thoroughly evaluates how various operating modes impact both energy savings and indoor comfort.

3.1.4 Justification of Research Design:

The justification for using an experimental research design lies in its ability to deliver concrete data on the operational efficiency and feasibility of kinetic façade systems in real-world scenarios. Conducting the study in a controlled laboratory environment allows for precise adjustments of environmental variables, ensuring that the results are both dependable and can be replicated. Furthermore, the combination of IoT technology with kinetic architecture introduces a novel approach to energy management within buildings, making this research particularly relevant to the fields of sustainable architecture and smart building design.

3.2 Data Collection Methods

3.2.1 Sensor Integration and Calibration

The integration and calibration of sensors are essential for the accurate and responsive operation of the kinetic façade system. The sensors chosen for this research were selected based on their precision in measuring environmental conditions, with a particular focus on light intensity, which is crucial for the functioning of the kinetic elements.

Sensor Selection:

The study primarily employs Light Dependent Resistors (LDRs) due to their high sensitivity to changes in light intensity. LDRs were chosen for their reliable performance in detecting ambient light levels and their compatibility with the control systems of the prototype. Additionally, temperature sensors were included to monitor and manage the thermal conditions within the system, though the main emphasis remained on light intensity.

Sensor Placement:

The LDRs were strategically positioned across the façade, with one sensor on each panel and additional sensors placed between panels to ensure accurate light detection and comprehensive monitoring of light intensity. This arrangement was designed to capture both direct and diffused sunlight from various angles, providing a more thorough assessment of the environmental factors influencing the façade. The placement strategy was carefully planned to minimize shadow effects and ensure real-time detection of light variations.

Calibration Process:

Before the experiments commenced, all sensors underwent a detailed calibration process to ensure data accuracy. The LDRs were calibrated using a controlled light source with known intensity levels, enabling the adjustment of sensor readings to reflect actual light conditions. Calibration was carried out under different environmental conditions to account for potential variations in sensor sensitivity, which was crucial in minimizing measurement errors and improving the reliability of the data used in subsequent analyses.

Data Collection Precision:

The precision and reliability of the collected data can be further enhanced by applying noise filtering techniques and periodically recalibrating the sensors. Noise filtering algorithms can be used on the raw data to eliminate any false readings caused by transient light fluctuations or electronic interference. Additionally, regular recalibration helps to correct any drift in sensor sensitivity over time, ensuring that the data remains consistent throughout the experimental process.

3.3 Data Logging and Monitoring

To effectively evaluate the performance of the kinetic façade system, accurate data logging and real-time monitoring are essential. These processes are crucial for capturing consistent data and assessing system behavior under varying conditions.

Data Logging:

Initially, using an SD card for local data storage seemed like a good idea. However, switching to the Arduino IoT Cloud Remote app made things much smoother. This platform allowed for real-time monitoring and gave more flexibility in managing data. It also integrated seamlessly with the sensors and devices used in the project, ensuring continuous data logging throughout the experimental stages.

Real-Time Monitoring:

Monitoring in real-time was crucial. The Arduino IoT Cloud Remote app made it possible to track every change in light intensity, motor movement, and panel positioning as it happened. This immediate feedback ensured that the data collected was both accurate and reliable. The app's interface was designed to be user-friendly, giving a clear overview of the system’s status at any moment.

3.2.1. Experimental Conditions and Variables

The conditions and variables during testing were crucial in determining how the kinetic façade system performed under different scenarios. The experiments aimed to see how the system responded to changes in light, both indoors and outdoors.

Experimental Conditions:

Testing was done in both indoor and outdoor environments to get a complete picture of the system's performance. Indoors, tests were conducted under standard room conditions. Outdoors, the system was tested in sunny and cloudy weather. The lighting conditions included complete darkness, partial light, and full sunlight. These scenarios helped assess how well the system adapts to various levels of light, which is important for optimizing its response to changes in the environment.

Controlled Variables:

To ensure that the results were consistent and accurate, several important variables were closely controlled:

- **Motor Power:** The force generated by the motors was adjusted to ensure that the panels opened and closed smoothly. Different motors were used to see how varying levels of power affected the system. For the project SG90 servo motor (x3) and MG996R servo motor (x1) were used for moving the kinetic façade. Two motors with different torque were used to see the effects of two different motors.
- **Distance Between Motor Arm and Panel:** The distance between the motor and the panel was kept the same throughout the experiments to ensure consistent movement.
- **Panel Opening Speed:** The speed at which the panels opened in response to light was carefully controlled. Different types of motors required different light sensitivity settings. In accordance with the usage of two different types of servo motors, different ranges of light scales were used. The LDR combined with the SD90 servo motor has maximum light sensibility of 850 as for the LDS combined with MG966R has maximum of 1023.
- **Panel Angle of Opening:** The angle at which the panels opened depending on the amount of light was critical for ensuring the system worked as intended.
- **Material Flexibility (Acetate):** The flexibility of the acetate material used for the panels was measured to simulate the behavior of more advanced materials like flexible PV panels.

Measurement Intervals:

Data was collected at different times during the testing phases, corresponding to the various lighting conditions. This approach provided a detailed look at how the system adjusted to changes in light.

3.4 Experimental Setup and Procedures

The experimental setup and procedures were carefully planned to evaluate how well the kinetic façade system performs under different light conditions. This section covers the mechanical and electronic components used and the methods applied to assess the system's functionality.

Motor Arm Movement and Panel Opening Mechanism

The performance of the kinetic façade system is directly influenced by the movement of the motor arm and the panel opening mechanism. These relationships are formalized as follows:

1.Motor Arm Displacement: The linear displacement of the servo motor arm (d_m) is directly related to the rotation angle (θ_m) of the motor and the radius (r) of the motor arm:

$$\boldsymbol{d_m = r.\theta_m}$$

- This equation is essential for determining the extent of panel movement resulting from a specific rotational movement of the motor.

2. Torque and Force Relationship: The torque (τ) generated by the motor must be sufficient to exert the necessary force (F) to move the panel. The relationship is expressed as:

$$\boldsymbol{\tau = F.r}$$

- This equation is critical for selecting appropriate servo motors (e.g., SG90, MG996R) to ensure that they generate enough torque to efficiently move the panels.

3. Energy and Power Consumption: The energy (E) consumed by the motor during operation can be calculated using the torque and the rotation angle:

$$E = \tau \cdot \theta_m$$

- The power (P) consumed by the system is then given by:

$$P = \frac{E}{t} = \frac{\tau \cdot \theta_m}{t}$$

Light Intensity and Panel Opening

The relationship between light intensity (I), the motor's power output (P), and subsequently the panel's opening angle (θ_p) is crucial for understanding the system's response to varying environmental conditions. This relationship can be expressed in a simplified model as:

$$P = k_1 \cdot I$$

Where:

- P is the power output of the motor (measured in watts),
- I is the light intensity (measured in lux or another relevant unit),
- k_1 is a proportional constant that quantifies the relationship between light intensity and motor power. It indicates how responsive the motor is to changes in light intensity.

The motor's power output directly affects the opening angle (θ_p) of the kinetic façade panels. This relationship can be expressed as:

$$\theta_p = k_2 \cdot P = k_2 \cdot k_1 \cdot I$$

Where:

- θ_p is the panel's opening angle (measured in degrees),
- k_2 is another proportional constant that relates the motor's power output to the panel's opening angle.

These equations demonstrate that as light intensity increases, the motor generates more power, leading to a greater panel opening angle.

Application in the Experimental Setup

- **Servo Motors:** The SG90 and MG996R servo motors were selected based on their torque capacities, ensuring they provided sufficient force to move the panels as required.
- **Panel Movement:** The displacement and torque calculations ensured that the panels opened and closed within the desired angles in response to varying light intensities, controlled by the light sensors.

These procedures and calculations formed the foundation of the experimental setup, allowing for a precise and quantifiable analysis of how the kinetic façade system responds to different light conditions. The relationships defined between light intensity, motor power, and panel opening angle provide a solid basis for optimizing performance in real-world applications.

3.5 Data Analysis Methods

The data analysis in this study focused on applying the mathematical models established in the methodology to systematically evaluate the kinetic façade system's performance under varying light conditions. The primary objective was to quantify the relationships between light intensity, motor power output, and panel opening angle to assess the system's responsiveness and energy efficiency.

Application of Formulas: The formulas $P = k_1 \cdot I$ and $\theta_p = k_2 \cdot P$ were utilized to process the experimental data. These equations were applied to calculate the motor's power output at different levels of light intensity and determine the corresponding panel opening angles. The use of these formulas allowed for a structured analysis of how the system adjusts to environmental changes.

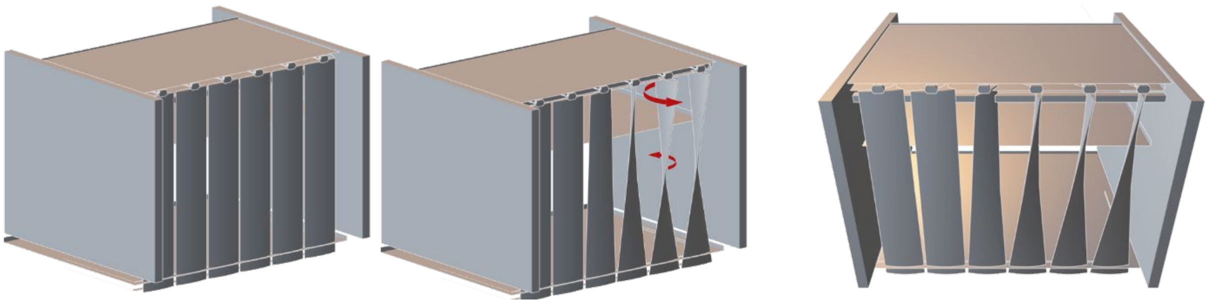

Figure 3: Prototype modeling views showing the panel layout and the red arrows indicating the opening direction.

Data Processing: The collected data were systematically processed to verify the theoretical models. Calculated values for motor power and panel angles were compared with the observed data to confirm the accuracy of the applied models. This comparison was crucial for validating the system's predicted behavior under varying light conditions.

Energy Consumption Analysis: Energy consumption was evaluated using the formula $E = \tau \cdot \theta_m$ to determine the energy required for panel movement under different light conditions. This analysis provided insights into the system's efficiency and identified potential areas for optimizing motor performance.

Statistical Methods: Descriptive statistics, such as mean and standard deviation, were employed to summarize the experimental data. Correlation analysis was conducted to explore the relationship between light intensity and motor performance, providing a quantitative assessment of the system's responsiveness.

Summary: The data analysis methods applied in this study provided a detailed understanding of the system's behavior under different environmental conditions. These methods laid the groundwork for further interpretation and discussion of the results, which will be addressed in the subsequent sections.

4. Prototype

In this project, a smart kinetic façade system was developed to optimize energy efficiency by adapting to varying weather conditions and the specific climate characteristics of the building's location. The prototype emphasizes a light-responsive façade design, wherein the façade elements automatically adjust based on light intensity, thereby enhancing the building's overall energy conservation.

The core concept involves the use of kinetic façade elements, constructed from acetate sheets, which respond dynamically to ambient light levels detected by integrated sensors. This adaptive system enables the façade to regulate sunlight exposure, contributing significantly to indoor energy management.

Concept development

The core concept focuses on designing a kinetic façade system that can automatically adapt to varying light conditions. The rectangular façade elements made from acetate sheets are programmed to respond to sensor data, opening or closing according to light intensity. This adaptive behavior effectively controls sunlight exposure, optimizing energy conservation within the building.

Prototype development

The development of the kinetic façade system was carried out through a series of systematic steps:

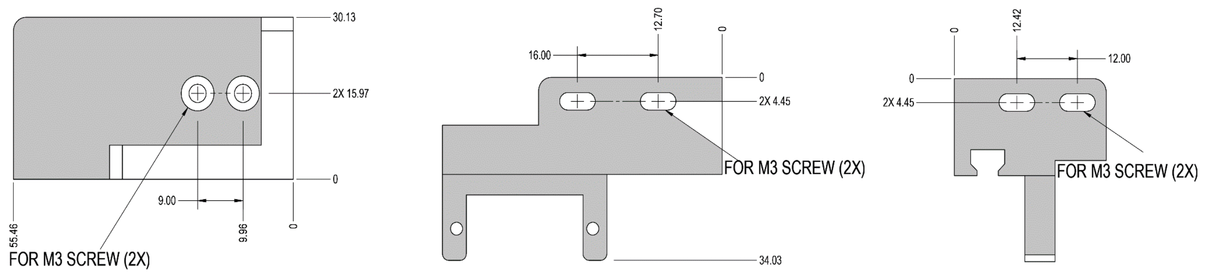

Figure 4: Above is the technical drawing of the 3D-printed motor housings used in the project, showcasing the dimensions and mounting points for the servo motors.

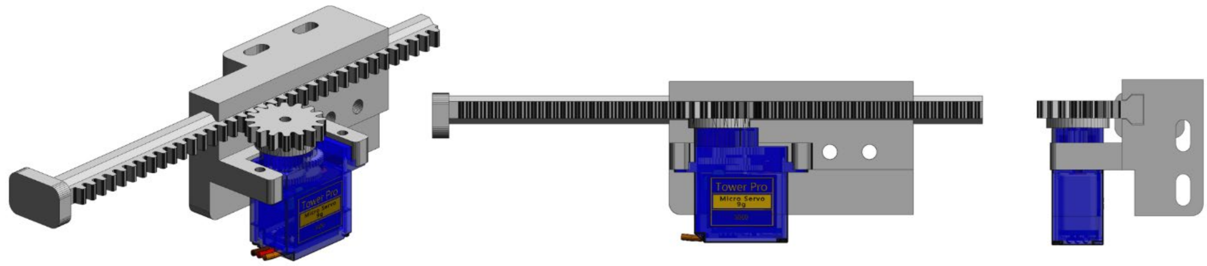

Figure 5: The gear and motor housing design for the façade movement

1.Fabrication of Façade Elements: Acetate sheets were chosen to model flexible photovoltaic panels with PET (Polyethylene Terephthalate) surfaces at the correct scale for achieving flexible, movable panels. The sheets were precisely cut into rectangular shapes, positioned at optimal intervals along the façade surface to allow responsive movement according to changing light levels.

2. Integration of Light Sensors: Sensors were strategically placed to detect environmental light levels and transmit signals to the Arduino microcontroller for processing.

3. Installation of Servo Motors: Servo motors were mounted behind each façade element to enable precise movement, controlled by the Arduino based on sensor data.

The 3D-printed motor housings were specifically designed to accommodate the *SG90* and *MG996R servo motors*, ensuring a secure fit and alignment with the façade panels. The motor mounts were custom-designed and fabricated using Blender 3D modeling software, followed by printing with a 3D printer to achieve the precise dimensions required for optimal performance.

The design process involved creating detailed 3D models tailored to the specific servo motors used in the project. These models were then translated into 3D-printed motor housings, ensuring that the servo motors were securely mounted and correctly aligned with the moving façade elements. The precision of these custom-made housings was critical for the reliable operation of the system.

4.Arduino Programming: The Arduino microcontroller was programmed to process real-time sensor data and control the servo motors, triggering the opening or closing of the façade elements based on predefined light thresholds. This systematic approach ensures that the prototype development process can be clearly replicated.

Prototype demonstration

The demonstration phase showcases how the façade elements dynamically respond to varying light intensities. The light sensors continuously monitor the environment and transmit data to the Arduino microcontroller when a specified threshold is exceeded. The microcontroller processes these signals and activates the servo motors, causing the façade elements to either close or open at the required angles.

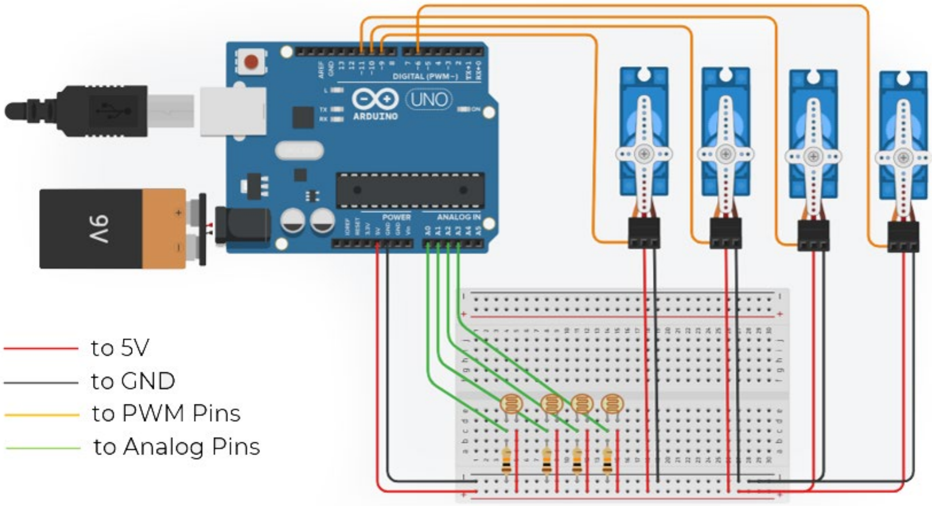

Figure 6: The layout of the components

Figure 7: Smart Motion Prototype

In scenarios of intense sunlight, the façade elements automatically close to mitigate excessive heat gain within the indoor space, thereby maintaining a cooler environment. Conversely, in low light conditions, the façade elements open fully to maximize natural lighting, reducing the reliance on artificial lighting and promoting energy efficiency. The façade's behavior can be customized according to seasonal requirements; for instance, during summer, closing the façade elements upon detecting high light intensity minimizes heat intrusion, while in winter, the system can be programmed to optimize natural lighting for warmth.

This prototype serves as a significant contribution to the development of smart kinetic façades, demonstrating how such systems can dynamically adapt to different climatic conditions, thereby improving energy management, enhancing building sustainability, and offering scalable solutions for modern architectural design.

5. Scientific results and discussion

5.1 Results

The experimental phase of our project focused on the behavior of kinetic façades equipped with light-sensitive sensors, observing their response to varying light conditions throughout the day. The study was divided into two primary observation periods: morning (6:00 AM - 12:00 PM) and afternoon (12:00 PM - 6:00 PM).

Morning Observations:

During the morning hours, the kinetic façade system demonstrated a clear response to increasing sunlight intensity. The façade's sensors detected the rising light levels, leading to a gradual opening of the façade panels. By analyzing the data, it was observed

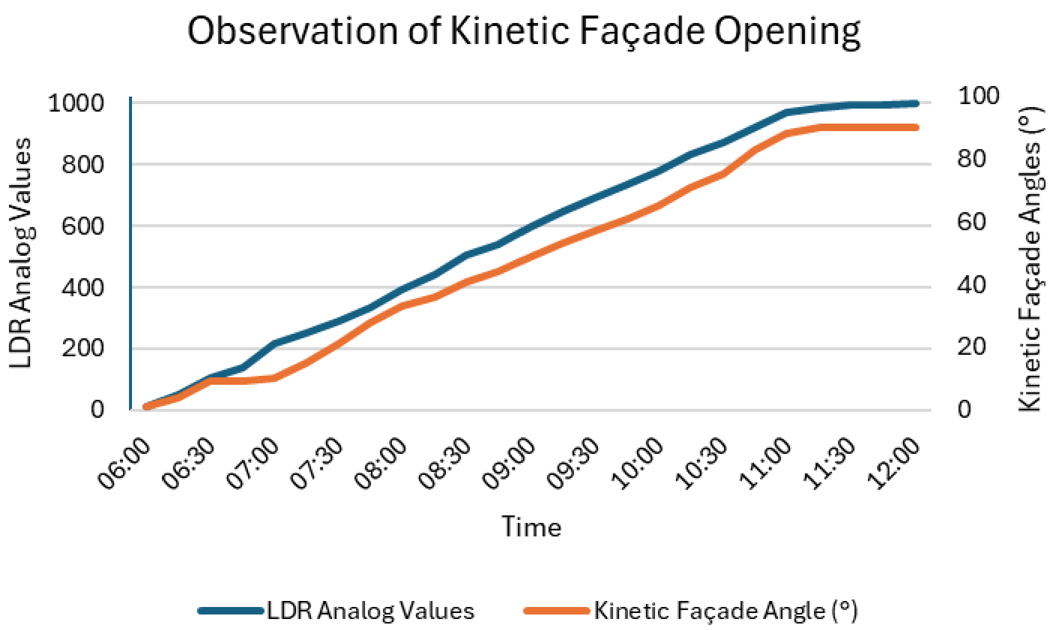

Figure 8: Observation of maximum kinetic façade opening

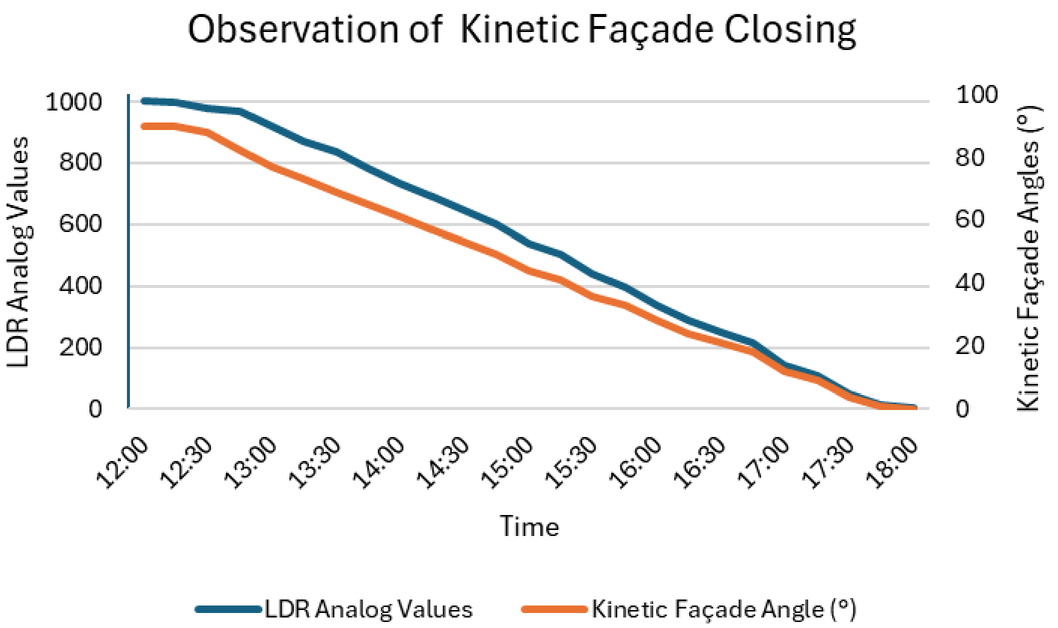

Figure 9: Observation of maximum kinetic façade closing

that the façade reached its maximum angle of opening during the peak sunlight hours between 10:00 AM and 12:00 PM. This behavior aligns with the system's design to maximize natural daylight penetration into the building, reducing the need for artificial lighting.

Afternoon Observations:

In contrast, the afternoon observations revealed a different behavior. As the sunlight intensity began to decrease after noon, the façade system responded by gradually closing the panels. This action was particularly prominent between 2:00 PM and 4:00 PM, indicating the system's ability to modulate based on both light intensity and the angle of sunlight. The closing of the façade during the afternoon helps to prevent excessive heat gain, contributing to the building's energy efficiency by reducing the load on cooling systems.

IoT Integration:

The kinetic façade system was integrated with an IoT-based interface using the Arduino Remote Cloud application. This interface allows for real-time monitoring and control of the façade system, providing users with the ability to adjust the façade position based on indoor and outdoor temperature data, as well as the façade's movement in response to light conditions. The interface also includes controls for indoor lighting, enabling further customization of the building's energy usage.

5.2 Discussion

The results of our study indicate that the kinetic façade system performs as intended, with the ability to dynamically adjust to varying light conditions, thereby optimizing both natural light usage and indoor comfort. The morning observations confirm that the system can effectively maximize daylight use, which is particularly beneficial for reducing reliance on artificial lighting during early working hours. The afternoon closing mechanism, on the other hand, helps to maintain cooler indoor temperatures by limiting direct sunlight exposure, thus supporting energy conservation efforts.

These findings demonstrate the potential of kinetic façades to significantly contribute to energy efficiency in buildings. By responding to real-time light conditions, the system not only enhances indoor comfort but also reduces the overall energy consumption of the building. The ability to integrate with an IoT platform adds an additional layer of functionality, allowing for remote monitoring and control, which is crucial for modern smart building management.

The implications of this study are twofold. First, the dynamic nature of the kinetic façade system shows promise for broader applications in various climatic regions, particularly those with significant daily variations in sunlight. Second, the integration with IoT technology underscores the importance of combining traditional architectural elements with modern digital tools to achieve optimal building performance.

One limitation of the study is the controlled environment in which the observations were conducted. The façade system's performance in real-world conditions, such as extreme weather events or irregular building orientations, was not tested. Additionally, the prototype's reliance on specific sensor calibration may limit its adaptability to different building types without further customization.

Future studies should focus on testing the kinetic façade system in diverse environmental conditions and on different building types to evaluate its broader applicability. Moreover, the development of more advanced sensor technologies that can adapt to a wider range of light intensities and environmental factors could further enhance the system's performance. Finally, exploring the integration of renewable energy sources, such as solar panels, with the kinetic façade system could provide a sustainable energy solution, making buildings not only energy-efficient but also energy-independent.

5.3 Conclusion

This study sought to answer the research question: "How can adaptive building components use IoT sensors and energy recovery technologies to enhance energy efficiency, improve indoor comfort, and reduce maintenance costs?"

To address this question, we focused on the implementation of kinetic façades integrated with IoT-based light sensors and controlled through Arduino programming. The primary goal was to explore how these adaptive systems could automatically respond to varying light conditions to optimize indoor environmental conditions and energy use.

Through the development and testing of our prototype, we found that kinetic façades could be effectively controlled to maximize energy efficiency and indoor comfort. The façades opened fully during periods of maximum daylight and closed during low-light conditions, thereby reducing the need for artificial lighting and maintaining a comfortable indoor temperature. This adaptive behavior, particularly when combined with seasonally adjustable modes, demonstrated potential for significant energy savings, especially in heating during winter and cooling during summer.

Moreover, the IoT-based control system we developed allowed for real-time monitoring and manual adjustments via a user-friendly interface. This system not only enhanced the adaptability of the façade but also provided valuable data on indoor and outdoor conditions, which could be used for further optimization.

In conclusion, this research connects the realms of innovative architectural design and practical application through the creation of a functional kinetic façade prototype. By integrating IoT-based light sensors and adaptive control systems, the façade not only enhances indoor comfort but also plays a key role in energy conservation and the reduction of maintenance costs. These findings underscore the feasibility and effectiveness of kinetic façades as a sustainable solution for contemporary building design, with future research possibilities in advanced predictive algorithms and broader IoT integration.

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