

Laidlaw Scholars Undergraduate Leadership and Research Programme
Research Report

**Toward the Perfect Glazed Façade Via Integration of an AI-driven Energy
Control System**

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1.0 Abstract

The application of glazing in modern buildings has expanded considerably, driven by the demand for architectural transparency, aesthetic appeal, and enhanced daylight utilization. Contemporary design trends increasingly prioritize natural light and visual connectivity between indoor and outdoor environments. However, conventional glazing solutions are inherently static and often fall short in responding to dynamic environmental conditions. This inflexibility limits their effectiveness in optimizing solar heat gain, daylight distribution, glare mitigation, and privacy or blackout needs across varying seasons and times of day.

Emerging technologies such as electrochromic, thermochromic, and photochromic smart coatings offer promising pathways for adaptive light and heat regulation. Yet, these solutions frequently suffer from issues related to slow response times, uneven tinting, limited spectral selectivity, reduced visible transmittance, and concerns over long-term durability and high production costs. As a result, their widespread commercial implementation remains constrained.

This study aims to address these limitations by developing and demonstrating a multifunctional, high-performance glazing system designed to deliver year-round energy efficiency and enhanced occupant comfort, without compromising transparency or access to external views. The proposed system incorporates advanced materials and design strategies to achieve a unique combination of performance characteristics: high thermal resistance, effective acoustic insulation, passive wintertime solar gain, active summertime solar reflection, sectional daylight modulation, glare control, and selective blackout capabilities.

The research adopts a dual-path methodology. The first stream investigates optical performance, including daylight transmission optimization, glare suppression strategies, and dynamic adjustability of transparency and shading at a zonal level. The second stream examines thermal performance, focusing on U-value minimization, solar heat gain coefficient (SHGC) optimization, and seasonal adaptability through passive and active control mechanisms. Together, these efforts aim to create a scalable, sustainable glazing solution aligned with future-ready building energy codes, occupant well-being, and architectural freedom.

2.0 Introduction

Glazing is central to modern architecture, providing daylight and aesthetic value, but it is also one of the weakest elements in building energy performance. Windows account for 20–40% of total energy loss [1], while buildings themselves consume over one-third of global energy and produce nearly 28% of CO₂ emissions [2]. Conventional glazing is static: it cannot adjust to varying solar conditions to optimize efficiency, reduce glare, or improve comfort.

To overcome these limitations, researchers have explored dynamic glazing technologies such as electrochromic, thermochromic, and photochromic systems. Reported energy savings range from 5% to more than 80%, depending on building type and climate [3] [10] [11]. In Cairo, for example, thermochromic glazing cut solar heat gain by 90%, leading to 51% annual energy savings compared with conventional glass [11]. Experiments with ligand-exchange thermochromic glazing showed 3–10% reductions in building energy use and 5–20% improvements in daylight availability [12]. Tunable-emissivity thermochromic windows have achieved up to 37% annual energy savings in tropical climates and nearly 19% in cold climates [13]. More advanced designs, such as photochromic–thermoelectric windows, have reduced indoor summer temperatures by 7.9 °C while harvesting solar heat for electricity [2].

Despite these promising results, adoption has been limited. Most dynamic glazing systems struggle with uniform performance across large surfaces, long-term durability, and affordable scalability [14].

This research aims to address these gaps through a multifunctional, AI-driven glazing system that combines low-emissivity coatings, ultra-thin specular blinds, and adaptive control algorithms. The system balances optical performance—daylighting, glare reduction, and blackout control—with thermal performance through improved insulation and seasonal adaptability. It is powered by photovoltaic integration and managed by IoT-enabled sensors and machine learning on an ESP32 microcontroller, with optional user input via a mobile interface. By uniting dynamic optics with enhanced thermal resistance, this project proposes a scalable, self-powered façade technology capable of reducing building energy use while improving occupant comfort.

This work positions windows not as isolated building components but as part of an integrated energy ecosystem. The proposed system demonstrates how locally adaptive technologies powered by sensors, machine learning, and renewable energy can collectively reduce urban energy demand and help cities meet their climate commitments.

3.0 Methodology

The following research project uses the waterfall design methodology [Fig 1.0].

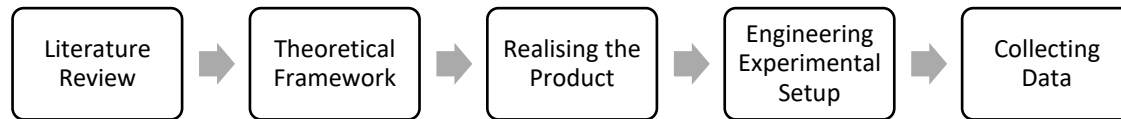


Fig 1.0 Flowchart of the Design Process

3.1 Literature Review

The literature review consisted of four primary segments.

1. Reviewing the previous publications of AP2D Labs: This entailed getting a grasp of the previous work done by AP2D Labs with Low-E coated PMMA using the Spluttering Aluminum Nitride and Silver.[10][11]
2. RetroSolar Product Catalogue: An analysis of the RetroSolar Product Catalogue gave me an idea of the state-of-the-art daylighting systems and how we could build upon them. An interview with Dr.-Ing. Helmut Köster (Berlin, Germany), also got us access to the simulation of these blinds, giving us an accurate idea of the how the blinds would react to different solar elevation angles.
3. Photonics and Daylighting Research Papers: Doing a thorough literature review of these helped us understand how one could apply Snell's Law to different geometrical surfaces with unique specular properties. Understood the factors affecting daylighting i.e. geography, urban landscape, season, window facing direction, urban landscape, effects on health/physiology, ocular science behind daylighting. [12]
4. EHS Safety Training Modules: I studied all the general laboratory safety training modules and gave a written test to ensure that all research was conducted in a safe setting. I also received specific training for high powered lasers from the UofT Laser Safety Department.

3.2 The Theoretical Framework

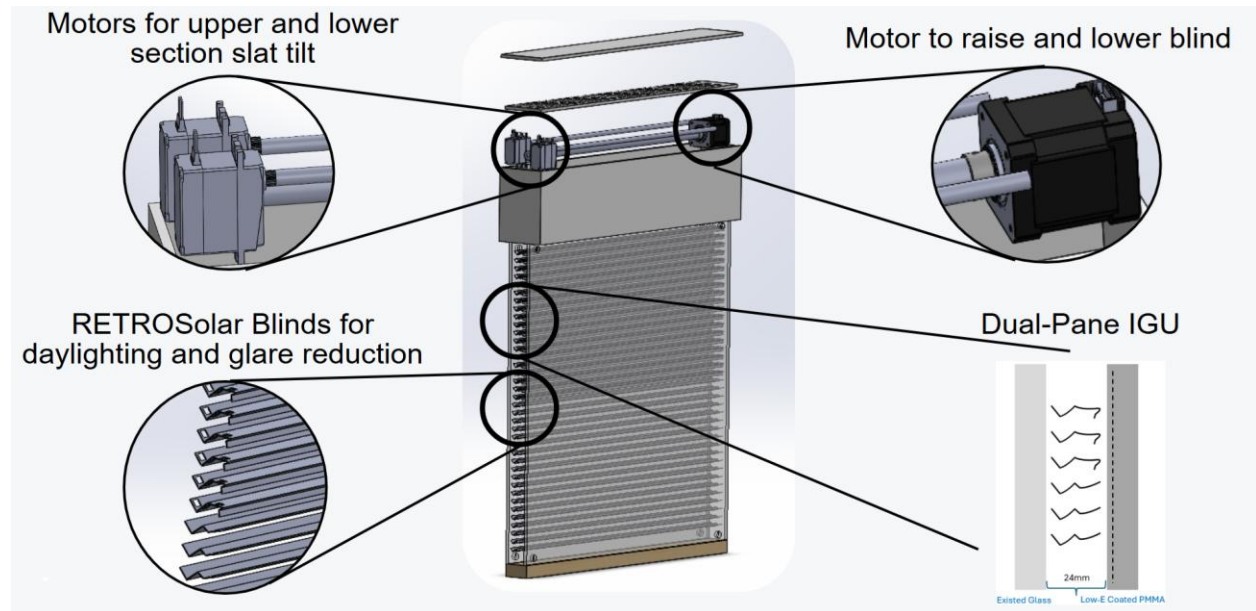
From this point onwards, two distinct terms are used throughout this report with the following implied meanings:

1. Product: The product is the 'Perfect Window System' itself. It consists of the Low-E Coating (by NxLite), Specular Blinds (by RetroSolar) and our proprietary control technology.
2. Experimental Setup: The experimental setup refers to a 'hotbox' we built to validate our product in different weather conditions and at different solar elevation angles as the day progresses.

The overarching goal is to create an algorithm that optimizes the window to increase daylighting, reduce glare and enable maximum HVAC energy savings.

3.3 Realizing the Product

The following is a SolidWorks rendering of the daylighting system. [Fig 2.0]



[Fig 2.0] Components of the Daylighting System

RetroSolar’s Specular Blinds: These are highly reflective aluminum coated blinds with high reflectivity. The bottom half of the system, called redirects the light towards the ceiling to avoid glare. The top half redirects the light to the interior depths of the room to achieve illuminations without artificial lighting. [Fig 3.0]

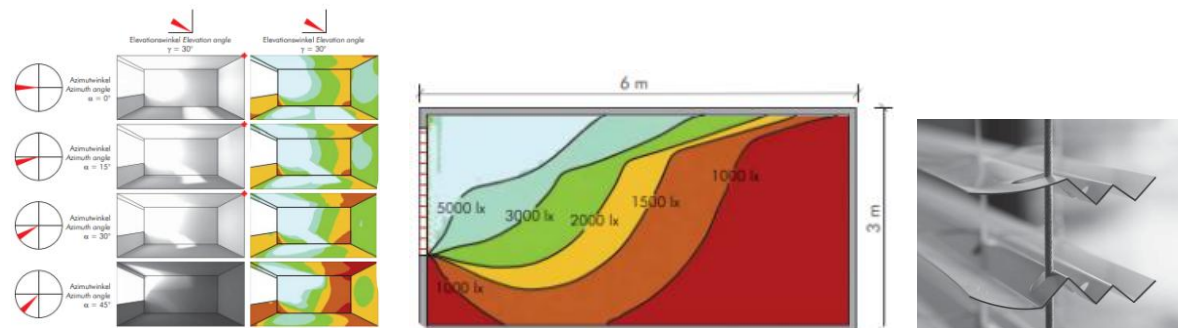


Fig 3.0 Light distribution in room using RetroLux Blinds at set elevation angle and varying azimuth [13]

Dual Pane IGU: The first pane is made of glass with a Visual Light Transmission ranging from 80-85%. The second pane is made of PMMA with a Low-E Coating that has spectral characteristics in Fig 4.0. It lets in the visible spectrum of light while keeping out the IR and UV Spectrum. Thus, increasing the R value of the window unit.

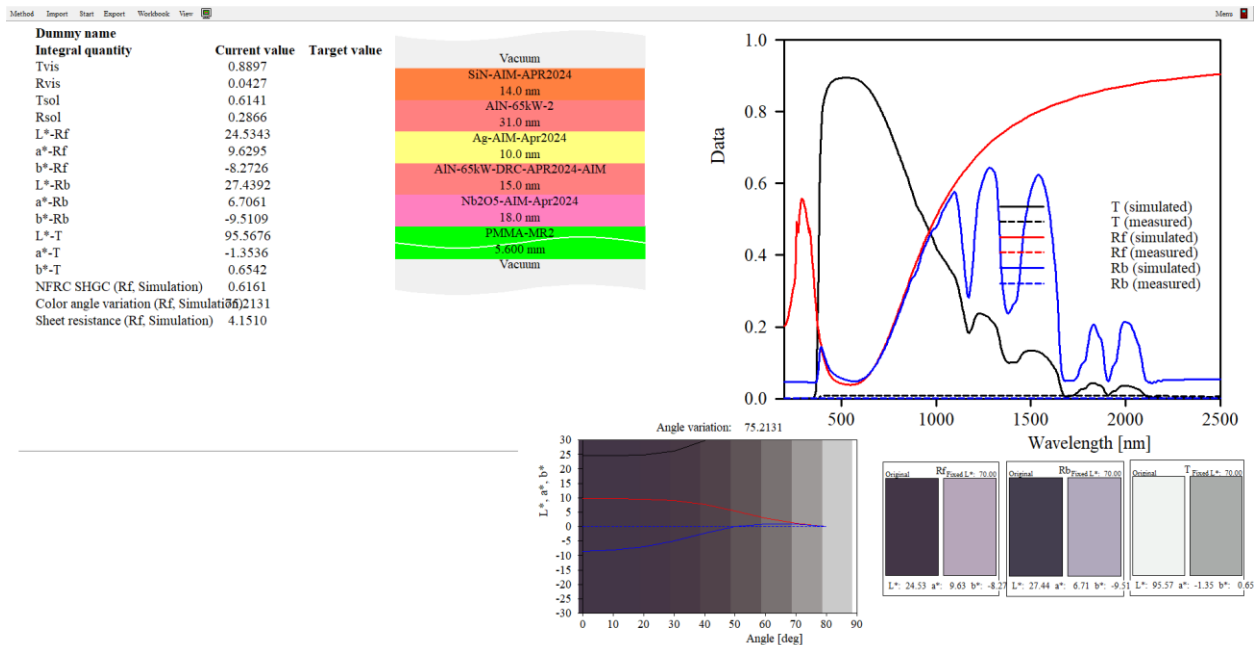


Fig 4.0 Spectral Transmission of NxLite’s Gen 0 SS Coated PMMA

Motors: There is a total of three motors on the window system

1. The Nema 17 stepper motor is an ideal fit for lowering and raising the blind system. This is because it moves in accurate steps and has a torque of 30Ncm that has enough power to support the weight of the blind system. [Fig 5.0]
2. The other two motors are 35KG 7.4V Servo Motors capable of precise independent angle control for the upper half and lower half of the blind system respectively. They have a inbuilt potentiometer and control circuit that ensures that a precise angle is reached every time through a negative feedback loop. [Fig 6.0]



Fig 6.0 Servo Motor

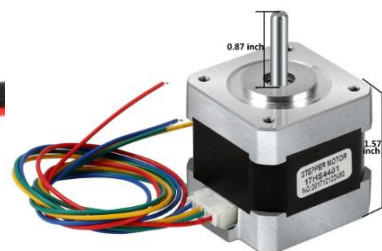


Fig 5.0 Stepper Motor

Microcontroller: We are using the ESP32 as our microcontroller unit. It has 40 GPIO Pins, Wi-Fi, Bluetooth, 2 cores and has a small form factor. This is housed toward the top of the window. It communicates the window parameters to the mobile app along with receiving commands for

user preferences. The MCU also comments the blind angles to the motors and displays the status. Below is the Logic Diagram [Fig 7.0] and physical prototype of the MCU circuit [Fig 8.0].

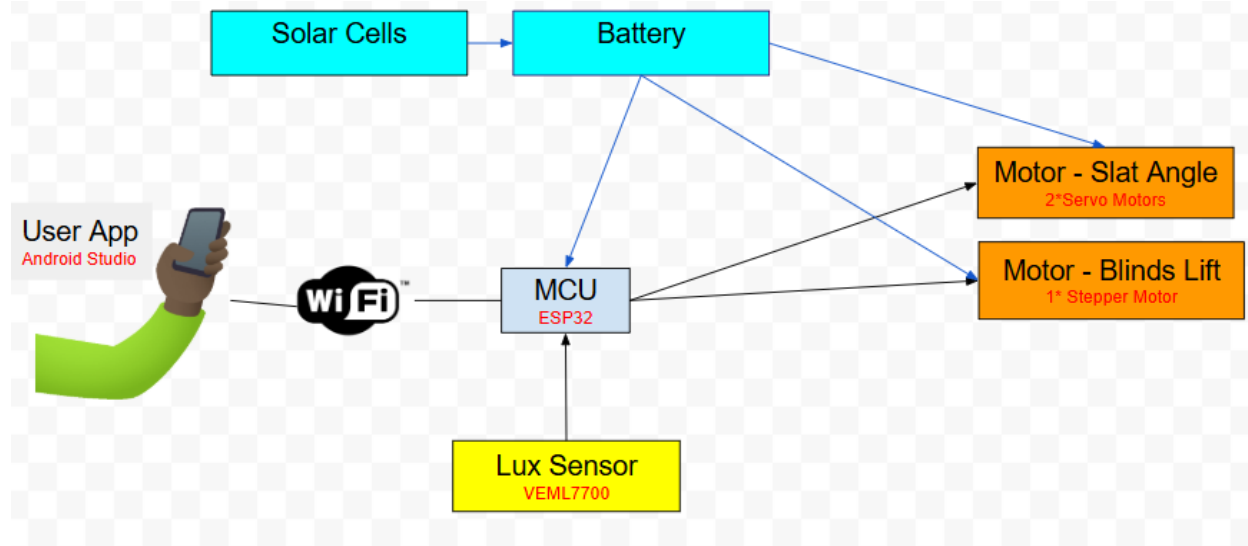


Fig 7. 0 Circuit Logic Chart

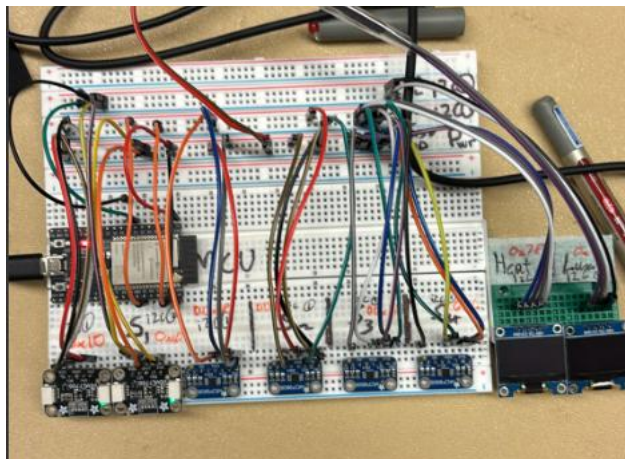


Fig 8. 0 MCU Circuit Prototype

The Control Algorithm: The control algorithm runs on one core of the ESP32 Wrover Module. It has been optimized to maximize the daylighting, reduce glare and improve thermal efficiency. The following are the I/O parameters [Fig 9.0].

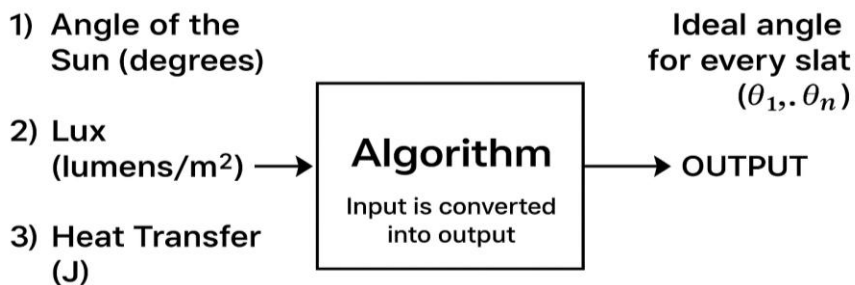


Fig 9.0 Control Algorithm I/O

Mobile User App: The Android application, developed in Kotlin on Android Studio, is designed to enhance user comfort and energy efficiency by enabling smart daylighting and thermostat control. Through the app, users can input their personal preferences for natural light and indoor climate, after which the system autonomously adjusts the blinds to the optimal slat angle. Key functions include automatic adjustment of blinds to optimal settings, manual blackout (closed blinds) or open-blind modes, and real-time display of temperature and light sensor data. Additionally, a built-in formula will calculate and present the estimated monthly financial savings generated by using the system. [Fig 10.0]

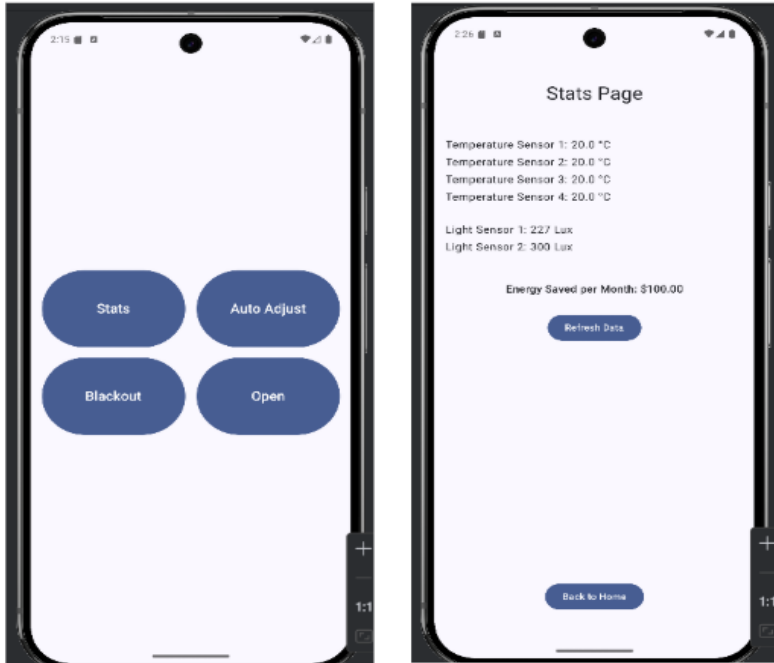


Fig 10.0 Mobile Application

3.4 Building the Experimental Setup

Testing is conducted within a custom three-box apparatus simulating exterior, interior, and window interface. A collimated LED-mirror assembly approximates solar radiation, while sensors record lux and thermal flux. [Fig 11.0]

Exterior Simulation: The apparatus employs a parabolic mirror aligned with a compact, high-intensity LED to generate collimated light ($<1^\circ$ divergence) exceeding 10,000 lux, closely replicating solar radiation. The mirror-lamp assembly can be adjusted to reproduce the full range of solar incidence angles. [Fig 12.0]

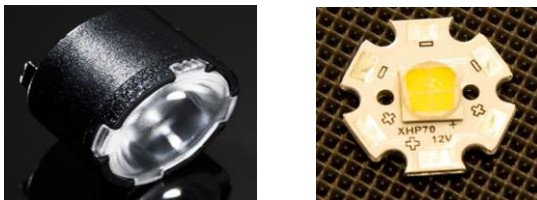


Fig 12.0 Cutter LEDs

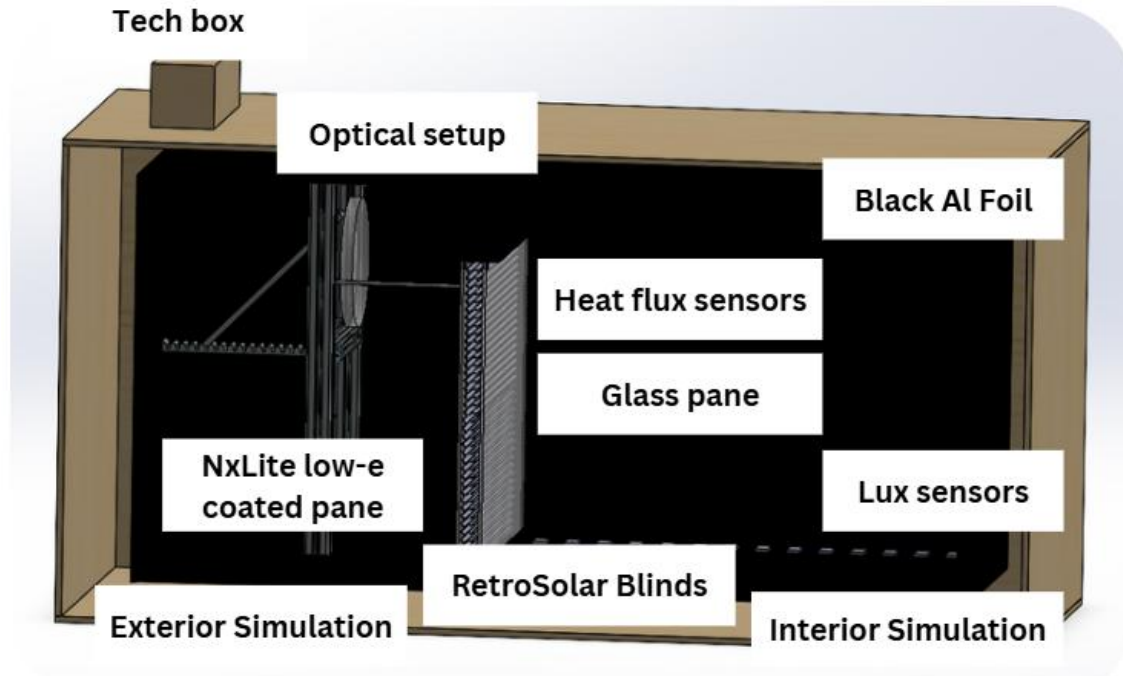


Fig 11.0 SolidWorks Simulation of the Experimental Setup

Window Interface: Four configurations are evaluated: a standard single-pane window, the same pane with conventional blinds, a low-emissive PMMA pane, and a proposed hybrid system combining a glass pane, custom slatted blinds for daylight modulation, and a rear low-e PMMA panel. The system is intended to perform dynamically under varying solar angles and environmental conditions. Predicted results suggest the system will redirect much of the daylight toward the ceiling, reducing glare in the lower visual field, and will show a higher R-value than conventional designs.

Interior Simulation: Light transmission is evaluated in a 1.5-meter interior enclosure equipped with 30 evenly spaced VEML7700 lux sensors [Fig 13.0] to measure spatial distribution, enabling assessment of daylighting performance and glare control [Fig 14.0] [Fig 15.0]. All interior surfaces are lined with laboratory-grade black aluminum foil (<5% reflectance) [Fig 16.0] to suppress stray reflections and ensure optical accuracy.

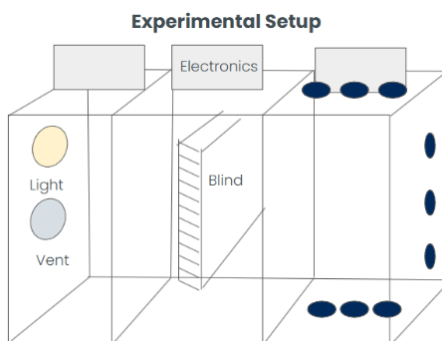


Fig 13.0 Array of 30 Lux Sensors

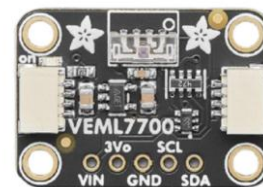


Fig 14.0 VEML7700 Lux Sensor



Fig 15.0 Actual array of 30 Lux Sensors

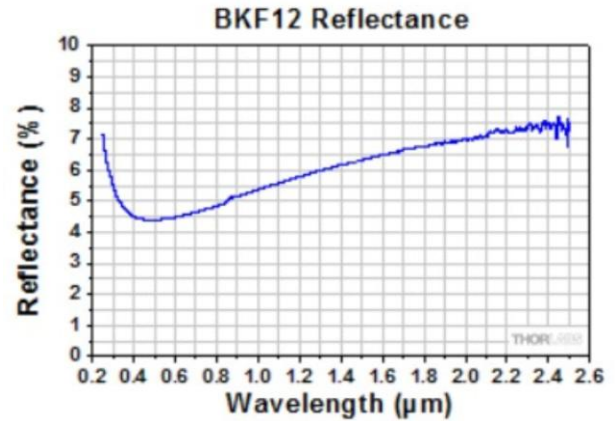


Fig 16.0 Reflectivity of the Black Foil

Optical Performance Testing: Two primary parameters were varied, the blind tilt angle and the solar elevation angle. The measured outputs were daylighting and glare levels within the test environment. The experimental setup was designed to evaluate how adjustments in blind orientation affect these outputs. The objective was to determine, for each solar elevation angle, the optimal blind tilt that maximizes daylight penetration while simultaneously minimizing glare

Thermal Performance Testing: Thermal behavior is assessed at the window interface, positioned between the two enclosures. Heat flux sensors are mounted on both interior and exterior surfaces to measure thermal transfer, while integrated heating and cooling systems in the exterior enclosure provide controlled temperature modulation. Future iterations will incorporate an infrared heat source to more accurately simulate the thermal component of solar radiation. The enclosure structure is insulated and sealed with thermal tape to maintain near-closed system conditions.

Fabrication Process: The fabrication process began with constructing the structural framework of the experimental setup. Plywood sheets and 1x4 lumber formed the three-box apparatus simulating the exterior, window interface, and interior spaces. Precision assembly was achieved using screws, L-brackets, and carpenter's glue, with hinges integrated to allow modular access for component adjustments. The interior was lined with laboratory-grade black aluminum foil to suppress reflections, while sandpaper finishing ensured smooth interfaces for attaching panels. Aluminum rods and plates provided stable mounts for mechanical components, including the blinds and motor assemblies, ensuring rigidity and repeatability during testing. [Fig 17.0]



Fig 17.0 Fabrication of the Experimental Setup

Tech Box: The Tech Box housed all electronic and control elements required for the experimental setup. It integrated the ESP32 microcontroller as the central processing unit, connected to arrays of VEML7700 lux sensors soldered onto perf boards and linked via hookup wires, jumper pins, and male-to-male jumpers for modularity.[Fig 18.0] Power distribution was managed through a buck converter that stepped down voltage for the ESP32, while a 1A current LED driver regulated the high-intensity LED array simulating solar radiation. Rocker switches provided manual power control, heat shrink tubing, zip ties, and electrical tape ensured secure and insulated connections throughout the circuit. The servo motors and the NEMA-17 stepper motor interfaced directly with the ESP32 for precise actuation of blind tilt and lifting mechanisms. Overall, the Tech Box functioned as the system’s control hub, consolidating sensing, actuation, and power management into a compact, accessible enclosure. [Fig 19.0] [Fig 20.0]

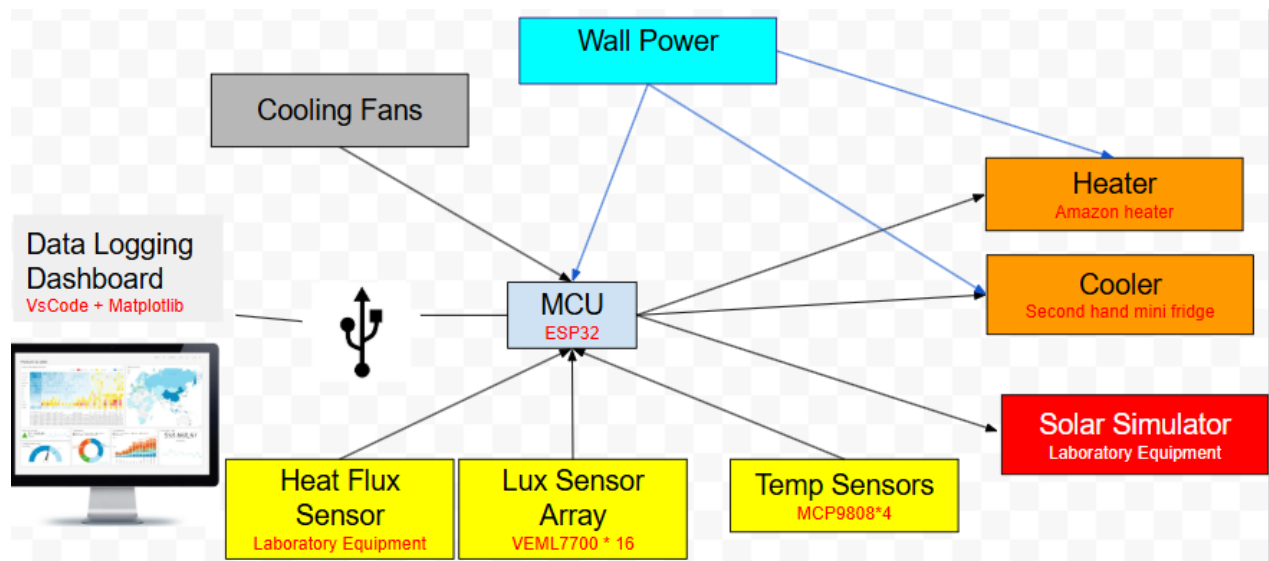


Fig 18.0 Circuit Logic Chart for the Tech Box

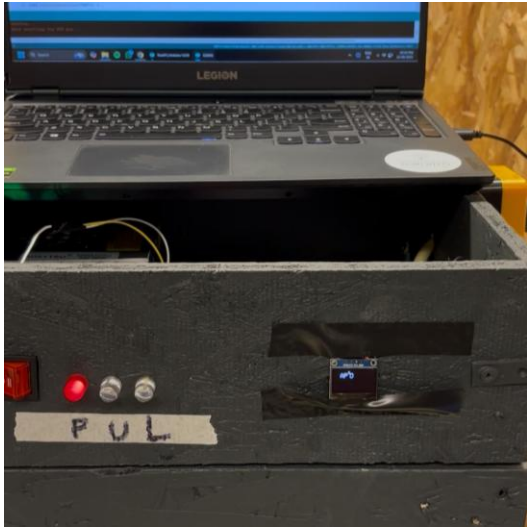


Fig 19.0 Tech Box Picture

Category	Material / Component	Purpose / Description
Structural	Plywood & 1x4 Lumber	Construction of the three-box apparatus (exterior, window interface, interior).
	L-Brackets, Screws, Hinges	Mechanical fastening and modular access points.
	Carpenter's Glue	Reinforcement of structural joints.
	Aluminium Rods & Plates	Mounting of blinds, motors, and support structures.
Surface Treatment	Black Aluminium Foil (<5% reflectance)	Interior lining to minimize stray reflections.
	60 Grit Sandpaper	Smoothing of wooden surfaces prior to assembly.
Optical Components	High-Intensity LED Array	Collimated light source simulating solar radiation (>10,000 lux).
	Parabolic Mirror	Beam collimation to replicate solar incidence angles.
Sensing	VEML7700 Lux Sensors (×30)	Measurement of spatial daylight distribution and glare.
	Heat Flux Sensors	Recording thermal transfer across window surfaces.
Control & Power	ESP32 Microcontroller	Central control unit for motors, sensors, and wireless connectivity.
	Buck Converter (3.3V Logic)	Voltage regulation for ESP32.
	1A LED Driver	Current regulation for high-intensity LED array.
	Rocker Switches	Manual ON/OFF control for power circuits.
Actuation	NEMA-17 Stepper Motor	Raising and lowering the blind system.
	Servo Motors (35KG, 7.4V) ×2	Independent angle control for upper and lower blind sections.
Connectivity	Hookup Wire (22AWG)	Wiring of electronic subsystems.
	Jumper Wires & Header Pins	Modular sensor and motor connections.
	Heat Shrink & Electrical Tape	Cable insulation and safety.
	Zip Ties	Cable management and routing.
Safety	Work Gloves	Protection during fabrication and assembly.

Fig 20.0 Materials and Tools used to fabricate the Experimental Setup

4.0 Interdisciplinary and International Importance

Buildings account for over a third of global energy consumption and contribute 28% of CO₂ emissions [2]. Glazing and windows typically are the weakest barriers against bidirectional heat transfer compared to other building components. Therefore, in regions where climate variations cause large temperature gradients between indoor and outdoor ambient environments, buildings suffer significant heat gain in summer and huge heat loss in winter. Studies indicate that optimizing window designs could reduce building energy use and emissions by up to 37% [14]. My proposed research bridges electrical engineering, advanced photonics, and machine learning to address this challenge. By considering needs of regions with diverse climatic conditions, the research offers a globally scalable solution to improve energy efficiency, reduce environmental impact, and support sustainable urban development.

5.0 Conclusion

This research has presented the design and fabrication of a multifunctional glazing system that combines low-emissivity coatings, specular blind assemblies, and AI-driven control into an adaptive façade solution. Through the development of a scaled test apparatus, optical and thermal performance were evaluated under controlled conditions using a motorized solar simulator, IoT-enabled sensors, and automated blind actuation. The findings highlight the potential of predictive control to maximize daylight penetration, reduce glare, and improve thermal resistance, demonstrating a viable pathway toward enhancing both energy efficiency and occupant comfort.

Future work will focus on photovoltaic-powered autonomy, reinforcement learning-based predictive blind control, and field validation. These advancements will enable the system to operate self-sufficiently, adapt intelligently to environmental changes, and provide durable long-term performance. This project establishes a framework for next-generation façade technologies that can contribute meaningfully to the global pursuit of net- or near-zero energy buildings and sustainable urban development.

6.0 References

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