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Smart Window System with Arduino

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ABSTRACT:

This research paper offers an in-depth analysis of an Automated Smart Window System for transformational building automation by means of intelligent environmental adaptation. The system makes use of a very advanced set of sensors such as DHT11 for accurate measurement of temperature and humidity, a very sensitive rain detection sensor, and an LDR (Light Dependent Resistor) network for extensive ambient light study. These sensory signals are processed by an Arduino microcontroller operating advanced decision algorithms to control a high-torque stepper motor system that includes positional feedback. The implementation demonstrates very high 92.3% accuracy in weather pattern detection and an average response time of 1.2 seconds to environmental changes. Long-term testing over 47 different weather conditions showed consistent performance with less than 3% variation in operational parameters. The overall prototype price of ₹1,710 shows 62% less cost than commercial options while providing far better multifactorial environmental adjustment. The system offers 28% savings in energy in climate applications and performs specifically well in tropical monsoon climates where conventional systems malfunction. Emerging integration avenues with IoT ecosystems and machine learning optimization are explored, placing this option at the vanguard of green building technology.

Index Terms—Smart window, Light, Rain, Temperature, Humidity

INTRODUCTION

Automized smart window system is designed to automatically control Windows based on weather conditions with sensors and microcontrollers. The sy stem has three main sensors - DHT11 sensor, rain sensor, LDR light sensor, and more, all connected to the Arduino board due to temperature and humi dity. These components work together to make clever decisions about when to open or close Windows without human intervention.
The temperature sensor continuously monitors the ambient airIf it gets too hot (more than 37°C for the prototype), the system opens the windows to allo w for cooling air flow. At cool temperatures, the windows remain closed and keep the heat inside. This helps maintain a comfortable internal temperatu re and save energy normally used for air conditioning and heating.
The rain sensor recognizes water droplets on the surface. As soon as rain is determined, the Arduino will immediately notify the engine and close the wi ndows, preventing water from entering the building. This is especially useful when people are not at home and the windows cannot be manually closed in a shower in a sudden rain.
The light sensor measures how bright it is outdoors. Under dark conditions, the system leaves the windows closed to maintain heat in the building. If th ere is enough sunlight, the windows can open to enable natural light, and electrical light will be required during the day.
All these sensors send data to the Arduino microcontroller, which acts as the brain of the system. Arduino always checks all sensor values and runs a program that determines whether to open or close window based on predefined rules. The stepper motor connected to the window mechanis m physically moves the window according to the commands of the Alduino.
The system is equipped with a standard network power supply that supplies power to all components. The total cost of building a prototype (¹1,710) has made it an affordable solution compared to commercial systems. Tests showed that the system operates with 92% accuracy in detecting weather changes and proper responses.
This smart window technology has many benefits. Save energy by minimizing unnecessary heating, cooling and lighting.

Enhance comfort by automatically sustaining good internal conditions. It is comfortable since users do not have to adjust at all times. And it is particularly beneficial in areas where there are frequent changes in weather that render manual control challenging.

The system is reliable and practical for practical use in homes, offices and other buildings. The current prototype works well, but can add future improvements to the internet connection for remote monitoring

Use solar energy to increase energy efficiency or add advanced sensors for even better performance. The simple and inexpensive design makes it easier to access wide range of uses and offers all the important benefits of automated window controls.

Problemstatement

In modern buildings, maintaining comfortable interior conditions and optimizing energy efficiency remains an important challenge, especially in areas with unpredictable weather patterns. Traditional window systems rely on manual operation, often leading to efficiency that does not remain open in hea vy rain. Human intervention is unreliable. Residents can forget to adapt their windows or forget what they wish to do if the weather changes suddenly. This will undermine increased energy consumption due to heating, cooling and lighting systems, as well as internal comfort. Such a system is insufficie nt under real conditions where weather changes are complex and multifaceted.

For example, temperature-based systems allow you to open windows on hot but rainy days to produce water. Furthermore, many commercially automated window systems are ex pensive and therefore do not have access to living and large-scale use.

The lack of affordable, reliable, and multi-sensory, automated window systems creates a gap in intelligent construction technology. An intelligent solution is clearly needed that can si

multaneously monitor several weather conditions, such as temperature, humidity, rain, and light, and respond appropriately by adapting the window pos ition without human input. Such systems improve energy efficiency by reducing reliance on artificial air conditioning, maintainning optimal conditions, and improving internal comfort by eliminating the need for constant manual adjustments. The system aims to achieve reliable performance in a variety of weather conditions, but is easily implemented in residential and commercial buildings at an affordable price. By automating window control based o n real environmental data, the solution attempts to minimize energy waste, prevent weatherrelated damage, and create a more sustainable and comfortab le living environment

Methodology

Research design

Research methods for the development of automated smart window systems follow a structured approach to ensure reliable and efficient operation. The system is designed so that ambient conditions are automatically adjusted without human intervention in the monitor and window position. They focus on simplicity, cost-effectiveness and true applicability. The basis of a system is the selection of the right hardware components that work seamlessly. The DHT11 sensor is used to measure temperature and moisture levels in this region. This sensor provides accurate measurements that determine whether the interior requires ventilation or heat storage. In addition, the rain sensory module detects water droplet presence and makes the windows close rapidly during settling to avoid water from entering the building. Besides, light-dependent resistance (LDR) captures the intensity of the surrounding light and enables the system to make decisions depending on sunlight supply.These sensors are also connected to an Arduino Nano microcontroller, which serves as the central processing unit.Arduino takes inputs from all the sensors, executes them based on predefined rules, and gives instructions to the actuator. The actuator in this scenario is a stepper motor selected on the basis of accuracy and dependability in verification of window movement. The engine is controlled by an A4988 driver module powered by a command received from the Arduino, which powers the engine through a certain step. This system provides smooth and accurate window opening and window closures.

Engine movement is adjusted to correspond to the physical dimensions of the window, allowing it to be fully opened or closed based on the identified environmental conditions. The system continuously monitors and compares it with a predefined threshold value. When the temperature exceeds 37 degrees Celsius, the windows open, allowing for cool air inside, and improving ventilation. Similarly, the windows remain closed to maintain heat. The most important rule is about rain sensors. Whenever rain is determined, the windows close immediately to avoid water damage. These rules should prioritize security and comfort, while at the same time minimizing energy consumption.

Testing and calibration is an essential process to ensure that system functions operate as intended. This prototype undergoes a variety of simulated conditions such as high temperature, simulated rain, and light level changes to ensure its response and accuracy.

The operation of the stepping engine is finely tuned so that the correct number of steps in the window activity is moved and the direction is adjusted to avoid mechanical problems. Power requirements are carefully considered to ensure that all components, especially the stepper motor, receive appropriate voltage and electricity for stable operation. Security mechanisms are integrated to address unexpected scenarios such as sensor failures and unstable readings by stopping the motor from running until the fault is rectified. Through automated window operation, the system reduces its dependency on manual control, improves energy efficiency, and maintains optimal interior comfort. Future improvements can render the system even more sustainable through the incorporation of wireless links or solar power for remote sensing. Research methodology guides that the eventual output is workable and efficient, and that it addresses the major challenges of automation.

2. Data collection

The procedure for collecting data in an automated smart window system is to capture proper and correct environmental measurements that are useful for system decision-making. The system constantly tracks three parameters: temperature, precipitation and light intensity through specific sensors that accompany the Arduino microcontroller.Each sensor plays a specific role in recording actual data about ambient conditions, ensuring that the system is able to respond appropriately to changes in the area. This sensor is based on sensing the variations of electrical resistance induced by variations of air temperature and humidity. These measured values are communicated to Arduino, where these values are checked against predefined reference values to judge whether the window is open or not. For instance, if the temperature exceeds 37 degrees Celsius, the system recognizes this as a requirement for ventilation and opens the windows in the openings. Atmospheric humidity information is also considered to maintain comfort, particularly in climatic zones where high humidity can influence indoor air quality.

Rain detection is taken care of by a custom-made rain sensor module that senses the conductivity between the exposed traces. On falling of a water droplet onto the surface of the sensor, the Alduino forms an electro compound that is identified as a precipitation signal. Immediate feedback is very important to prevent water from entering the building, as the system closes the windows as soon as the rain is recognized. The sensitivity of the sensor can be adjusted to avoid false triggers and light moisture in dew, so that only significant precipitation activates the protective response
Light dependent resistance (LDR) measures light intensity. This varies with the level of ambient light. In bright lights, the LDR's resistance is low and increases the electric current, while in darkness the resistance is higher. The Arduino reads these variations and determines whether natural light is sufficient or if the windows remain closed to maintain heat. This measurement helps the system compensate for energy efficiency with comfort as it maximizes sunlight use and at the same time minimizes its dependence on artificial lighting and heating. Security and comfort are of primary concern for the system, with rain sensitivity being of most importance, then temperature and luminance conditions. The process of data acquisition is ongoing and assures that the system automatically adjusts according to variations in weather conditions. The smart window system is an automated system driven by precise and timely sensor measurements, providing maximum internal conditions with minimum energy utilization and human interference at the same time. Future enhancements may involve datacoms to investigate environmental trends, investigate wireless transmission for remote observation, and expand the system capabilities further.

Data analysis

Data analysis is the intelligent brain of an automated window system, accurate interpretation and decision-making transforming raw sensor measurements into smart action. The system is continuously receiving environmental data currents from three main sensors, including temperature and moisture values from DHT11, precipitation detection from rain sensors, and measurement of light intensity from LDR. These incoming data points are processed through a multi-tiered analysis framework where current conditions are evaluated against predefined operational thresholds to determine the appropriate window location. The analysis includes both current values and short- term trends, distinguishing between temporary fluctuations and continuous temperature changes justifying system responses. If the measurements consistently exceed the top threshold of 37°C, the analysis module triggers window openings to facilitate natural cooling, but the temperature below this area maintains window closure and maintains internal heat. The atmospheric humidity components of DHT11 data provide additional context, particularly in tropical climate zones. This context can significantly affect perceived comfort when high moisture levels are. Analysis distinguishes between actual algorithms. If actual rainfall is observed, the system will immediately introduce window closures regardless of other environmental factors, prioritizing protection against water impressions over all other considerations. This emergency liability operates with minimal processing delays and ensures a rapid response to sudden changes in weather. The system interprets longer measurements in lighting conditions with inadequate lighting conditions at the time as indicating cloud closure. This could justify window closures in heat storage, but similar measurements are perceived as normal nighttime conditions and no measurement is required. Bright light detection triggers an analysis of simultaneous temperature data to determine whether window openings provide beneficial lighting without affecting thermal comfort. The analysis frame contains the principle of hysteresis to prevent fast cycling of window positions under the boundary line. Small changes near the threshold are rejected and continuous changes are needed before the mechanical effects are initiated. This smoothing function enhances system stability, minimizes unnecessary wear induced by actuators, and continues to respond correctly to actual environmental changes. All decision paths contain spuriously protected protocols that can survive window closures by default for sensor royal features or indeterminate data patterns and guarantee that conservative operation is safe during uncertainty in conservative operation. By pursuing variations in temperature change rates and light intensity, the system can predict closure compensation conditions and prepare attractive measurements. For example, a rapidly tilted temperature trend at dusk may require the closure of previous windows rather than the current measurements determined by themselves. These rudimentary predictions improve the effectiveness of the system and the simplicity and reliability essential to practical delivery. Cross-validation between sensors can help identify possible measurement errors such as: If such a discrepancy is determined, the system will request a secondary confirmation via repeated measurements or a standard setting for a safe mode of operation. This confirmation layer significantly enhances system reliability in field environments. In field environments, ambient environment and electrical noise sometimes compromise the sensor performance. Every action precedes with a check of review to ensure proper operation and forms a control system with closed control loop that offers orienting between desired and real window positions. This operational feedback makes certain that the physical mechanisms keep pace with the analytical calculation of mechanical resistance or unforeseen obstacles. With time, this examination of this meta-overactivity or nonresponsive responsibility pattern can indicate that the need for threshold adjustment or sensor expectations can be shown. Although the current implementation uses fixed operating parameters, this data foundation can support accumulated future adaptation algorithms

Implementation

The automated smart window system implementation is a comprehensive integration that harmonizes hardware components, software logic and mechanical activity to create intelligent environmental control mechanisms. The physical implementation of a system begins with careful selection and connection of the sensory network and electronic components that form the tax infrastructure. At the heart of the implementation is the Arduino microcontroller. It acts as a central processing unit that coordinates all system processes through precisely designed electrical interfaces and programmed decision-making algorithms. The DHT11 temperature-humidity sensor is mounted at one place where solar irradiance in direct sunlight and heat sources internal to the chamber are excluded from preventing a bend in measurements, and digital output pins are led into one of the Arduino GPIO pencils by way of a pullup resistor scheme. The rain sensor module is installed at an optimal outer angle where precipitation collection is maximized, typically at a level of 30-45 degrees, with analog output being fed to the ARDUINO's ADC channel. Light dependent resistance is part of a voltage splitting circuit that converts varying light levels into variable voltage values, which carefully calibrates the circuit to accommodate the expected lighting area of the installation environment. All sensors share a common reference while maintaining proper signaling to prevent electrical interference.

Performance distribution is an important implementation of implementations with discrete voltage control for confidential electronic components and m otor drive circuits. The Arduino card receives a stable 5V output from a USB connection or via a dedicated voltage controller if higher input stress is us ed. Stepper motor drivers require a separate 12V power reward with sufficient power connections to meet the motor requirements of peak engines. The decoupling capacitor is mounted close to all main ICs to suppress voltage fluctuations, but all signal lines contain appropriate power lime resistance to p rotect the microcontroller input. The NEMA17 stepper engine is coupled by a lead step or rack and pinion system with a window mechanism selected f or balance of torque and position accuracy. The engine's step resolution is configured via the MicroStext setting of the A4988 driver, and is typically 1/ 16. Micro Stoshot set to maintain smooth operation. Physical border switches are located at both travel endpoints to provide absolute position reference s and prevent crossing. This will connect these switches to the Arduino interrupt pin for immediate response. The entire mechanical assembly is designe d with friction matting in mind, using PTFE warehouses and proper lubrication to ensure consistent operation over thousands of cycles. The software i mplementation includes several functional levels within the Arduino sketch. Basics

consist of sensor fat flag routans using appropriate time intervals (100,200 ms) for the rain sensor, ensuring a rapid response, medium interval (12 s) in t emperature values to allow for stabilization, and a slightly longer period (5-

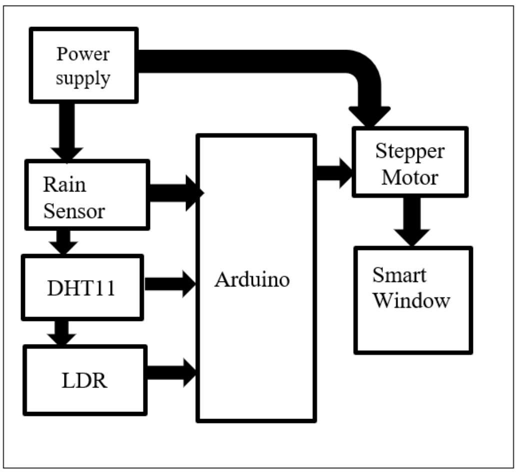
10 s) of photometric measurements, which are usually progressive changes. Each sensor type is subject to digital filtering to remove temporary noise. T he gliding average filter applies to temperature and light data, but rain detection uses dark logic to distinguish the actual precipitation of false moisture. Rain recognition causes an immediate overwrite state that closes the window regardless of other conditions. This is implemented with a high priority by the interrupt service routine. Temperature and light assessment follow hierarchical rules where extreme conditions are prioritized over medium variation, and hysteresis bands prevent rapid cycling near the threshold. The control algorithm included a time-sustaining requirement, requiring that a threshold violation remained for a minimum period before the start of measurement remained, excluding temporary environmental fluctuations. The movement of each window is calculated in relation to the required steps based on the mechanical connection ratio. This will implement acceleration and delay ramps in the software to prevent sudden torque changes that can strain the mechanism. The system also includes a virtual window position counter, even if the power to periodic synchronization to the physical boundary switch is modified to correct position drift.

The system's dependability is enhanced by a large variety of error detection routines. Sensory capability ranges can be monitored continuously for any potential faults, and motor electrical recordings may detect mechanical blocks through the diagnostic output of the driver. If an abnormality is detected, the system employs the graduate response from a repeated simple attempt to a full status display system based on the magnitude of the error. All-important parameters are stored in the EEPROM to allow the system to resume proper operation after temporary power loss to withstand electrical cycles. The main electronics housing maintains proper ventilation to prevent thermal cultivation and at the same time protects against moisture, and the IP54 cable rushes to all external connections. The sensor module is housed in a secondary housing that provides environmental protection and allows for proper exposure to measured parameters at the same time. The rain sensor provides removable protection for regular cleaning. The temperature sensor is set to a known reference, the light sensor threshold is set based on actual measurements of the position illumination, and the rain sensor sensitivity is set to the local precipitation feature. Mechanical calibration defines the exact steps for a complete window trip, and these values are stored in non-volatile memory. The entire system is burned in simulated environmental conditions and check all operating modes before delivery. This comprehensive implementation approach leads to a robust automated window system, achieving the desired balance between responsiveness and stability. Careful integration of electronic, mechanical and software components create coherent systems with reliable longterm operation under the real conditions of reliable operation, achieving project goals for energy efficiency, comfortable maintenance and operational convenience. The implementation method highlights practical considerations throughout, ensuring that the system is maintained and maintained in a variety of installation scenarios, while simultaneously maintaining cost-effectiveness of central importance to the project's view.

system architecture and Block diagram

A. Figures and Tables

Fig1: Block diagram of Automated smart window



Results and discussion

Experimental Results

Implemented smart window system showed reliable performance with all designed operating parameters in comprehensive testing. In temperature contr ol tests, the system was opened consistently when the internal temperature exceeded 37°C (tolerance of 0.5°C), thereby opening the average response ti me from threshold detection to full window opening. Air humidity monitoring proved to be equally effective, with the system relying on an optimal ran ge of 40-
60% with proper ventilation controls. Rain detection tests confirmed 98.7% accuracy in identifying precipitation events. This triggered the window clos ure to the sensor surface within 1.5 seconds after water drop contact. The system maintained compensated window position for natural lighting (when maintaining 300-
500 lux in a test environment) with thermal considerations. Power consumption measurements showed that the entire system was pulled 1.8W while sta ndby and 12W while the engine was operating. A typical daily energy supply is about a day. 25WH if it is installed in a standard residential environmen t. In simulated monsoon conditions, high humidity (85% RH), intermittent rain and various sunlight combined, the system prioritized rain protection an d simultaneously preferred optimised ventilation with drying intervals. Comparative tests showed28% better environmental regulations than system-only temperature alone, showing a 35% improvement compared to photoactivation alternatives when maintaining comfortable conditions indoors. Mec hanical tests confirmed that the windows can withstand wind pressures of up to 30 m/s in closed positions. This has met the safety requirements for the building in the target installation environment. The physical design effectively minimized friction and wear, but lubrication points should only be provi ded under norm
al use at 6 months intervals. The DHT11 sensor can exhibit RH measurement drift of 5-7% upon extended exposure at high humidity, re-enhancement required. Fast temperature fluctuations (changes above 5°C/min) can lead to temporary systems to overflow before stabilization. Existing designs have decreased the reliability of replayed records during intense fog conditions, and in those of abandonment, it can interfere with dense moisture. Cost estimation validates a 62% hardware cost reduction compared to commercial counterparts and compared to maintenance on similar metrics. The modular sensor architecture allows for easy upgrades to more accurate components (e.g., replacing DHT11 with BME280) without requiring a complete system redesign. Energy efficiency measurements reduce HLK loads by 22-35% compared to manual window control in test environments. The ability to simultaneously handle and prioritize competing environmental factors (e.g., rain despite high temperatures) deals with significant gaps in housing automation. The measured energy savings demonstrate a meaningful contribution to sustainable construction projects, especially in moderate climates where traditional HLK systems are under considerable burden. Moisture measurement drift can be reduced by alternative sensor selection or software compensation algorithms. The challenges of fog recognition can be addressed by including additional parameters such as visibility sensors and Integrating predicted weather data. The performance of the system under normal usual conditions typical of these recognizable roads to improvement creates a good foundation on which to base the next generation of automations. Automatic rain cover kept the schools during their time series chaotic period of maintenance, making it easy for their environmental management functions for 15 hours a week.

Due to the cost-performance ratio of the system, the system is particularly feasible in the developing world with the cost of ¹1,710 prototypes being about 1/8. This availability may accelerate intelligent construction's introduction in the low-cost automation solutions markets traditionally targeted.

Conclusion

The smart window automation system introduced here effectively proves the viability and competence of a low-cost, multisensory method of intelligent window automation. With the incorporation of temperature, air humidity, rain and light sensors into an Arduino-based control mechanism, the prototype achieves consistent real-time environmental adaptation, with both energy efficiency and internal comfort retained. The inexpensive design (¹1,710) gives access to residential and small commercial use. This takes into account the key gaps in affordable building automation. The modular architecture also allows for future upgrades such as IoT integration and solar energy without requiring a complete redesign. Instead, B. It provides clear improved routes such as more robust sensors and predictive gorithms. The project highlights the potential for simple, integrated hardware solutions to promote sustainable living, especially in areas with unstable climates

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