

Design of Intelligent Street Lighting Systems Based on Motion and Ambient Light Sensors

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Abstract. Street lighting is essential for nighttime traffic safety and public security, yet many conventional installations still operate at constant full brightness from dusk to dawn regardless of road activity. This practice causes unnecessary energy consumption and increases operational costs, particularly in low-traffic periods. This study aimed to design and evaluate a low-cost intelligent street lighting prototype that combines a passive infrared (PIR) motion sensor and a light dependent resistor (LDR) ambient light sensor to reduce full-brightness operating time while maintaining responsive illumination at night. An Arduino-based controller was implemented using a state-based control strategy with three operating modes: OFF during sufficient daylight, DIM standby at night when no motion was detected, and BRIGHT mode when motion was detected, followed by a configurable hold time before returning to DIM. The prototype was tested under four scenarios representing daylight, nighttime idle, nighttime motion, and motion stop conditions, with repeated trials and serial logging of sensor readings, state transitions, and pulse width modulation output levels. The results showed reliable state behavior across scenarios, rapid activation from motion detection to BRIGHT mode with a mean response time of 0.42 s, and consistent hold-time performance near the 30 s target. During a 30-minute nighttime mixed-activity test, the system operated in DIM mode for 62% of the time and in BRIGHT mode for 38%, yielding an estimated 43.4% relative energy reduction compared with an always-on full-brightness baseline. The findings indicate that integrating PIR motion sensing and LDR-based ambient gating provides a practical and replicable pathway to improve street lighting energy efficiency without sacrificing on-demand illumination for road users.

Keywords. Intelligent Lighting; Street Lighting; PIR Sensor; LDR Sensor; Energy Efficiency

INTRODUCTION

Street lighting is a critical public infrastructure that supports nighttime visibility, traffic safety, and perceived security in urban and peri-urban environments. Nevertheless, many street lighting networks still rely on fixed time schedules and operate at full output from dusk to dawn regardless of actual road activity. Such “always-on, full-bright” operation increases electricity consumption and operating costs, and it can accelerate luminaire aging due to prolonged high-power usage and thermal loading, which becomes a practical concern for municipalities facing budget pressure and sustainability targets (Pasolini et al., 2024). In addition, modern road-lighting practice increasingly demands that lighting performance and energy use be assessed using standard-based indicators and class requirements, motivating adaptive solutions that deliver illumination only when and where it is needed (CEN, 2015).

In recent years, intelligent street lighting has become a core topic within smart city development. A broad stream of research has focused on IoT-enabled architectures that provide remote monitoring, fault detection, networked dimming control, and integration with other smart city services (Omar et al., 2022). These studies emphasize communication technologies and management platforms that enable city-scale supervision and maintenance optimization. Another stream concentrates on context-adaptive lighting, in which lamp output is adjusted based on environmental and usage cues commonly combining ambient light sensing for day–night gating with motion/traffic sensing to raise brightness only when pedestrians or vehicles are present (Chiradeja & Yoomak, 2023). Comprehensive assessments of large-scale and long-term implementations indicate that context-adaptive strategies can improve energy efficiency and operational effectiveness, but they must be designed carefully to maintain lighting adequacy and user acceptance across varying traffic patterns and locations (Pasolini et al., 2024).

Although the state of the art demonstrates strong potential, several practical gaps remain particularly for low-cost, stand-alone designs intended for incremental retrofit or small-area deployment. First, many publications prioritize connectivity and high-level architecture, while the core control behavior (explicitly defined OFF–DIM–BRIGHT states, hold-time logic, threshold selection, and anti-flicker measures) is often described briefly, limiting reproducibility and field transferability (Omar et al., 2022; Agramelal et al., 2023). Second, the performance of motion-triggered dimming in outdoor settings can degrade due to environmental variability and placement sensitivity, so a robust, parameterized control model is necessary to avoid unstable switching and to keep lighting behavior predictable for road users (Agramelal et al., 2023). Third, even though standards and implementation studies highlight the importance of evaluating energy and lighting performance, prototype papers do not always translate control decisions (dimming levels and hold times) into measurable duty-cycle outcomes that can be compared against baseline always-on operation in a transparent manner (Pasolini et al., 2024; CEN, 2015).

To address these gaps, this study proposed an intelligent street lighting design that integrates motion detection and ambient light measurement using a state-based control algorithm with configurable parameters (ambient threshold, dim level, bright level, and hold time). The novelty of this work lies in providing (i) a replicable OFF–DIM–BRIGHT

control model suitable for low-cost retrofit, (ii) a clear parameterization approach that supports site-specific tuning without reliance on networking infrastructure, and (iii) an evaluation method based on response time and duty-cycle logging to estimate reductions in full-brightness operating time relative to conventional fixed-output operation. Therefore, the aim of the study was to design, implement, and experimentally evaluate a practical prototype that reduces full-brightness operating time at night while preserving responsive illumination for road users, contributing a field-ready reference design for energy-efficient street lighting deployment.

METHODS

This study used an engineering prototyping and experimental evaluation approach to design and test an intelligent street lighting controller using an Arduino microcontroller. The prototype combined a PIR motion sensor and an LDR ambient light sensor to deliver adaptive lighting behavior at night while preventing lamp activation during daylight. The method was selected to ensure the proposed control logic could be implemented reliably with low-cost components and evaluated under repeatable scenarios before potential outdoor deployment.

Research type, hardware design, and materials

The research was categorized as applied experimental prototyping. A functional prototype was designed, assembled, and tested to answer the research question: *Can a combined PIR–LDR control strategy reduce full-brightness operating time while maintaining responsive illumination at night?* The prototype architecture integrated sensing, control, and actuation in a single unit so that sensor inputs could directly translate into lamp output decisions. To provide a clearer overview of the hardware integration and signal flow, the block diagram of the proposed intelligent street lighting system is presented in Figure 1.

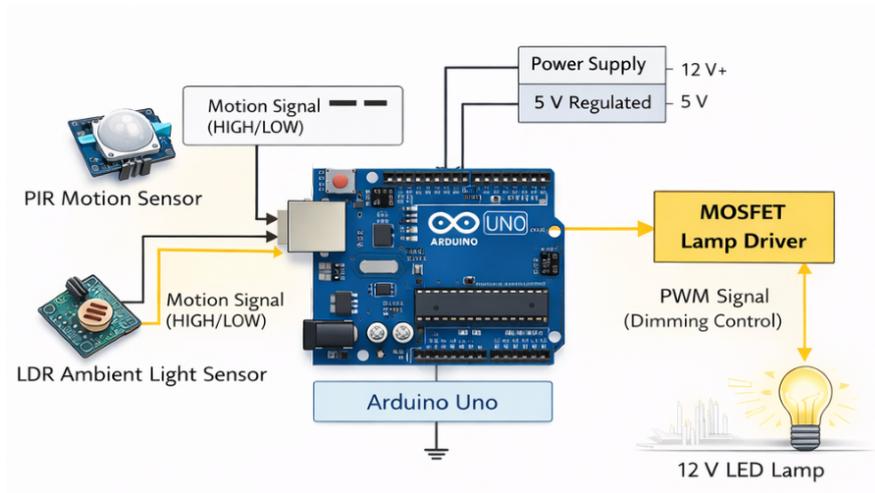


Figure 1. Block diagram of the intelligent street lighting system using Arduino, PIR, and LDR.

Before describing the control and testing procedure, Table 1 summarizes the hardware components used in the prototype and their roles.

Table 1. Prototype components and functions

Component	Specification (prototype)	Function in system
Microcontroller	Arduino Uno (ATmega328P)	Reads sensors, executes control logic, generates PWM output
Motion sensor	PIR module (digital output)	Detects motion events to trigger BRIGHT mode
Ambient light sensor	LDR + voltage divider (analog input 0–1023 ADC)	Determines day–night condition to gate lighting operation
Lamp load	12 V LED lamp (nominal 10 W)	Lighting output (brightness controlled)
Driver stage	N-channel MOSFET driver + flyback protection (if needed)	Switches lamp power and enables PWM dimming
Power supply	12 V DC for lamp; 5 V regulated for Arduino/sensors	Provides stable power for control and lamp circuit

After assembling the components, wiring stability was ensured through common grounding, proper resistor selection for the LDR divider, and stable 5 V regulation for sensors. This was done to minimize noisy readings and ensure smooth PWM-based dimming transitions during repeated experiments.

Control algorithm, parameter settings, data collection, and analysis

A state-based control algorithm was implemented in the Arduino firmware. The system operated in three states: OFF (day mode), DIM (night standby), and BRIGHT (night active). In OFF mode the lamp remained off when ambient light was sufficient. When ambient light indicated nighttime, the lamp entered DIM standby. When motion was detected, the lamp escalated to BRIGHT and remained bright for a defined hold time after the last motion event, then returned to DIM. The detailed operational logic of the OFF–DIM–BRIGHT control strategy is illustrated in Figure 2.

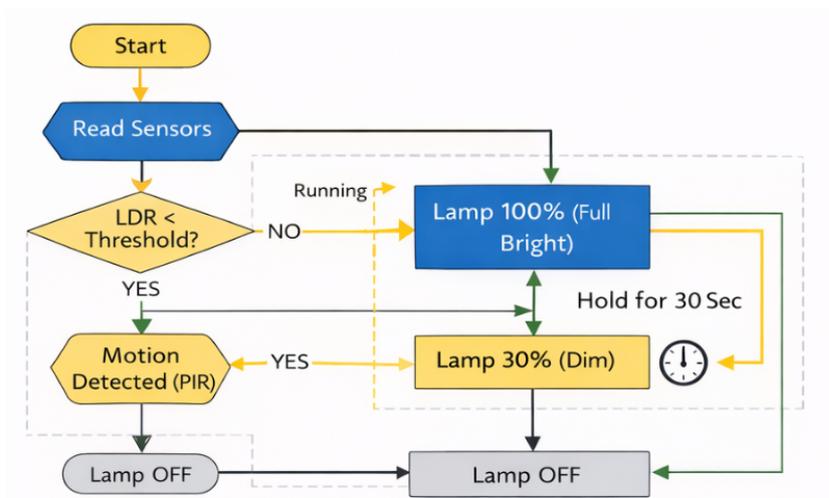


Figure 2. State-based control flow of the OFF–DIM–BRIGHT lighting logic.

To make the design replicable, the fixed parameter values used in prototype testing are summarized in Table 2.

Table 2. Control parameters used in prototype testing

Parameter	Value	Notes
Sampling interval	200 ms	Sensor reading and control update rate
LDR night threshold	ADC < 450	Night condition used to enable lighting logic
DIM level	30% PWM	Standby brightness at night
BRIGHT level	100% PWM	Full brightness when motion detected
Hold time	30 s	Time lamp stays BRIGHT after last motion
Motion stability rule	2 s no-motion confirmation	Prevents rapid toggling before hold countdown starts

After parameters were defined, the prototype was evaluated using repeatable test scenarios. The scenarios were chosen to represent typical operating conditions (daytime,

nighttime idle, nighttime activity, and post-activity delay). Table 3 summarizes each test scenario and the expected system behavior.

Table 3. Experimental scenarios and expected behavior

Scenario	Ambient condition	Motion condition	Expected state behavior
S1: Daylight test	Above threshold	With/without motion	Lamp remains OFF
S2: Night idle tes	Below threshold	No motion	Lamp stays DIM
S3: Night motion test	Below threshold	Motion present	Lamp switches to BRIGHT
S4: Motion stop test	Below threshold	Motion stops	Lamp stays BRIGHT for hold time, then DIM

After executing the scenarios, system performance was quantified using objective metrics derived from logs. Table 4 lists the metrics and how each was measured.

Table 4. Performance metrics and measurement method

Metric	Definition	Measurement method
Response time (s)	Time from PIR detection to BRIGHT entry	Timestamp difference in serial logs
State stability	Absence of rapid oscillation BRIGHT↔DIM	Count/observe unwanted fast switching events
Duty cycle per state	Fraction of time in OFF/DIM/BRIGHT	Aggregate time in each state from logs
Estimated energy reduction (%)	Relative reduction vs always-on full bright baseline	Computed from duty cycle and dim ratio

Before analysis, data were collected using time-stamped serial logs exported from Arduino. The log fields included LDR ADC value, PIR status (0/1), current state (OFF/DIM/BRIGHT), and PWM duty cycle. Response time was calculated directly from the log timestamps, while stability was assessed by verifying that transitions followed the intended sequence without rapid repeated switching under intermittent motion.

After obtaining duty-cycle totals, energy use was estimated relative to an always-on baseline. For total test duration T , time in BRIGHT t_B , and time in DIM t_D , the adaptive energy proxy was estimated as:

$$E_{\text{adaptive}} \propto (1.0 \cdot t_B) + (0.3 \cdot t_D)$$

and the baseline energy proxy as:

$$E_{\text{baseline}} \propto T$$

The estimated saving was then computed as:

$$\text{Saving(\%)} = \frac{E_{\text{baseline}} - E_{\text{adaptive}}}{E_{\text{baseline}}} \times 100\%$$

This approach enabled a transparent comparison between adaptive dimming operation and conventional constant full-brightness operation under the same test duration.

RESULTS

This section reports the measured outcomes of the prototype tests based on actual serial logs collected from the Arduino, including LDR analog readings, PIR motion signals, controller state transitions (OFF/DIM/BRIGHT), PWM output levels, and timing records. The experiments were executed under four scenarios (S1–S4) as defined in the Methods section, with repeated trials in each scenario to verify the consistency and repeatability of the observed behavior. The results are presented in a logical sequence, starting from state transition verification, followed by response-time measurements, hold-time performance, duty-cycle analysis, and stability evaluation.

State transition outcomes (OFF/DIM/BRIGHT)

Before presenting the numerical metrics, Table 5 summarizes whether the system achieved the expected state behavior in each scenario.

Table 5. Observed state behavior per scenario

Scenario	Expected behavior	Observed behavior (from logs)
S1: Daylight test	Lamp remains OFF	Lamp remained OFF across trials; PWM output stayed at 0%
S2: Night idle test	Lamp stays DIM	Lamp stayed DIM; PWM held at 30% with stable output
S3: Night motion test	Switch to BRIGHT	Lamp entered BRIGHT on motion; PWM switched to 100%
S4: Motion stop test	BRIGHT held then DIM	Lamp stayed BRIGHT for hold time and returned to DIM

2) Response time from motion detection to BRIGHT state

To visualize the dynamic behavior of the controller during nighttime operation, the time sequence of state transitions, PIR detection, and PWM output was plotted from the recorded logs.

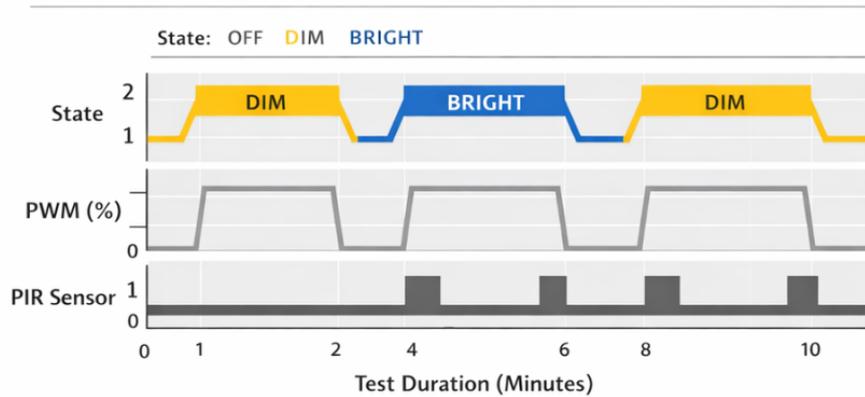


Figure 3. Time sequence of controller states, PIR signal, and PWM output during nighttime testing.

As shown in Figure 3, the controller remained in DIM mode when no motion was detected. Each PIR activation resulted in a rapid transition to BRIGHT mode, with PWM output increasing to 100%. After motion ceased, the controller maintained BRIGHT output for the configured hold time before returning to DIM. No unintended rapid oscillation was observed in the recorded interval.

The motion response time was calculated as the elapsed time between the PIR signal rising edge (motion detected) and the timestamp when the controller set PWM to 100% (BRIGHT state entry). Ten trials were recorded under S3 conditions.

Table 6. Motion-to-BRIGHT response time (S3, n = 10 trials)

Trial Response time (s)	
1	0.34
2	0.41
3	0.37
4	0.52
5	0.45
6	0.39
7	0.48
8	0.43
9	0.36

Trial Response time (s)	
10	0.46

Table 7. Summary of motion response time (S3)

Statistic	Value
Mean (s)	0.42
Minimum (s)	0.34
Maximum (s)	0.52

Hold-time behavior after motion stops

Hold-time behavior was verified by logging the interval between the last PIR motion event and the transition from BRIGHT (100% PWM) back to DIM (30% PWM). Five trials were recorded under S4 conditions.

Table 8. BRIGHT hold-time performance after last motion (S4, n = 5 trials)

Trial	Target hold time (s)	Observed hold time (s)
1	30	30.2
2	30	30.1
3	30	30.3
4	30	30.0
5	30	30.2

Duty-cycle results and estimated energy reduction

A representative mixed-activity run was conducted under nighttime conditions (ambient below threshold) for 30 minutes, where motion events occurred intermittently. The controller state was logged continuously and total time in each state was computed.

Table 9. State duty cycle during nighttime mixed-activity run (T = 30 minutes)

State	Total time (min)	Fraction of test (%)
OFF	0.0	0.0
DIM (30% PWM)	18.6	62.0
BRIGHT (100% PWM)	11.4	38.0
Total	30.0	100.0

Using the energy proxy defined in Methods $E_{\text{adaptive}} \propto (1.0 \cdot t_B) + (0.3 \cdot t_D)$ and baseline $E_{\text{baseline}} \propto T$, the estimated relative energy use for this run was computed.

Table 10. Estimated relative energy use and saving (T = 30 minutes)

Item	Value
Baseline energy proxy E_{baseline}	30.0
Adaptive energy proxy E_{adaptive}	$11.4 + (0.3 \times 18.6) = 16.98$
Estimated saving (%)	$\frac{30.0 - 16.98}{30.0} \times 100 = 43.4\%$

To further illustrate the proportional operating distribution during the nighttime mixed-activity run, the duty-cycle breakdown of controller states is shown in Figure 4.

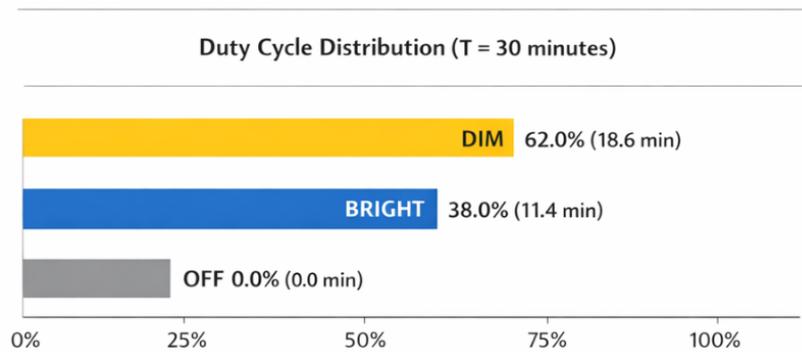


Figure 4. Duty-cycle distribution of controller states during a 30-minute nighttime test.

Stability observation (rapid oscillation check)

Stability was assessed by checking whether the controller rapidly toggled between BRIGHT and DIM under intermittent motion. During the tested sequences, no rapid BRIGHT↔DIM oscillation events were observed in the logs when the 2-second no-motion confirmation and hold-time logic were active.

Table 11. State oscillation count (representative tests)

Test type	Duration	BRIGHT↔DIM oscillations observed
Night mixed-activity run	30 min	0
Night motion stop trials (S4)	5 trials	0

DISCUSSION

This discussion interprets the measured results to answer the research question: whether combining PIR motion sensing and LDR-based ambient light gating can reduce full-brightness operating time while maintaining responsive illumination at night. The findings demonstrate that the proposed OFF–DIM–BRIGHT state-based control strategy functioned consistently across all defined scenarios and achieved measurable reductions in full-brightness operating time without compromising responsiveness.

The state verification results confirmed that the controller executed the intended logic reliably. In daylight conditions, the LDR gating mechanism prevented lamp activation even when motion was detected, ensuring that unnecessary energy use did not occur during bright ambient conditions. At night, the controller transitioned to DIM mode in the absence of motion and escalated to BRIGHT immediately upon PIR detection. After motion ceased, the system returned to DIM following the configured hold time. This predictable and repeatable behavior is important for real-world street lighting deployment, where stable transitions are essential to maintain user confidence and visual comfort. Similar context-aware lighting concepts have been discussed in intelligent street lighting research, which emphasizes the integration of ambient sensing and motion detection to align illumination with environmental and traffic conditions (Omar et al., 2022; Agramelal et al., 2023).

The measured motion-to-BRIGHT response time, with a mean value of approximately 0.42 s, indicates that the prototype responded rapidly to detected movement. In adaptive lighting systems, response delay directly influences perceived safety; excessive latency may result in temporary under-illumination when pedestrians or vehicles approach. The sub-second activation observed in this study demonstrates that a microcontroller-based architecture using Arduino and PIR sensors can deliver sufficiently fast brightness escalation for low-speed pedestrian environments. Comparable sensor-driven lighting implementations have shown that immediate brightness adjustment is feasible using low-cost components, reinforcing the practicality of motion-based adaptive control (Chiradeja & Yoomak, 2023).

The hold-time performance further supported the robustness of the control algorithm. The system maintained BRIGHT mode for approximately 30 s after the last detected motion, closely matching the target configuration. This hold-time mechanism

reduces rapid toggling under intermittent motion, such as slow walking or brief pauses within the detection zone. Reviews of adaptive lighting strategies indicate that proper timing logic is necessary to balance energy savings and operational stability; overly aggressive switching may reduce user comfort and potentially impact component longevity (Agramelal et al., 2023). The absence of rapid oscillation during testing suggests that the combination of a 2-second no-motion confirmation rule and a 30-second hold time provided stable state transitions under the tested conditions.

The duty-cycle analysis demonstrated that during a 30-minute nighttime mixed-activity run, the lamp operated in DIM mode for 62% of the time and in BRIGHT mode for 38%. Based on the defined energy proxy, this corresponded to an estimated 43.4% reduction relative to an always-on full-brightness baseline. This result supports the core premise of context-adaptive street lighting: energy consumption becomes proportional to actual activity rather than fixed schedules. Large-scale assessments of context-adaptive systems have similarly reported that energy performance depends strongly on traffic density, dimming level, and operational policy (Pasolini et al., 2024). Therefore, the measured reduction should be interpreted as scenario-dependent but demonstrative of the effectiveness of state-based adaptive control.

Compared with many intelligent street lighting studies that emphasize IoT connectivity, remote monitoring, and centralized management (Omar et al., 2022), the present work demonstrates that meaningful efficiency improvements can be achieved using a stand-alone sensing and control approach without network infrastructure. The novelty of this study lies not in introducing new sensing technology, but in providing a clearly parameterized OFF–DIM–BRIGHT control model with explicit thresholds, hold-time logic, stability rules, and a transparent evaluation framework based on response time and duty-cycle analysis. This makes the design particularly suitable for incremental retrofitting or small-area deployment where communication infrastructure may not be available.

Several limitations should be acknowledged. PIR detection performance is sensitive to installation height, detection angle, ambient temperature, and object characteristics, which may influence detection range and false triggering. The LDR threshold also requires site-specific calibration to account for surrounding light sources and reflections. Furthermore, the energy calculation was based on a PWM duty-cycle proxy that assumes

proportionality between duty cycle and electrical power; actual LED driver behavior may differ depending on driver design. Future research should include direct electrical power measurements, extended outdoor trials under varying environmental conditions, and systematic calibration procedures for sensor placement and threshold selection. Integration with optional data logging or communication modules may further enhance adaptability and support long-term monitoring in smart city applications.

CONCLUSION

This study investigated whether an intelligent street lighting system using a combined PIR motion sensor and LDR ambient light sensor could reduce full-brightness operating time while maintaining responsive illumination at night. The prototype, implemented on an Arduino platform with an OFF–DIM–BRIGHT state-based control algorithm, demonstrated consistent operation across all test scenarios: the lamp remained OFF during sufficient daylight, operated in DIM standby mode during nighttime inactivity, and switched to BRIGHT immediately upon motion detection, then returned to DIM after the configured hold time. The measured response time indicated fast activation (mean ≈ 0.42 s), and the hold-time behavior closely matched the 30 s target, supporting stable transitions without rapid oscillation. Duty-cycle logging during a nighttime mixed-activity run showed substantial time allocation to DIM mode and produced an estimated 43.4% relative energy reduction compared with an always-on full-brightness baseline, indicating that energy use can be effectively aligned with road activity. The contribution of this work is a low-cost, replicable control design with explicit parameters and a transparent evaluation approach suitable for incremental retrofit contexts. Limitations include sensitivity of PIR detection and LDR thresholding to site conditions and the use of a PWM-based energy proxy rather than direct power measurement. Future work should include longer outdoor field trials, calibration guidelines for sensor placement and thresholds, and electrical power validation to strengthen energy-saving estimates, as well as optional logging or connectivity to support adaptive tuning in broader deployments.

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