



Development of an Automatic Street Lighting System Using Embedded Controllers

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Abstract

Conventional street-lighting installations commonly operate at full output throughout the night, even when daylight is sufficient or road activity is low. This methodology paper develops a low-cost automatic street-lighting architecture centered on an embedded microcontroller, an ambient-light sensor, a motion sensor, and a pulse-width-modulated LED driver. The controller first determines whether the environment is dark enough to require lighting; after dusk, it maintains a reduced illumination level during low activity and raises selected luminaires to full output when pedestrian or vehicle motion is detected. The proposed design emphasizes local autonomous operation, short response time, low component count, and compatibility with later networked monitoring. A design-case evaluation is formulated for ten 20 W LED luminaires operating for a 12 h night period. Using stated traffic and dimming assumptions, the controller reduces calculated nightly energy use from 2.40 kWh for conventional full-output operation to approximately 1.48 kWh, corresponding to an estimated energy saving of 38.5%. The methodology provides a reproducible sequence for sensor calibration, controller logic development, driver integration, safety verification, and performance estimation. The design is intended as a practical foundation for campus roads, residential streets, parking areas, and other low-to-medium traffic applications

Introduction

Street lighting is essential for nighttime mobility, visibility, and perceived safety, but conventional installations often rely on fixed schedules or simple contactors that keep lamps fully energized for the entire night. The transition to LED luminaires and embedded digital control creates an opportunity to match lighting output more closely to environmental and traffic conditions. Shahidehpour et al. [1] described the wider evolution of streetlights toward intelligent communication and control infrastructure, while Todorović and Samardžija [2] demonstrated that sensor-network-based road lighting can reduce unnecessary energy use without abandoning traffic-safety requirements. These studies

motivate a simpler local controller that can deliver much of the operational benefit with fewer components and without requiring a permanent communication network.

An automatic street-lighting controller should perform two decisions reliably. First, it should distinguish day from night so that lamps are not energized when ambient illumination is adequate. Second, during darkness it should adapt lamp output to road use. Ożadowicz and Greła [3] showed that organized lighting-control strategies can materially reduce street-lighting energy consumption, and Marino et al. [4] showed the value of predictive or adaptive control rather than a fixed all-night operating

state. For a low-cost embedded implementation, these ideas can be translated into threshold-based sensing and PWM dimming that can execute on an 8-bit microcontroller.

The objective of this paper is therefore to develop a methodology for an automatic street-lighting system using an embedded controller, an LDR-based ambient-light input, and PIR/IR motion detection. The proposed system is designed to switch off during daylight, operate at a safe dimmed level during low traffic, and increase LED brightness immediately when movement is detected. The contribution is not a claim of completed municipal field deployment; instead, the paper defines the hardware, control algorithm, calibration procedure, and a transparent design-case energy evaluation that can be reproduced and later validated experimentally.

Literature Review

Research before and during 2019 shows a clear progression from timer-based street lighting toward sensor-driven and adaptive illumination. Todorović and Samardžija [2] proposed a wireless sensor network in which distributed nodes detect vehicles and coordinate neighboring lamps, establishing the principle that lighting output can follow actual road usage. Ożadowicz and Grela [3] organized street-light control into functional efficiency strategies and reported that increasingly active control and monitoring can achieve substantial savings compared with uncontrolled operation. Marino et al. [4] introduced predictive control for street lighting, further demonstrating that temporal and demand information can be used to avoid excessive illumination.

Beyond basic switching, optimization and system-level design became important. Carli, Dotoli, and Pellegrino [5] developed a decision-making tool for street-lighting energy-efficiency optimization, illustrating the need to balance lighting performance with energy objectives. Park et al. [6] combined smart LED streetlights with distributed energy storage and IoT management, showing how intelligent luminaires can become part of a broader energy-management infrastructure. Juntunen et al. [7] used movement tracking for dynamic route lighting and demonstrated the practical relevance of presence-based adaptive illumination in an urban environment.

Studies published in 2019 expanded the design criteria from energy savings to safety, user response, and data-driven intelligence. Cho et al. [8] designed connected security lighting for pedestrian safety, reinforcing the importance of responsive illumination when users are present. Mohandas, Dhanaraj, and Gao [9] applied artificial neural networks and fuzzy logic to smart street lighting and reported reductions in unnecessary utilization, although the computational method is more complex than needed for a basic local controller. Beccali et al. [10] evaluated an advanced public-lighting system from both energy-saving and user-satisfaction perspectives, indicating that efficiency improvements should not be achieved at the expense of acceptable lighting quality. The present methodology therefore adopts a deliberately simple embedded approach: reliable sensing, deterministic logic, and PWM dimming, with future provision for communication if a larger smart-city network is required.

Table 1. Selected literature informing the proposed methodology (all references are 2019 or earlier).

Ref.	Approach	Main contribution	Design implication
[2]	WSN road lighting	Vehicle detection and distributed coordination	Use demand sensing to avoid full-night output
[3]	Functional control strategies	Demonstrated strong energy-saving potential from control	Include daylight and dimming states
[4]	Adaptive/predictive control	Lighting varies with expected demand	Use adaptive brightness rather than ON/OFF only
[5]	Energy optimization	Balances lighting and energy objectives	Evaluate savings with explicit assumptions
[7]	Movement tracking	Dynamic illumination follows users	Use presence-triggered full output
[8]	Connected safety lighting	Responsive lighting supports pedestrian safety	Prioritize fast transition when motion is detected
[9]	ANN/fuzzy control	Demand-based smart operation	Keep local logic simple for low-cost MCU
[10]	Advanced public lighting	Energy savings considered with user satisfaction	Maintain a minimum background illumination

Methodology

Step 1 - System Requirements and Operating States

The system is defined around four operating states: DAY, NIGHT-IDLE, NIGHT-ACTIVE, and FAULT-SAFE. In DAY state the LED output is zero because measured ambient illumination exceeds the darkness threshold. In NIGHT-IDLE the controller supplies a reduced duty cycle, selected here as 30%, to provide background visibility with low power demand. NIGHT-ACTIVE is entered when motion is detected; the relevant lamp is driven at 100% duty cycle for a hold interval before returning to the dimmed state. FAULT-SAFE is used when a sensor reading is implausible or the controller is reset; the lamp is commanded to a conservative predefined output during darkness so that a sensor failure does not leave the road completely unlit. This deterministic state-machine approach is consistent with the practical control philosophy in earlier intelligent street-lighting systems [1]-[4].

Step 2 - Hardware Architecture and Component Selection

The embedded controller may be implemented with an ATmega328P-class microcontroller or a comparable low-cost MCU that provides an analog-to-digital converter, digital inputs, timers, and PWM outputs. An LDR forms a voltage divider connected to an ADC channel to estimate ambient illumination. A PIR sensor, or an IR/ultrasonic alternative where vehicle detection is more important, provides a digital motion input. The MCU drives the LED power stage through a logic-level MOSFET or an isolated PWM-compatible LED driver. A regulated low-voltage supply powers the control electronics, while the luminaire is supplied from an appropriately rated DC source or certified LED driver. Protection should include input fusing, reverse-polarity protection for DC prototypes, transient suppression, and adequate creepage/clearance whenever mains voltage is present.

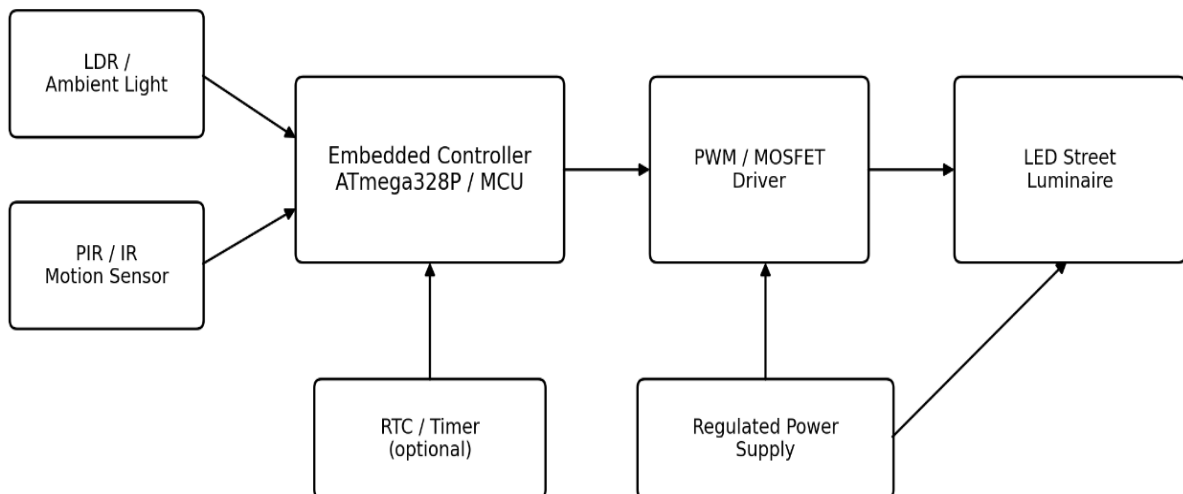


Figure 1. Proposed embedded-controller architecture for automatic street lighting.

Step 3 - Sensor Calibration

LDR calibration is performed by recording ADC values under representative daylight, twilight, and nighttime conditions. A darkness threshold L_{th} is selected between twilight and night values, and hysteresis is added to prevent rapid switching around the threshold. For example, the controller may enter night mode when the filtered ADC value corresponds to less than the chosen illuminance threshold for 30 s and return to day mode only after the value remains above a higher threshold for 60 s. Motion-sensor placement is then adjusted so that the detection zone covers the required road or pedestrian

approach while minimizing false triggering from vegetation or adjacent areas. A short digital debounce/filter interval is applied to the motion signal.

Step 4 - Embedded Control Algorithm

At each sampling interval the controller reads the ambient-light channel, applies a moving average, and determines whether night conditions exist. If daylight is detected, PWM duty cycle D is set to 0%. Under darkness, D is set to 30% when no motion is present and to 100% when motion is detected. The 100% state is held for a configurable interval T_{hold} , such as 20-60 s, after the latest valid motion event. In compact form,

the control law is $D=0$ for daylight; $D=100\%$ for darkness with motion; and $D=D_{dim}$ for darkness without motion, where D_{dim} is the selected background duty cycle. A watchdog timer resets the controller if program execution stalls. This logic is intentionally less computationally intensive than ANN or fuzzy methods [9], making it suitable for low-cost embedded controllers while retaining the adaptive behavior emphasized in [4], [7], and [8].

Step 5 - Driver Integration and Prototype Construction

The PWM output is first verified with a low-power LED load. The MOSFET or LED driver is then connected to the target luminaire, ensuring that the switching frequency is high enough to avoid visible flicker and is compatible with the driver specification. The LDR should be shielded from direct light emitted by the controlled luminaire; otherwise, the system can oscillate because turning the lamp on changes the measured ambient-light level. The motion sensor is mounted facing the approach path rather than the lamp itself. Wiring between sensor nodes and the controller is kept short for a local prototype, and decoupling capacitors are placed near the MCU supply pins.

Step 6 - Functional Verification

Verification is carried out using a test matrix that covers bright daylight, gradual dusk, darkness without motion, darkness with motion, repeated motion, sensor disconnection, and MCU restart. The acceptance criteria are: no lamp activation in normal daylight; stable night-mode entry without chatter; immediate transition from dim to full output after a valid motion event; automatic return to dim output after the hold interval; and a safe output after reset. Where the controller is expanded to multiple lamps, the motion event can also activate the current lamp and one adjacent lamp ahead of the detected user, following the distributed-lighting principle

reported in [2] and the route-lighting concept in [7].

Step 7 - Energy Evaluation Method

Energy consumption is evaluated from the rated lamp power, the number of lamps, and the equivalent operating hours at each duty level. For N lamps of rated power P , nightly energy is $E = N \times P \times \sum(D_k \times t_k)$, where D_k is the fractional output level during interval k and t_k is the duration in hours. Percentage saving is calculated as $\text{Saving} = (E_{\text{conventional}} - E_{\text{automatic}}) / E_{\text{conventional}} \times 100$. For the design case below, ten 20 W LED luminaires are compared over a 12 h night. Conventional operation is 100% output for all 12 h. Automatic operation assumes 4 h of high activity at full output, 7 h in which motion produces an average 44% equivalent output (20% of the time at full output and 80% at 30% dim output), and 1 h at the 30% background level. These assumptions are stated explicitly so the result can be recalculated for a different site rather than being mistaken for field-measured data.

Results

Table 2 presents the design-case calculation obtained from the methodology. The conventional arrangement consumes 2.40 kWh per night for ten 20 W luminaires. The proposed automatic strategy consumes approximately 1.48 kWh per night under the specified activity profile, producing an estimated reduction of 0.92 kWh per night or 38.5%. For a 365-day operating year, the corresponding design-case reduction is about 337 kWh for the ten-lamp prototype scale. The magnitude is consistent with the general range of savings reported for controlled street-lighting strategies in earlier studies [3], while remaining conservative enough to preserve a 30% background illumination state as recommended by the safety and user-oriented literature [8], [10].

Table 2. Design-case performance comparison for ten 20 W LED luminaires.

Performance item	Conventional system	Proposed automatic system	Interpretation
Night duration	12 h	12 h	Same lighting window
Rated connected load	200 W	200 W	No reduction in installed capacity
Control strategy	100% all night	0/30/100% sensor-based PWM	Output follows daylight and motion
Calculated energy/night	2.40 kWh	1.48 kWh	0.92 kWh/night reduction
Estimated energy saving	0%	38.5%	Design-case value, not field measurement
Annualized saving	-	~337 kWh/year	If the same profile repeats for 365 nights

The proposed controller also offers qualitative benefits that are not captured by the energy calculation. The logic is locally autonomous, so lighting operation does not depend on continuous Internet connectivity. The sensor and PWM interface can be implemented with inexpensive microcontrollers, and the state machine is simple enough to audit and troubleshoot. At the same time, the architecture can later be extended with LoRa, Zigbee, PLC, or cellular communication for centralized fault reporting and scheduling, aligning with the networked infrastructure direction discussed by Shahidehpour et al. [1] and Park et al. [6]. The main limitations are the sensitivity of LDR thresholds to placement and weather, false triggering from poorly positioned motion sensors, and the need to validate dimming levels against applicable road-lighting standards before real deployment.

Conclusion and Discussion

This paper developed a step-by-step methodology for an automatic street-lighting system using embedded controllers. The design combines ambient-light detection, motion sensing, deterministic MCU logic, and PWM-based LED control. Its principal advantage is that it does not require complex artificial intelligence or permanent communication infrastructure to achieve adaptive operation. Daylight lockout prevents unnecessary daytime lighting, while a dim background level reduces energy consumption during low activity and full output is restored when road users are detected. The resulting architecture therefore reflects the main findings of pre-2020 literature: intelligent control improves energy efficiency [2]-[5], movement-responsive lighting can support practical urban use [7], and lighting quality and safety should remain central design constraints [8], [10]. Under the stated ten-lamp design case, estimated nightly energy use decreases from 2.40 kWh to 1.48 kWh, equivalent to approximately 38.5% savings. This value is a calculated methodology result and should be replaced by measured data when a physical installation is tested. A future experimental study should record illuminance at defined road points, sensor detection probability, false-trigger rate, PWM response time, actual watt-hour consumption, temperature of the driver components, and user-perceived lighting adequacy over several weeks. Networked fault diagnostics could then be added using the smart-infrastructure concepts of [1] and [6]. With those validation steps, the proposed embedded platform can evolve from a low-cost prototype

into a scalable automatic lighting node for campuses, residential roads, parking areas, and smart-city applications.

Practical Implementation Considerations

For real deployment, the most important design issue is not the microcontroller itself but the quality and placement of the sensing and power interfaces. The LDR should be oriented toward ambient sky illumination and mechanically shielded from the controlled lamp, vehicle headlamps, and nearby advertising displays. The darkness threshold should be derived from measurements taken over several evenings instead of a single laboratory reading. Likewise, the PIR or IR detector must be mounted at a height and angle that matches the intended target. A pedestrian path may require a different detection geometry from a vehicle lane. In a multi-lamp installation, the sensing range and hold time should be tuned so that a moving user does not enter a dark region between two luminaires. This is compatible with the coordinated-node concept demonstrated for road lighting in [2] and the movement-tracking approach of [7].

Electrical safety also determines whether the prototype can be translated into an outdoor product. The control board should remain on an isolated low-voltage rail wherever possible, while the LED power stage should use a certified constant-current driver or a suitably protected DC supply. Outdoor enclosures require moisture protection, cable glands, surge protection, and thermal management because street-light poles are exposed to rain, dust, lightning-related transients, and high internal temperatures. A watchdog timer, brownout reset, and a defined power-up state reduce the risk of undefined lamp behavior after a supply disturbance. If remote communication is added later, it should supplement rather than replace the local autonomous logic so that a network outage does not prevent basic lighting operation. This layered philosophy follows the smart-infrastructure direction discussed in [1] and [6] while preserving the low-cost objective of the present design.

The selected 30% background dimming level is a design parameter rather than a universal requirement. Actual values must be chosen after checking road classification, luminaire photometry, spacing, mounting height, and the applicable lighting standard. The design should therefore be validated with an illuminance meter at representative points along the road, including minimum and average illuminance and

uniformity. Energy saving alone is not sufficient: a lower duty cycle is acceptable only if the resulting visual conditions remain safe and usable. The safety-oriented lighting work of Cho et al. [8] and the energy-and-user evaluation of Beccali et al. [10] both support this combined criterion. A practical field trial should consequently compare electrical energy, detection performance, and lighting quality at the same time.

Limitations and Future Validation

The present numerical result is intentionally a transparent design-case estimate, not a substitute for measured field data. Traffic activity can vary by hour, season, weather, and location, so the 38.5% saving will change when the motion-occupied fraction changes. LDR readings can also drift with component tolerance and aging, while PIR sensors may respond differently to ambient temperature and target speed. Future work should log time-stamped sensor states, PWM duty cycle, lamp power, ambient illuminance, and motion events over at least several weeks. These records can be used to calculate actual energy saving, false-trigger rate, missed-detection rate, mean response time, and the percentage of time that each operating state is active. If the simple threshold logic is later shown to be insufficient, more advanced optimization or data-driven control such as the approaches in [5] and [9] can be incorporated without changing the basic sensing and driver architecture.

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