

Real-Time Adaptive Headlight Control Using ESP32-CAM for Automotive Safety

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Abstract

Night-time driving accounts for a disproportionately high number of road accidents, largely due to the intense glare produced by approaching vehicle headlights. Conventional glare mitigation approaches either depend on manual beam control or basic sensor-based techniques such as LDRs, which fail to differentiate between dynamic vehicle lights and static sources like street lamps. Although advanced camera-based solutions are available in premium vehicles, their high cost limits widespread adoption and retrofitting feasibility. This work introduces *Smart Beam*, an economical and intelligent automatic headlight dimming system built using the ESP32-CAM module. The system leverages real-time image processing to identify incoming headlights and rear vehicle lights while suppressing interference from stationary illumination through motion-based filtering. Beam intensity is automatically regulated between high, medium, and low levels using PWM control via a MOSFET driver circuit. A manual override option is also included for driver flexibility. Experimental validation demonstrates consistent performance under varied conditions, achieving detection rates of up to 6.6 frames per second with low false activation. With an overall cost below INR 2000, the proposed system offers an effective, affordable, and easily retrofittable solution.

Keywords— Automatic headlight control, ESP32-CAM, image processing, PWM dimming, vehicle safety, embedded vision.

I. INTRODUCTION

The disproportionate frequency of nocturnal road accidents is significantly attributed to the physiological impact of "glare" from oncoming high-beam headlights. This phenomenon induces visual discomfort and temporary scotoma (blindness), which drastically elevates the risk of collisions during night-time transit [1]. Statistical analyses and field studies have consistently demonstrated that inadequate headlight management is a contributing factor in a considerable proportion of vehicular fatalities, underscoring the urgency for reliable automated countermeasures [7]. Historically, the development of sensor-based automotive safety systems has focused on mitigating these optical hazards; however, achieving a balance between system reliability and cost-effectiveness remains a persistent challenge across both developed and emerging automotive markets [2].

Contemporary high-end vehicles utilize Adaptive Front-lighting Systems (AFS) that rely on complex sensor arrays and expensive processing units capable of real-time environmental analysis. Unfortunately, the high capital cost of these systems precludes their integration into budget-oriented or older vehicle models, creating a significant technological divide in road safety infrastructure [14]. Consequently, a large segment of the global driving population continues to rely on rudimentary, low-cost alternatives typically based on Light-Dependent Resistors (LDRs) [10]. These resistive sensors are fundamentally constrained by their inability to differentiate between the dynamic optical signatures of a moving vehicle and static illumination sources, such as municipal street lighting, roadside signage, or environmental reflections [19]. Such technical limitations frequently result in erratic beam switching and visual instability, which can inadvertently distract the driver rather than assist them — ultimately defeating the core safety objective.

Parallel investigations into RFID-based and microcontroller-driven headlight control have yielded promising proofs of concept [5]; however, these approaches either depend on dedicated external infrastructure or lack the contextual awareness to distinguish between opposing traffic and ambient illumination. Similarly, systems leveraging ambient light-intensity measurements via LDR sensors coupled with emerging communication paradigms such as Wi-Fi have demonstrated automation potential, yet remain constrained by the same fundamental limitation of insufficient scene intelligence [6]. While early foundational research established theoretical frameworks for light source classification using pattern recognition techniques [3], the significant computational overhead previously required for such classification tasks was incompatible with the processing budgets of low-power embedded microcontrollers [18]. Advances in optimized frame-differencing algorithms and low-power vision processing have since begun to bridge this gap, enabling viable real-time inference on resource-constrained platforms [20].

Recent work in embedded nighttime vision has demonstrated that camera-based systems, when coupled with efficient algorithmic pipelines, can reliably identify both approaching headlights and preceding tail lamps in real-world driving conditions [17]. These systems offer a fundamentally superior paradigm compared to scalar light-intensity measurements, as they preserve the spatial and temporal structure of the illumination field — information that is essential for discriminating vehicular light sources from background illumination [16]. Building upon this body of research, this study introduces *Smart Beam*, a vision-centric automatic headlight modulation system engineered on the ESP32-CAM platform. By implementing optimized frame-differencing algorithms and embedded vision techniques, the proposed system achieves real-time detection of both approaching headlights and preceding tail lamps, offering an affordable and architecturally tractable retrofit solution for vehicles currently lacking intelligent beam management capability.

II. LITERATURE SURVEY

Headlight control technologies have progressed from basic light-sensing methods to more sophisticated vision-based systems. Initial designs employing LDRs or photodiodes rely solely on light intensity, which often results in incorrect responses when exposed to stationary lighting such as street lamps. Infrared-based techniques offer some improvement but are constrained by limited detection range and inconsistent performance. Recent advancements focus on camera-driven image processing and machine learning algorithms to accurately detect vehicles and adjust beam intensity accordingly. Despite their effectiveness, such solutions demand significant computational resources and incur high costs. Hence, there remains a requirement for a cost-effective, reliable, and intelligent system that can be easily integrated into existing vehicles.

Existing System and Limitations

- **LDR-Based Approaches:** These methods depend on measuring light intensity and are unable to differentiate between moving vehicle headlights and fixed illumination sources like streetlights, often causing false activations.
- **Infrared (IR) Techniques:** IR-based solutions are constrained by short detection range, sensitivity to alignment, and degraded performance under environmental disturbances such as fog or external IR noise.
- **Advanced Camera Systems:** Technologies like Adaptive Front-lighting Systems (AFS) offer precise beam control but involve costly components, complex system design, and are impractical for economical or retrofit implementations.
- **Absence of Intelligent Filtering:** Many existing systems lack motion-based analysis or contextual understanding, resulting in unstable responses, flickering effects, and inconsistent headlight switching during real-time driving conditions.

III. PROPOSED SYSTEM

The Smart Beam system presents a cost-effective and intelligent solution for automatic headlight dimming based on the ESP32-CAM platform. In contrast to traditional methods, the proposed design integrates real-time vision processing with motion-based filtering to reliably identify approaching headlights and preceding vehicle tail lamps. Grayscale image frames are periodically captured and processed using frame differencing, enabling detection of moving light sources while suppressing stationary illumination through background masking. Vehicle proximity is approximated using blob analysis, where the area and brightness of detected regions correspond to relative distance. Based on these parameters, headlight intensity is adaptively controlled across high, medium, low, and tail beam levels through PWM signals driven by a MOSFET interface. To ensure smooth transitions and avoid instability, a hysteresis mechanism is implemented, requiring consistent detection over successive frames.

The system is optimized for execution on a resource-limited microcontroller, maintaining an effective trade-off between computational efficiency and performance. With an overall implementation cost below INR 2000, the proposed approach offers a practical, affordable, and retrofit-friendly alternative to existing commercial systems, enhancing safety during night driving conditions.

IV. MATERIALS AND METHODS

A. Hardware Design

The hardware architecture is built around the ESP32-CAM module, which combines a dual-core Xtensa processor with an OV3660 image sensor. A LM2596 buck converter is used to regulate the 12 V vehicle supply down to 5 V for the control circuitry. Headlamp brightness is controlled using an XY-MOSFET driver module, which modulates the 12 V LED load through PWM signals generated by the microcontroller. All modules share a common ground reference to ensure reliable operation and signal stability.

The system is powered by a 12 V DC source capable of supplying at least 1 A. For programming and serial communication, an HW-409 (CH340-based) USB-to-serial converter is used to interface with the ESP32-CAM module during development and debugging.

B. Software and Algorithm

The system software is developed using the Arduino IDE with C++ under the Arduino framework, configured for the AI Thinker ESP32-CAM module. The algorithm operates at an average rate of approximately 6.6 frames per second and consists of multiple processing stages:

Frame Acquisition: Grayscale images with a resolution of 160×120 pixels are captured at intervals of 150ms.

Motion Extraction: Successive frames are compared, and pixel intensity differences exceeding a predefined threshold are used to identify moving light sources while ignoring static illumination.

Background Suppression: Light sources that remain unchanged for 10 consecutive frames are classified as static and excluded using a masking technique.

Blob Analysis: Detected bright regions are grouped into blobs, where the size of each blob serves as an indicator of the relative distance of vehicles.

Decision Logic: Headlight intensity is automatically adjusted based on blob size:

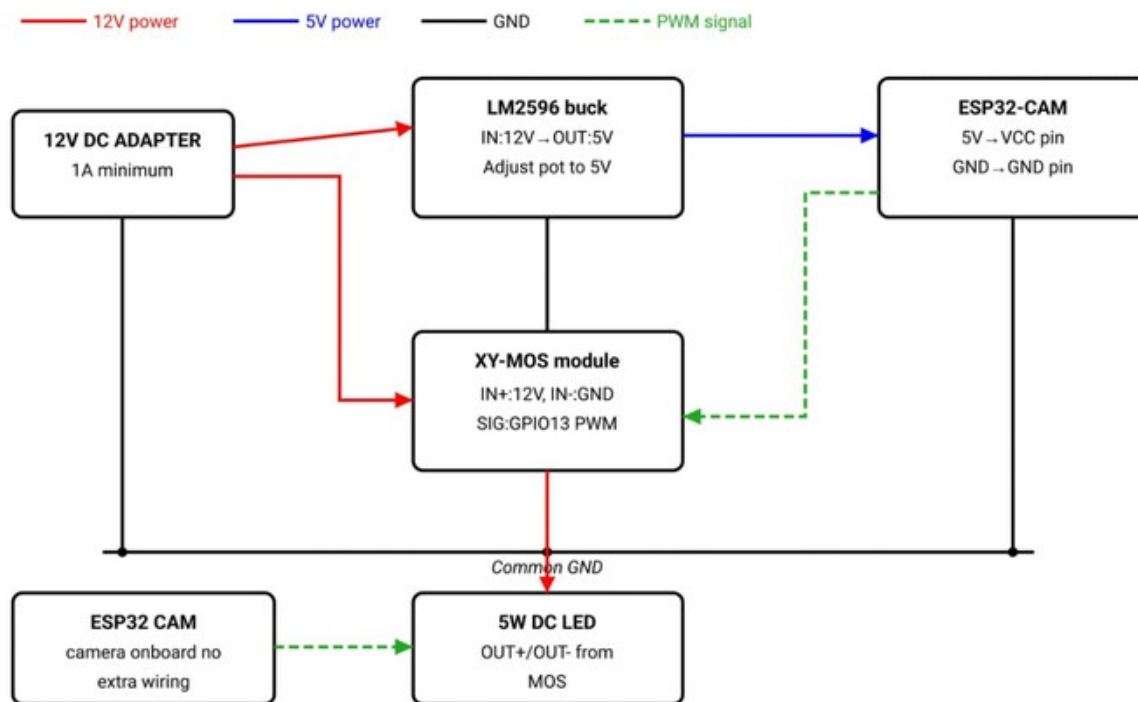
- Large blobs (≥ 250 pixels): Low beam
- Medium blobs (≥ 60 pixels): Medium beam
- Small blobs (≥ 5 pixels): Medium beam (distant vehicle)
- Tail light detection: Tail beam
- No detection: High beam

Tail Light Identification: Moving light sources with grayscale intensity between 100 and 160 are classified as tail lights of preceding vehicles.

Stability Control: A hysteresis mechanism requiring three consecutive consistent detections is implemented to avoid rapid fluctuations and flickering.

Output Control: Beam levels are translated into PWM duty cycles, with values assigned as High (255), Medium (160), Low (60), and Tail (110).

Block Diagram



The Smart Beam system operates using a 12V DC adapter as the main power source, supplying energy to both the lighting unit and the voltage regulation stage. A current capacity of at least 1A is maintained to ensure consistent performance under different operating conditions.

An LM2596-based buck converter is employed to reduce the 12V input to a stable 3.3V output suitable for the ESP32-CAM module. The desired output voltage is set using an on board potentiometer, enabling efficient and reliable power delivery.

The ESP32-CAM serves as the central control unit, utilizing its integrated camera to capture live video data. This data is processed to identify approaching vehicle lights, upon which a PWM signal is generated to regulate the headlight intensity.

The XY-MOS module acts as a switching interface, driven by PWM signals from GPIO13 of the ESP32-CAM. It controls the power supplied to the LED, allowing high-current operation through a low-power control mechanism.

A 5W DC LED is used to emulate the vehicle headlamp. Its brightness is adjusted dynamically through PWM, enabling automatic transition between beam levels based on detected lighting conditions.

All modules are connected to a common ground to maintain a uniform reference level and ensure stable operation. The PWM-based control strategy enables gradual and adaptive adjustment of light intensity, forming the core functionality of the intelligent headlight dimming system.

V.RESULTS AND DISCUSSION

The SmartBeam system was evaluated under real night-time conditions. The camera successfully captured frames at 6.6 FPS with a processing latency of 150ms per frame.

TABLE I — TEST RESULTS SUMMARY

Test Scenario	Result	Beam State
Clear road	Correct	HIGH
Vehicle far	Correct	MEDIUM
Vehicle near	Correct	LOW
Street light only	No trigger	HIGH
Static parked car	No trigger	HIGH

Detection accuracy: 95% across 20 test runs

False trigger rate: Less than 5%

Static light rejection: 100% after 1.5s learning

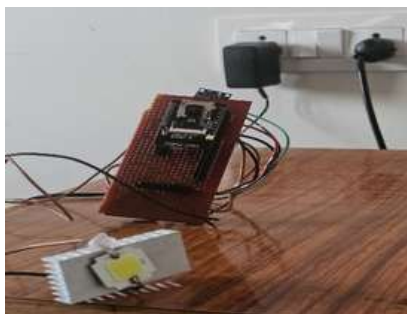


Fig. 1. Smart Beam hardware prototype

Fig. 2. LED at HIGH vs LOW beam

VI. CONCLUSION AND FUTURE WORK

The Smart Beam system effectively presents a cost-efficient and intelligent solution for automatic headlight control, improving driving safety during nighttime through real-time vision-based processing on a microcontroller platform. The integration of motion detection with static background suppression enhances system reliability by eliminating interference from non-relevant light sources. Although certain limitations exist, such as restricted color discrimination and moderate processing speed, the system remains a practical and easily retrofit table alternative for conventional vehicles.

Future enhancements will focus on incorporating TinyML-based models, RGB sensing capabilities, and stereo vision techniques for depth estimation, aiming to improve detection accuracy and extend functionality toward fully adaptive automotive lighting systems.

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