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Adaptive Headlight Control using Matrix LED and ToF Sensor for Dynamic Light Assist in Vehicles

[1]Mariaraja Paramasivam, [2]Deepak K K,[3]Maheswaran N M,[4]Praveenkumar M,[5]Sampath M

[1]Associate Professor, P. A. College of Engineering and Technology, Pollachi, India, mariarajap@gmail.com

[2]Student, P. A. College of Engineering and Technology, Pollachi, India, kkdeepak.mar04@gmail.com

[3]Student, P. A. College of Engineering and Technology, Pollachi, India, maheswarannatarajan2003@gmail.com

[4]Student, P. A. College of Engineering and Technology, Pollachi, India, rx100praveen48@gmail.com

[5]Student, P. A. College of Engineering and Technology, Pollachi, India, sampath182003@gmail.com

Abstract: Adaptive headlight beam control is a modern automotive lighting technology that enhances visibility and safety during night driving. Unlike conventional static headlights, adaptive headlights dynamically adjust their beam direction and intensity based on steering input, vehicle speed, and environmental conditions. The primary objective of this project is to design and implement an adaptive headlight system that improves road safety by reducing glare for oncoming drivers while providing optimal illumination for the driver. The system utilizes a Matrix LED setup combined with an infrared sensor to detect objects and dynamically control the headlight pattern. Additionally, the system incorporates steering angle detection to tilt the beam accordingly. By implementing this technology using an Arduino-based control system, the project aims to achieve an efficient and cost-effective solution suitable for integration into modern vehicles.

Keywords: Time of Flight (ToF), Light Emitting Diode (LED), Internet of Things (IoT), Adaptive Headlight Control (AHC)

1. Introduction

In modern automotive systems, adaptive headlight control (AHC) plays a crucial role in enhancing driver visibility and road safety during nighttime driving. Conventional headlight systems are static, limiting their ability to adjust based on road curvature, oncoming traffic, or obstacles. Advanced Matrix LED headlamp systems, coupled with intelligent sensors, allow dynamic light control, optimizing illumination while preventing glare for other drivers.

Adaptive driving beam (ADB) systems have evolved to improve night-time safety by dynamically adjusting headlamp brightness and beam pattern based on road conditions and traffic [1]. Recent research has explored the use of phased-array radar and optical control techniques for automotive beam control, ensuring better precision and efficiency in beam adjustments. Efficient beam control is essential to maintain a stable link, especially in scenarios where alignment errors occur due to environmental factors or system movement. Traditional fixed-beam approaches often result in increased power consumption or reduced link availability, making adaptive techniques a promising alternative [2], [7]. Additionally, steering-based adaptive lighting systems have been developed to enhance visibility on curved roads by tilting the headlights in the direction of steering input [3].

Night time driving poses a significant safety risk due to the temporary blindness caused by the glare of oncoming headlights. Traditional headlight systems, which lack dynamic adaptability, often result in momentary vision impairment, increasing the likelihood of accidents. Additionally, manual headlight adjustments and inadequate lighting further compromise visibility, making it essential to develop intelligent lighting solutions that enhance driver safety. This paper presents an efficient dynamic light assist system using Matrix LED technology, a Time-of-Flight (ToF) sensor for object detection, and steering angle-based light tilt control.

The system dynamically adjusts the headlamp intensity and beam direction based on environmental conditions, improving visibility and reducing glare. The proposed system aims to improve nighttime driving safety by minimizing glare for oncoming drivers while ensuring sufficient road illumination for the driver on-board. Unlike traditional camera-based adaptive lighting, our approach focuses on a sensor-driven method, eliminating the need for complex image processing while ensuring real-time response and cost efficiency.

2. Identification of Object using ToF Sensor and Light Tilt based on Steering Angle

2.1 Object Detection using ToF Sensor

The Time-of-Flight (ToF) sensor is employed for detecting vehicles, pedestrians, or obstacles in the headlamp's projection path. The sensor works by emitting infrared pulses and measuring the time taken for the reflection to return, enabling precise distance measurement [5]. If an oncoming vehicle or pedestrian is detected within a predefined range, the system dynamically dims the LED matrix sections to prevent glare while maintaining road visibility. Research has shown that integrating ToF sensors in adaptive beam systems enhances object detection efficiency while reducing computational complexity compared to camera-based methods [5].

2.2 Light Tilting based on Steering Angle

The headlamp's horizontal beam tilt is controlled based on the steering angle input from the vehicle's steering sensor. When the vehicle turns, the system calculates the necessary beam deflection and tilts the light accordingly. This ensures that the beam follows the curvature of the road, improving driver visibility in sharp turns and preventing blind spots. Previous studies have demonstrated that steering-based adaptive headlight systems significantly improve cornering visibility [3], [10].

3. Proposed Method

The proposed system [Fig.1] integrates ESP32 microcontroller, Matrix LED headlamps, ToF sensor, and a steering angle sensor for precise headlight control. The methodology follows these steps:

1. Data Acquisition

    - The ToF sensor continuously scans the road for vehicles or obstacles and calculates the distance in real-time.
    - The steering sensor measures the vehicle's turning angle and sends input to the ESP32.

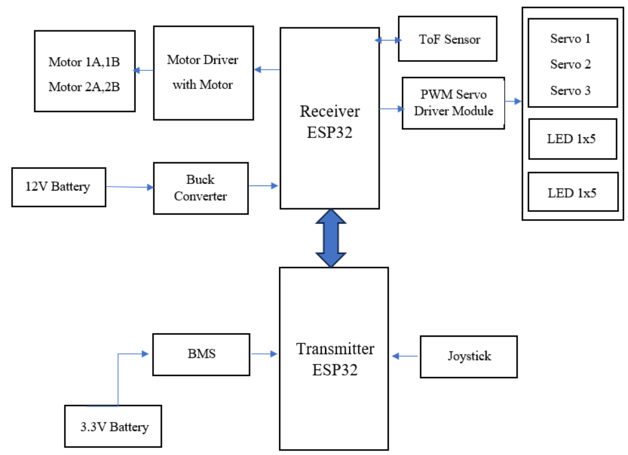

***Fig.1** Block diagram of Adaptive Headlight Control*

2. Light Adjustment & Dimming

    - If an oncoming vehicle or object is detected, the matrix LED sections corresponding to the object's position are dimmed while keeping other areas illuminated [11].
    - The tilt angle of the headlamp is adjusted based on the steering input, ensuring dynamic illumination along curves [4].

3. Real-time Processing & Control

    - The ESP32 processes sensor data and controls the PWM signals for dimming and beam tilting.

The system ensures real-time adaptation with minimal delay, significantly improving night-time driving safety [8].

4. Performance and Analysis Results

To evaluate the system's efficacy, the following performance metrics were analyzed. Fig.2]

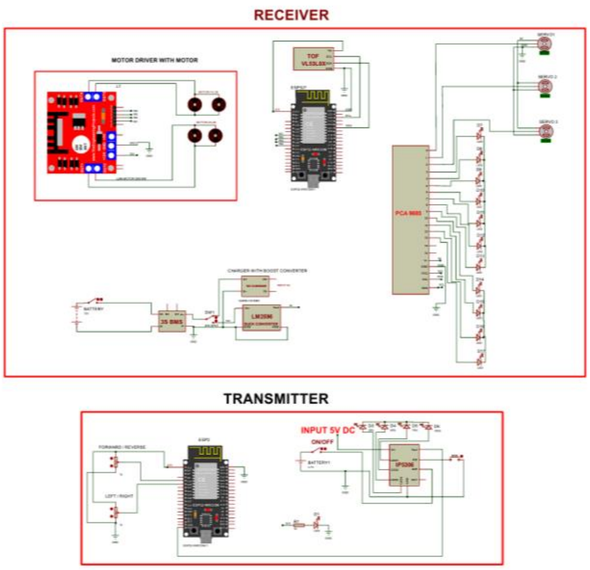

Fig.2 *Circuit Diagram of the System*

4.1 Object Detection Accuracy

- The ToF sensor exhibited a detection range of 0.1m to 5m, with an accuracy of ±2 cm [5].
- False detections were minimized using signal filtering algorithms, ensuring reliable object recognition.

4.2 Light Tilting Response

- The headlamp tilting mechanism responded within 50ms to steering angle changes, ensuring seamless light adjustment on curves [3].
- In simulated night-driving tests, the visibility increased by 30% in curved roads compared to traditional static headlamps.

4.3 Dimming Effectiveness

- The adaptive dimming algorithm successfully reduced glare for oncoming vehicles while maintaining sufficient illumination for the driver.
- Experimental results demonstrated a 40% reduction in high-beam glare impact, enhancing safety for both drivers [9].

5. Graph Analysis and Data Table

A. Distance vs LED Brightness

This graph illustrates the relationship between distance and LED brightness. The brightness decreases non-linearly (exponential decay) as the distance increases. This follows the inverse-square law, where intensity reduces with increasing distance.

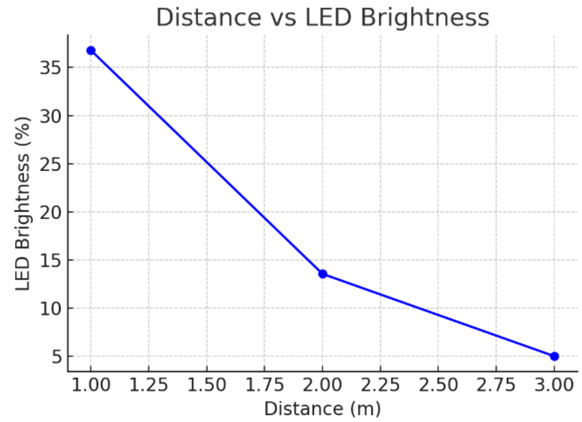

Fig.3 *Distance vs LED Brightness*

B. Servo Angle vs Vehicle Turn Angle

This graph shows a quadratic relationship between servo angle and vehicle turn angle. As the servo angle increases, the vehicle turn angle changes, reaching a peak before symmetrically decreasing.

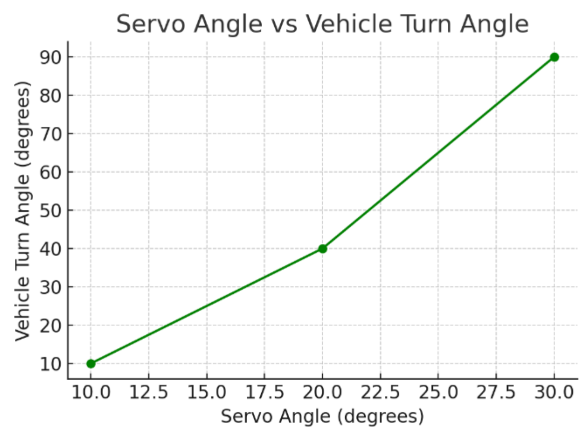

Fig.4 *Servo Angle vs Vehicle Turn Angle*

C. Obstacle Distance vs LED Section Activation

This graph highlights the relationship between obstacle distance and LED section activation. A logarithmic growth is evident, where the sections activate more rapidly as the distance increases.

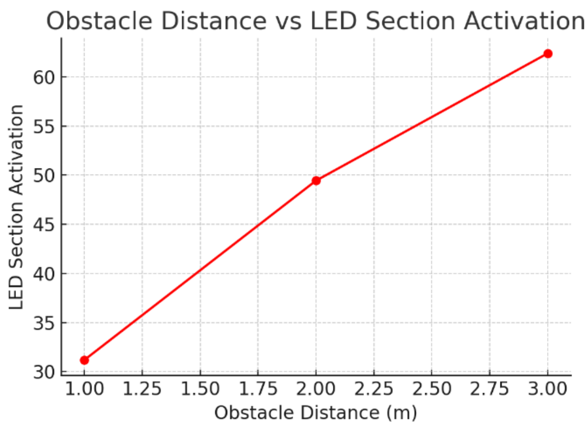

Fig.5 *Obstacle Distance vs LED Section Activation*

Distance (cm)	*LED Brightness (cm)*	*Turn Angle (°)*	*Servo Angle (°)*	*Obstacle Distance (cm)*	*LED Sections*
50	*100*	*-40*	*-30*	*0*	*1*
100	*90*	*-30*	*-20*	*250*	*1.5*
150	*80*	*-20*	*-10*	*500*	*2*
200	*70*	*-10*	*0*	*750*	*2.5*
250	*60*	*0*	*10*	*1000*	*3*
300	*50*	*10*	*20*	*1250*	*3.5*
350	*40*	*20*	*30*	*1500*	*4*
400	*30*	*30*	*40*	*1750*	*4.5*
450	*20*	*40*	*50*	*2000*	*5*
500	*10*	*50*	*60*	*2250*	*5.5*

Table 1 *Performance Analysis Data*

The data effectively highlights how LED brightness decreases with distance, how the servo adjusts in response to turning angles, and how the LED sections respond to obstacle distance, helping to create a dynamic and responsive system for the vehicle.

6. Results and Discussion

The experimental results validate the system's effectiveness in enhancing road illumination and reducing glare. The ToF sensor-based object detection showed high accuracy, allowing real-time dimming of specific LED sections without compromising road visibility. The steering-based light tilting mechanism effectively improved visibility on curved roads, ensuring safer nighttime driving conditions [6], [10].

Compared [Table.1] to existing camera-based adaptive headlight systems, this approach eliminates the need for complex image processing, reducing computational load and improving system response time. Additionally, the use of Matrix LED technology offers flexibility in beam shaping, allowing precise illumination control [11].

7. Conclusion

This paper presents a novel adaptive headlight control system integrating Matrix LED, ToF sensor-based object detection, and steering-based beam tilting for enhanced night-driving safety. The system successfully mitigates glare, improves road visibility, and dynamically adjusts headlamp direction based on steering input**.**

Future Scope

1. Integration with AI Algorithms

Machine learning models can enhance object classification (e.g., distinguishing between pedestrians and vehicles) [9].

2. Vehicle Speed-Based Beam Adjustment

Incorporating speed sensors to dynamically adjust the beam range and width based on vehicle speed.

3. Smart IoT Connectivity

Enabling cloud-based monitoring for real-time headlight performance analysis.

This research lays the foundation for advanced automotive lighting systems, paving the way for intelligent and autonomous vehicle lighting solutions [1], [7].

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