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Development of an LDR-Integrated PDLC Film for Automatic Glare Reduction in Vehicles

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ABSTRACT

The high risk of glare from vehicle headlights at night often becomes a significant contributor to traffic accidents, particularly for motorcyclists and drivers of lightweight vehicles. To address this issue, a smart glare-blocking system based on a PDLC (Polymer Dispersed Liquid Crystal) film has been developed. This research proposes the design, development, and testing of a PDLC film system integrated with an LDR (Light-Dependent Resistor) sensor to automatically detect light intensity and adjust the film's opacity in real-time. The goal is to enhance driver visibility and comfort without compromising overall road safety. The experimental setup involved placing the prototype system at varying distances (0–9 meters) from a controlled light source at night. Measurements were conducted to collect data on light intensity, voltage output, resistance of the LDR, and the degree of light attenuation achieved by the PDLC film. The results showed that at a distance of 1 meter, the PDLC film could block up to 99.85% of incoming light, reducing 12080 Lux to only 17 Lux. Moreover, the film began to react at 6 meters with an output voltage of 34V. It became fully transparent at 8–9 meters with an output of 50V. The findings demonstrate that the PDLC system functions effectively in detecting potential glare and reducing its impact before it reaches the driver's eyes. This intelligent system offers a promising solution for minimizing night-driving hazards by dynamically adapting to changing light conditions.

1. Introduction

The headlamp, commonly referred to as the front light of a motor vehicle, plays a crucial role in ensuring driving safety, particularly during nighttime or adverse weather conditions [1, 2]. With the continuous advancement of technology in motor vehicles, headlamp technology has undergone significant evolution. However, this development has led to a recurring issue: glare. For decades, glare from oncoming vehicles has been a significant concern for drivers and traffic safety researchers globally. A 2019 study conducted in the United Kingdom revealed that approximately 60% of 1,215 drivers reported being dazzled by headlights from oncoming traffic, often struggling to distinguish between low-beam and high-beam lights. SUVs were often cited as frequent offenders due to their elevated lamp positions [3].

Nighttime driving is significantly riskier than daytime driving. According to Ackaah, W. et. al [4], the likelihood of vehicular accidents at night is three times higher than during the day, despite lower traffic volumes. Supporting this, the World Health Organization [3] reports around 1.3 million deaths annually due to road traffic accidents. In Indonesia, data from DataIndonesia.com indicate an increase in accident cases, rising from 100,028 in 2020 to 103,645 in 2021 [5]. One fatal incident in 2022 involved a motorcyclist who fell into a five-meter-deep construction hole after being blinded by high-beam lights from an oncoming vehicle [6].

National regulations, such as Indonesian Law No. 22 of 2009 and Government Regulation No. 55 of 2012, explicitly mandate that every motor vehicle must meet technical requirements and roadworthiness standards, including the lighting system. The misuse of headlamps that causes glare is thus a legal and safety concern. In another incident in 2022, a traffic accident involving three motorcycles and a car on the Daan Mogot flyover occurred due to glare from direct sunlight [7]. This highlights not only artificial but also natural sources of glare. Anjar Rosjadi, Head of Marketing Product Planning Division at Astra Daihatsu Motor, emphasized that sun visors are explicitly designed to minimize such sun glare [8].

Sun visors are standard equipment in almost all vehicles, designed to reduce direct sunlight and enhance driver comfort. However, as noted by Tutunea, D. et al. [9], the design of sun visors has remained relatively unchanged since the 1930s. Given this stagnation, alternative solutions are necessary to enhance visual comfort and driving safety. One promising alternative is the use of Polymer Dispersed Liquid Crystal (PDLC) film, which consists of a thin polymer layer embedded with liquid crystal (LC) microdroplets dispersed within a matrix. PDLC films can change from opaque to transparent states when an applied voltage is applied, making them a suitable substitute for conventional sun visors [10, 11]. However, a major limitation lies in the control unit, which is often costly, with commercial controllers priced over six million Indonesian Rupiah, as observed in online markets.

Integrating PDLC film into automotive sun visor systems offers the potential for dynamic, electronically controlled glare reduction. However, a research gap remains in developing cost-effective control mechanisms and evaluating their effectiveness in real-world driving conditions. Prior studies have highlighted the importance of adaptive systems in reducing glare and improving visibility [12]. Therefore, this study aims to explore the feasibility of a smart PDLC-based anti-glare system as an innovative and affordable alternative to conventional sun visors.

2. Methodology

2.1 Research Design

The experimental testing was conducted to assess the performance of a PDLC (Polymer Dispersed Liquid Crystal) film system in automatically adjusting its transparency in response to varying levels of light intensity. The test aimed to simulate real-world lighting conditions particularly exposure to motorcycle headlamps under controlled nighttime conditions, eliminating ambient light interference as recommended in similar smart window evaluations [13].

The core components of the system included a motorcycle headlamp as the primary light source, a transparent acrylic sheet embedded with PDLC film, an LDR (Light Dependent Resistor) sensor for light detection, a control circuit for voltage regulation, a digital lux meter to measure light intensity, and a digital multimeter to monitor the resistance and output voltage. The PDLC film, in this system, would adjust its opacity based on the electrical signal derived from the LDR's response to incoming light, similar to approaches used in automotive glare-reduction systems [14].

To facilitate the measurements, a measuring tape was extended in a straight line from the headlamp, marking distances from 0 to 9 meters. At each distance point, the PDLC film module, including the LDR sensor and control circuitry, was positioned. The lux meter was initially used to record the light intensity before the light passed through the PDLC film. Following this, the multimeter recorded the resistance of the LDR, and the output voltage from the control circuit was measured. Finally, the lux meter was placed behind the PDLC panel to measure the amount of light that passed through the film, thereby evaluating the film's ability to block or transmit light.

Measurements were taken sequentially at each one-meter interval, starting from 0 meters up to 9 meters. This process allowed for the observation of how the system responded to decreasing light intensity as the distance increased. To ensure data accuracy and minimize anomalies, the voltage output test was repeated thirty times under the same conditions. The data collected from these repeated tests were compiled into a voltage response curve to visualize consistency and system behavior, in line with experimental validation standards for optical smart materials [15].

The observations were carefully documented in a series of tables that showed the relationship between distance and various parameters, including incoming lux values, LDR resistance, output voltage, and the percentage of light blocked by the PDLC film. These results were then analyzed further through graphical representations, illustrating how the PDLC film system adapted to light intensity by modulating its transparency in real-time.

This experimental procedure successfully demonstrated the system's effectiveness in dynamically responding to varying light inputs. The PDLC film was proven to block significant amounts of light under high-intensity exposure and allow greater transmittance under dimmer conditions, verifying the functional integration between the sensor, control circuit, and PDLC technology.

2.2 Experimental Instrument

The accuracy and reliability of the instruments used in the study are crucial for obtaining valid results. All instruments used in this study were verified to meet the proper technical standards and were calibrated prior to data collection. The digital lux meter and multimeter used had sufficient resolution and accuracy to ensure reliable measurements in a laboratory setting. The instruments used in this study are summarized in Table 1:

Table 1. The instruments used in this study

No	Instrument	Specification
1	Digital Lux Meter	Measurement range: 0–200,000 lux; Accuracy: ±4% + 10; Resolution: 1 lux
2	Digital Multimeter	- DC Current: up to 10A; Accuracy: ±1.0% + 5 digits; Resolution: 0.01A - DC Voltage: up to 600V; Accuracy: ±0.5% + 3 digits; Resolution: 0.001–0.1V - Resistance: up to 60MΩ; Accuracy: ±0.8% + 3 digits; Resolution: 0.1Ω–0.01MΩ
3	Measuring Tape	Used to measure light source distance precisely
4	Stationery Tools	For manual recording of measurements during the experiment

2.3 Instrument Validation and Data Analysis

The collected data were analysed using descriptive statistics. For each variable (light intensity, sensor resistance, and output voltage), the mean, minimum, and maximum values were calculated to examine the overall response of the system. In addition, percentage changes in voltage were used to assess the level of transparency as the light intensity varied with distance. The analysis applied the following basic formulas, as shown in Eqs. 1 and 2.

$$\bar{x} = \frac{\sum x}{n} \tag{1}$$

Where : $\bar{x}$ = Mean

x = Observed Value

n = Number of observations

$$P = \frac{\sum x}{Total\ value} \times 100\% \quad (2)$$

Where : P = Percentage
x = Observed Value

3. Result and Discussion

3.1 Prototype

The PDLC film device prototype was designed and developed with a focus on controlling the voltage output through an LDR (Light Dependent Resistor) sensor, which operates based on the principle of a voltage divider. In this research, the LDR's resistance is used to read light conditions, as the resistance of the LDR changes with varying light intensity. The LM317HV integrated circuit (IC) was chosen to regulate the output voltage based on the resistance of the LDR. As the distance between the light source and the LDR sensor increases, the resistance of the LDR decreases, causing the LM317HV to output higher voltage levels, which in turn control the PDLC film. The voltage output curve, generated from the experimental results, is shown in Figure 4.11. Polynomial regression analysis was used to model the relationship between light intensity and the output voltage.

The system operates with an AC power supply (PLN), which is converted to 12V DC through a PSU (Power Supply Unit) with a 10A capacity. The 12V DC is then routed through a main switch to control the device's power. This voltage is subsequently distributed to a cooling fan, a DC-to-DC step-down converter, and a DC-to-DC step-up converter. The step-down converter reduces the voltage from 12V to 5V, supplying power to the Arduino board, DHT11 temperature sensor, and a 5V relay. Meanwhile, the step-up converter increases the voltage to 50V, which the PDLC controller then adjusts to manage the PDLC film. The system schematic is shown in Fig. 1, which illustrates the complete voltage distribution and flow throughout the device.

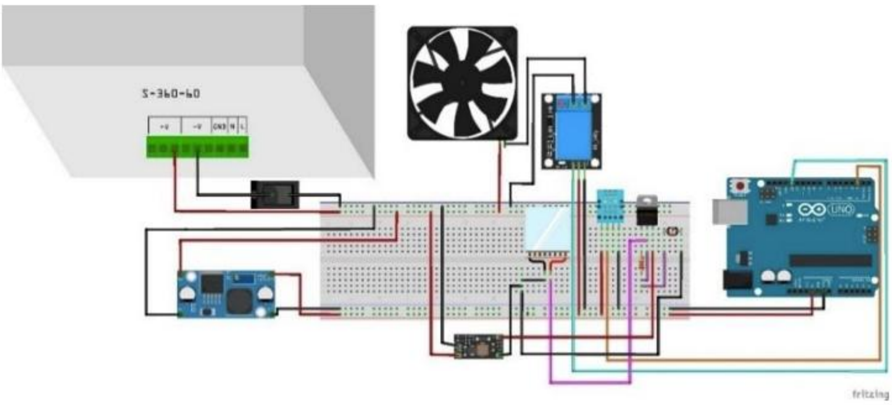

Figure 1. Schematic of the system

The PDLC controller circuit employs the LM317HVT IC to regulate the voltage supplied to the PDLC film. The LM317HVT IC has three pins: the adjust pin, the output pin (V_{out}), and the input pin (V_{in}). The adjust pin is connected to the LDR, which acts as the input sensor to monitor light intensity. The resistance from the LDR affects the output voltage when an input voltage of 57V is applied. The LM317HVT adjusts the output voltage accordingly, enabling the

PDLC film to react to varying light conditions [16]. The detailed schematic for the PDLC controller is shown in Fig. 2.

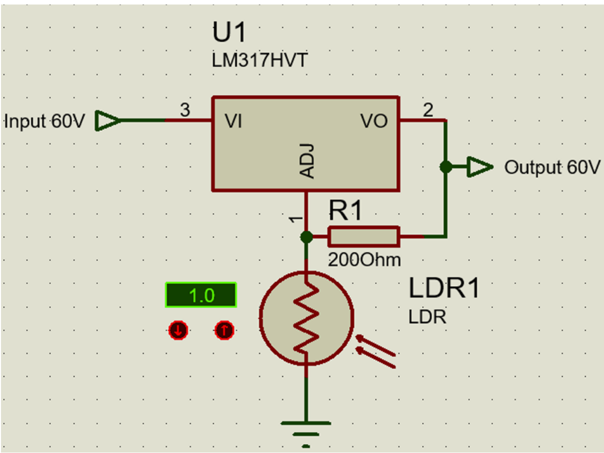

Figure 2. Schematic wiring diagram PDLC

A cooling system was implemented to maintain the temperature of the components within the normal operating range. The 12V power supply from the PSU powers the system, and this voltage is distributed to a cooling fan. A DC-to-DC converter is used to step down the voltage to 5V, which supplies power to the Arduino board, DHT11 sensor, and relay. The cooling system is controlled via software written in Arduino IDE, ensuring that the fan operates when needed to prevent overheating of the system during operation [17]. The complete assembly of the prototype is shown in Fig. 3.

Figure 3. Assembly of the prototype

3.2 Prototype Testing

As illustrated in Fig. 4, the output voltage of the PDLC film system increased linearly with the distance from the light source. At a distance of 1 meter, the system recorded an output voltage of 9.8 V, corresponding to a light intensity reading of 12,080 kilolux. This relationship suggests that the closer the distance to the light source, the higher the intensity measured by the sensor, and consequently, the greater the voltage output. As the distance increased, the voltage reached 50V at a distance of 8 meters, demonstrating that the PDLC film system becomes fully transparent, thereby ensuring better visibility for the driver [18].

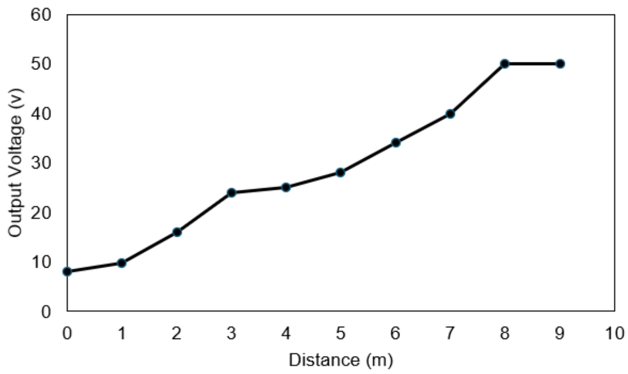

Figure 4. Measured Light Intensity and Corresponding Output Voltage Based on Distance from Light Source

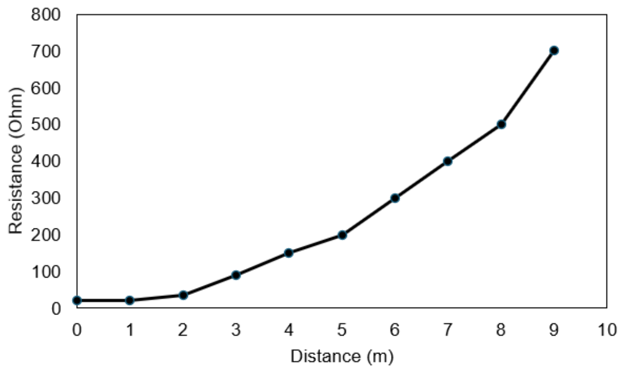

Figure 5. Table of Light Intensity and LDR Resistance at Various Distances from the Light Source

At 6 meters, the PDLC film began to function optimally, with a voltage of 34V and a light intensity of 277 lux. This result aligns with the system's goal of adjusting the opacity of the PDLC film in response to light intensity, thereby effectively protecting the driver from potentially blinding light [19]. The system's ability to block light gradually diminished as the distance increased, with the PDLC film becoming fully opaque at a distance of 2 meters, blocking 99.98% of the light, as shown in Table 2.

Table 2. Percentage Change in Lux Levels with Distance

No	Distance (m)	Lux Before	Lux After	Percentage (%)
1	0	158400	30	99.98
2	1	12080	17	99.85
3	2	2990	28	99.06
4	3	1300	40	96.92
5	4	623	56	91.01
6	5	425	53	87.52
7	6	277	41	85.11
8	7	162	30	81.48
9	8	111	23	79.27
10	9	83	45	45.78

Fig. 5 presents the resistance of the LDR and the corresponding voltage output for each distance and light intensity. The resistance of the LDR decreased with increasing light intensity, which is expected due to the nature of LDRs [20]. As the light intensity increases, the resistance of the LDR decreases, allowing more current to pass through, thereby increasing the output voltage. This trend is evident from the measurements, as the resistance at 1 meter was 20 Ohms. In contrast, at 9 meters, it rose to 700 Ohms, reflecting the decrease in light intensity with distance.

At a distance of 1 meter, the LDR measured a light intensity of 12,080 lux, resulting in a relatively low resistance of 20 Ohms. At this point, the PDLC film was able to block a significant amount of light (99.85%), reducing the lux value from 12,080 lux to 17 lux. This shows that the PDLC film is highly effective at close range, with a light-blocking efficiency of 99.85%, as indicated in Table 2. However, as the distance increased, the light-blocking efficiency gradually decreased. At 9 meters, the light-blocking efficiency dropped to 45.78%, where the lux value after passing through the PDLC film was recorded as 45 lux [21].

4. Conclusion

The testing of PDLC film technology, both experimental and analytical, led to important conclusions regarding its performance and suitability for use in automotive applications. The system effectively reacts to variations in light intensity. The transparency of PDLC film shifts dynamically when exposed to light, particularly from nearby sources such as headlights or bright sunlight. The movie becomes unclear when exposed to bright lights from a short distance. This feature minimizes glare and enhances visibility for drivers, particularly in situations where bright light may pose a safety risk.

The second conclusion highlights the system's output voltage. The output voltage increases linearly with the distance of the light source. At a distance of 1 meter, the voltage measures 9.8 volts, while at 8 meters, it increases to 50 volts. The voltage regulates the transparency of the PDLC film, creating a reliable connection between the light intensity, the resistance of the LDR sensor, and the system's output voltage. Predictability is essential for refining the film's behavior in real-world scenarios. The short-range light-blocking effectiveness of PDLC film is outstanding. The film blocks as much as 99.98% of light at a distance of 0 meters. It has an effectiveness of over 80% at distances of up to 7 meters, making it suitable for a wide range of practical uses. After 8 meters, efficiency starts to decline, reaching its lowest blocking capability of 45.78% at 9 meters. This drop indicates an optimal operational range where the system performs most effectively.

The activation range of the system is another significant outcome. The PDLC film reacts to light at a distance of 6 meters when provided with a 34-volt output voltage and a light intensity of 277 lux. The system becomes increasingly transparent from this point, achieving complete transparency at a distance of 8 meters. On the other hand, complete opacity at 2 meters enables the system to respond to varying lighting conditions and maintain driver visibility instantly. The experiments demonstrate that the PDLC film system is suitable for use in automotive settings. The adaptive light-filtering enhances both driver comfort and safety. This device minimizes glare from oncoming headlights and intense sunlight, enhancing safety and comfort while driving in low-visibility or high-glare situations. The results indicate that the PDLC film presents a dependable and innovative option for vehicle design.

Conflict of interest

The authors declare that they have no conflict of interest.

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