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Original Article

Solar Powered LED Street Light with Movement Detection and Intensity Control

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***Abstract** - This proposed solar-powered LED street lighting prototype project is an eco-friendly option to improve energy efficiency with sufficient lighting for enhanced human environments' safety and visibility. To this end, a prototype was built by using a Zybo Zynq-7000 development board, BC547 transistor, TP4056 battery charger, Light-Dependent Resistor (LDR), chargeable battery, LED and resistors as a proof of concept using FreeRTOS task scheduling and priority management. The system's sensors track ambient light levels and movement to intelligently modify the LED lights' brightness by dimming the light during low vehicles or pedestrians-related activity to conserve energy and immediately brighten upon detecting movement. With the goal of maximizing solar energy usage and minimizing waste, it extends battery life and improves overall system reliability during low-demand periods, thus lowering maintenance and operating costs. The proof of concept suggests a simplistic solution to address energy saving and urban lighting sustainability by utilizing solar energy and incorporating smart control mechanisms, paving the path towards more resilient and ecologically conscious cities. For future research, performance indicators like lighting effectiveness, energy savings, dependability, and user happiness can be proposed to assess the system's viability and suitability for broad implementation.*

***Keywords** - Energy efficiency, Intensity control, LED street light, Movement detection, Solar energy, Sustainable development.*

1. Introduction

This prototype project proposes to develop a proof of concept for Light-Emitting Diode (LED) street lighting with movement-activated intensity control driven by solar power. As power generation is critical, to maximize power efficiency, the LED streetlight will be turned off during the day. This is to enable the photovoltaic cells to collect solar energy and charge the battery so that it can be turned on at night. LED streetlights are set to alternate between low and high-intensity lighting, based on sensors' detection of pedestrian movement, to maximize solar energy usage at night. The circuit will also protect the battery from under and overvoltage to extend its lifespan. As solar energy resources are renewable, there is a huge opportunity to reduce conventional energy dependence as well as enhance energy conservation.

1.1. Research Gap

Despite substantial developments in solar-powered LED street lighting systems, most existing solutions focus solely on energy economy and sustainability, neglecting the integration of advanced motion detection and dynamic intensity control methods. Although solar-powered lights help cut down on carbon emissions, there is still room to improve energy efficiency by modifying light intensity in response to movement detected in real-time. Additionally, the current literature lacks thorough research addressing the performance and cost-effectiveness of combining solar energy with smart lighting control systems in diverse environmental and urban environments. The need for more study into the creation of intelligent, adaptable solar-powered street lighting systems that maximize energy efficiency and public safety is highlighted by this research gap.

1.2. Problem Statement

The increasing demand for energy-efficient and sustainable lighting solutions has driven the need for innovative street lighting systems. Traditional streetlights consume significant amounts of electricity and often remain at full intensity even in low-traffic conditions, leading to unnecessary energy waste. This paper proposes a solar-powered LED street lighting system integrated with movement detection and intensity control aimed at optimizing energy usage and enhancing operational efficiency. By utilizing renewable solar energy and employing motion sensors to adjust light intensity based on real-time movement, the system offers an environmentally friendly, cost-effective solution that addresses the limitations of conventional street lighting.

2. Literature Review

Because they are sustainable and energy-efficient, initiatives on solar-powered LED street lighting systems with intensity control and movement detection are becoming more and more popular. Current research focuses on many approaches to improve these systems' efficiency, dependability, and affordability. The goal of this literature review is to give readers a thorough grasp of the state of technology in this subject by examining various techniques and highlighting their advantages and disadvantages. Important techniques that individually improve solar-powered street lighting include intelligent control systems, digital dimming operations, vehicle movement detection, and traffic intensity adaptive control.

A detailed comparative analysis of methods used in research involving solar-powered LED streetlights with movement detection and intensity control is being investigated in the literature, shown in Table 1.

Table 1. Comparative analysis of methods used in solar-powered LED street lights with movement detection and intensity control research

Method	Strengths	Weaknesses	Citation
Traffic Intensity Adaptive Control	• High energy efficiency through adaptive control • Maintains lighting quality and safety • Significant energy consumption reduction	• Requires high-quality LED luminaires • Implementation complexity	[1]
Digital Control for Dimming Operation	• Optimal battery charging • Control LED brightness based on surrounding light • Use of Arduino ensures low cost	• Requires precise calibration of sensors • Dependence on weather conditions for solar energy	[2]
Detecting Vehicle Movement	• Significant energy savings • Automatic adjustment based on traffic • Ensures pedestrian safety	• Initial setup costs can be high • Potential false positives/ negatives in sensor detection	[3]
Automatic Street Lighting Using Solar	• Low energy consumption • Extended system lifespan • Uses white LEDs for better light quality	• Requires a dependable charge controller • Performance is heavily dependent on sunlight availability	[4]
Intelligent Control with Fuzzy PI	• High prediction accuracy • Low energy consumption • Long battery life	• Complex control algorithms • Higher initial development and implementation costs	[5]
IoT-Based Hybrid Street Light System	• Utilizes both wind and solar energy • Off-grid operation reduces dependency on the grid • IoT integration allows for remote monitoring and control	• High initial cost • Requires dependable IoT infrastructure	[6]
Dual-Axis Solar Tracker	• Maximizes solar panel efficiency • Reduces dependency on conventional energy sources • Uses energy-efficient LEDs	• Mechanical parts may require regular maintenance • Higher initial installation cost	[7]
Smart Street Lighting System	• Cost-effective and eco-friendly • Eliminates manual operation • Promotes significant energy savings	• Requires comprehensive sensor network • It may need regular updates and maintenance	[8]
Adaptive Fuzzy PI Solar LED Control	• Low power consumption • High stability and accuracy • Effective for smart city applications	• Complex implementation • Higher initial costs for development and setup	[2]
Brightness Controlled Intelligent Street Light	• Significant power savings • Automated control based on motion and ambient light • Extended LED lifespan	• Requires reliable sensor network • Initial setup can be costly	[9]

Although it involves complicated implementation and high-quality LEDs, the approach outlined in [1] changes street lighting based on traffic intensity, assuring great energy efficiency and safety. Regarding the work in [2], this method relies greatly on precise sensor calibration and meteorological conditions. It employs Arduino for digital control, enabling optimal battery charge and brightness modification. Although this system in [3] saves energy and improves safety by adjusting lighting according to vehicle movement, it can be expensive to set up. It may experience problems with sensor detection because of the sensitivity of the sensor.

In order to achieve low energy consumption and a long lifespan, the author in [4] employs solar power with white LEDs; however, this system depends on a dependable charge controller and enough sunlight. Fuzzy PI control is a technique used by [5] to achieve precise and economical lighting. It has a high prediction accuracy and low energy usage, but it is expensive and requires complicated algorithms. [6] suggested a method for effective off-grid operation and remote control that integrates solar and wind energy with IoT; however, it has large upfront expenditures and needs a strong IoT infrastructure.

Dual-axis tracking in this method [7] reduces energy dependency and increases solar panel efficiency, but it comes with greater installation costs and possible maintenance problems. Regarding [8], this environmentally friendly system uses a large sensor network and frequent maintenance to automate street lighting, which results in significant energy savings. The technology, which is similar to the method created by [2], provides precise and reliable lighting management at a low power consumption, making it appropriate for smart cities. However, it requires a difficult setup process and expensive implementation. [9] implemented an intelligent system that adjusts brightness in response to motion and light, saving energy and prolonging the life of LEDs. However, the system requires a dependable sensor network and can be expensive to set up.

This work novelty, compared to existing work in literature (Table 1), is a proposal for a simplistic solution with minimum setup to address energy saving and urban lighting sustainability by utilizing solar energy while incorporating smart control mechanisms.

3. Materials and Methods

The proposed solar-powered LED street light prototype is built by using Zybo Zynq-7000 development board, BC547 transistor, TP4056 battery charger, Light-Dependent Resistor (LDR), chargeable battery, LED and resistors as shown in Figure 1. The configuration of the proposed system is completed by using Xilinx Vivado software for synthesis and analysis of circuit and microchip development. A block design of the system, which included a custom General-Purpose Input/Output (GPIO) IP block, ZynQ processing system IP block, Analog-to-Digital Differential Converters (XADC) GPIO IP block, timer IP block and Pulse Width Modulator (PWM) IP block are constructed in Xilinx Vivado software as shown in Figure 2. The bitstream is generated and included in the Software Development Kit (SDK) in order to program the Zybo board.

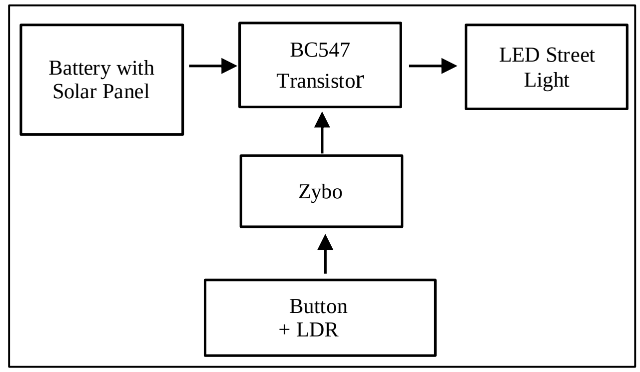

Fig. 1 Proposed LED street light prototype driven by solar power

The LED streetlight prototype is driven by solar power stored in a photovoltaic battery. A solar panel is connected to a battery charger, TP4056, to charge the photovoltaic battery. BC547 transistor is a Negative-Positive-Negative (NPN) transistor and is used as a switch to control the LED streetlight. When there is no input, the transistor remains open as normal. Whereas, when there is an input triggered, the transistor becomes close normally to supply power to the LED streetlight.

LDR, known as a Light-Dependent Resistor sensor, and additional buttons are used as the prototype input. The button is used to indicate that an incoming vehicle or pedestrian is passing by the street, whereas the LDR sensor is used to measure light intensity during daytime as well as nighttime. LDR measures the intensity of light during daytime and nighttime to turn on or off the LED streetlight.

During the daytime, the light intensity is higher. Once LDR detects higher light intensity, it triggers the BC547 transistor to switch off the LED streetlight. Conversely, during nighttime, with reduced light intensity, LDR triggers the BC547 transistor to turn on the LED streetlight. During the daytime, the button is not in use. During the nighttime, the button is pressed to assume an arbitrary vehicle or pedestrian passing by the street.

When there is no vehicle or pedestrian in the vicinity, the LED streetlight will be dimmed to save power. Once the button is pressed that indicates a vehicle or pedestrian around, the LED streetlight will be brighter. Zybo is used to schedule all the tasks that run in the street light system. A method called ‘priority’ is assigned to each task. The scheduler performs all the tasks according to the priority of each task.

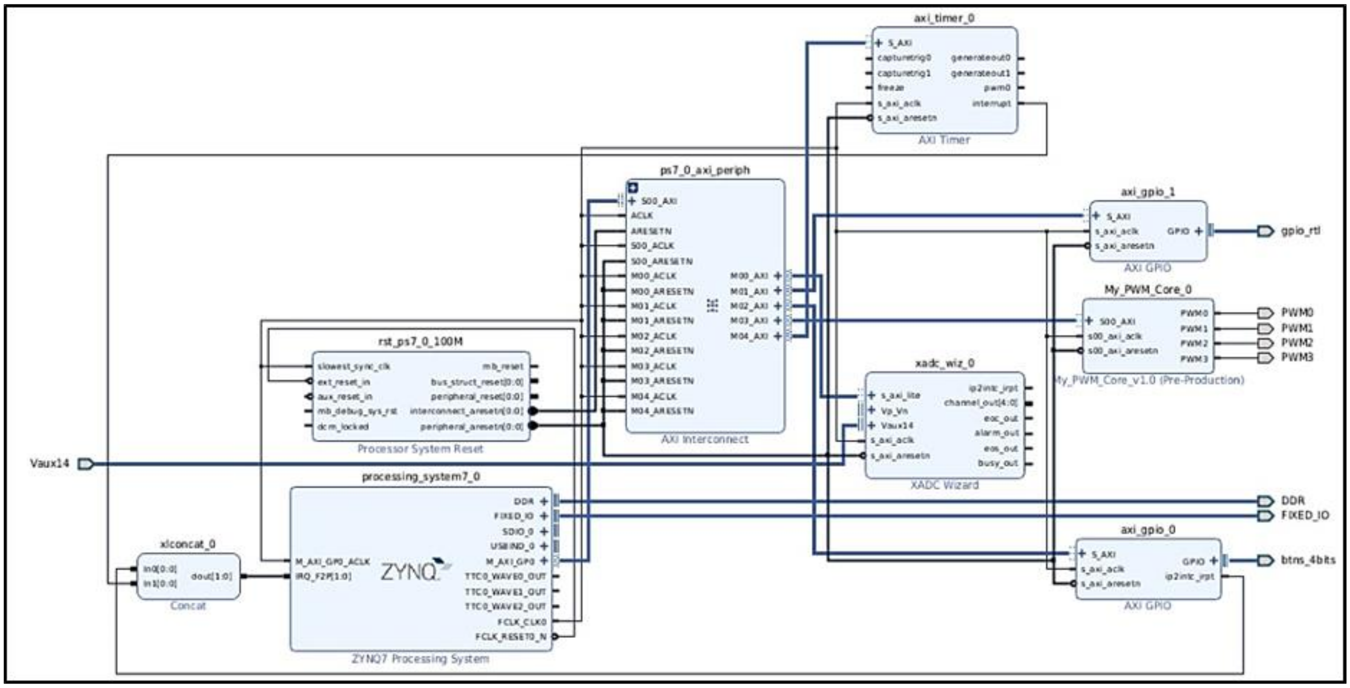

Fig. 2 Proposed system block design using Xilinx Vivado software

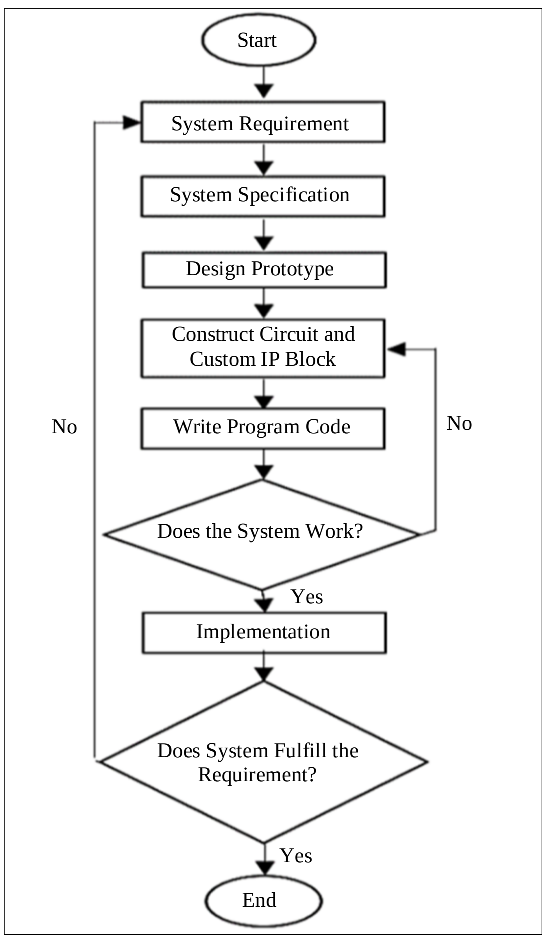

Fig. 3 Flow chart of the proposed prototype

The higher priority task will pre-empt the low priority task. FreeRTOS is the operating system used in this project. Figure 3 shows the flow chart of the proposed system design.

4. Results and Discussion

The solar-powered LED street light prototype with movement detection and intensity control is completed with the scheduling in FreeRTOS by using the Zybo board. The task of the button as the indication of movement detection to sense light intensity is the highest priority task, whereas the task of LDR is low priority task. The button task pre-empts the LDR task. The scheduler in Zybo executes high priority tasks followed by low priority tasks by using Semaphores.

The FreeRTOS task scheduling and priority management (Table 2) with the prototype built (Figure 4) and the design's schematic is constructed (Figure 5). The proposed street light prototype is low on power consumption by using solar energy. The LED street light is turned on according to the two inputs: button and LDR. During the daytime, light intensity is high, and the LED street light is turned off, as shown in Figure 6.

During night time, the LED street light is turned on by using the LDR. When the LDR detects low light intensity, the LED street light is switched on by a BC547 transistor. The button simulates the role of a sensor to indicate the detection of a vehicle or pedestrian. When the button is pressed, which means a vehicle or pedestrian is passing through the street, the LED street light is triggered to be brighter, as shown in Figure 7. When no button is pressed, the LED street light is turned on but with a dimmer light, as shown in Figure 8.

Table 2. FreeRTOS task scheduling and priority management using Zybo board

Task	Priority	Pre-empts	Semaphore Used	Description
Light Intensity Sensing	Highest	LDR Reading, Other Tasks	Yes	Task to sense light intensity, highest priority pre-empts other tasks.
Light Dependent Resistor (LDR) Reading	Low	Other Low Priority Task	Yes	Task to read from the Light Dependent Resistor (LDR), low priority.
Other Low Priority Task	Low	None	Yes	Other low priority tasks are executed when higher priority tasks are not running.

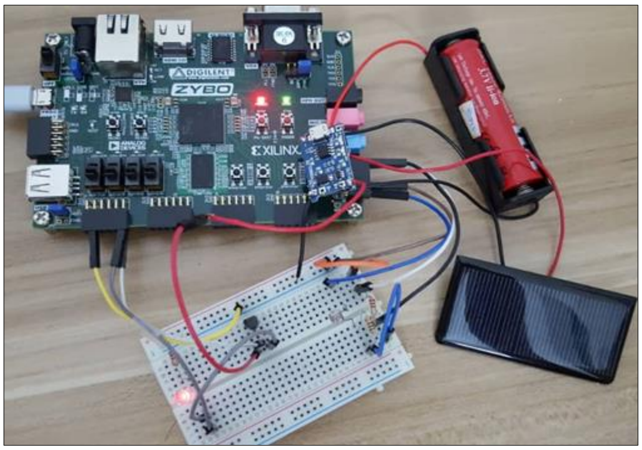

Fig. 4 Prototype of the proposed system

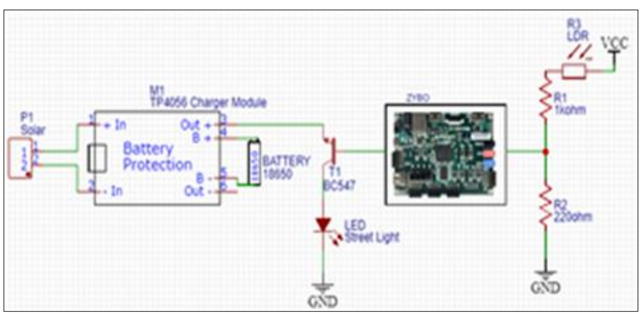

Fig. 5 Schematic of proposed system design

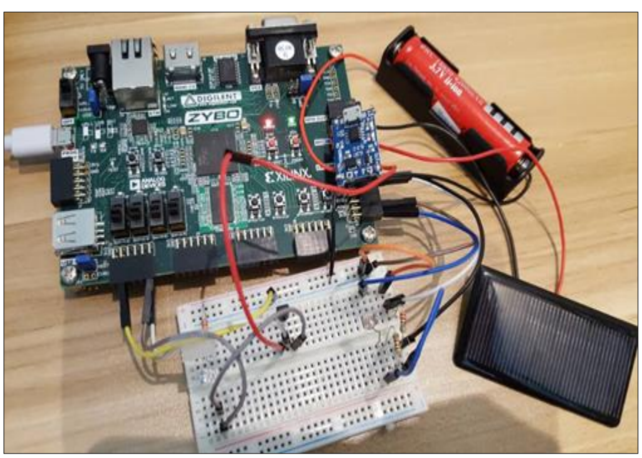

Fig. 6 LED street light is turned off during daytime

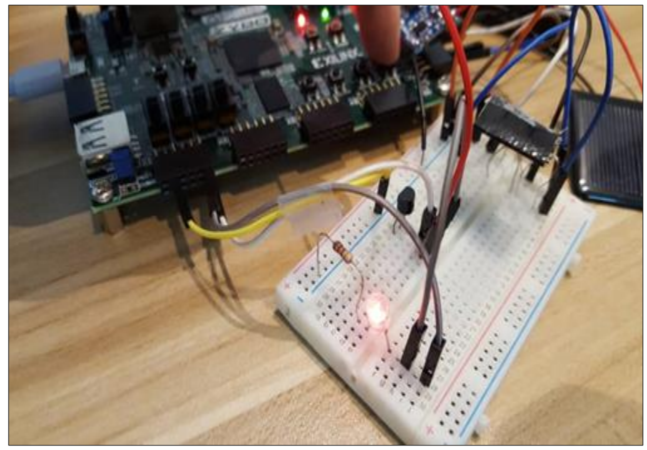

Fig. 7 LED street light is brighter when the button is pressed

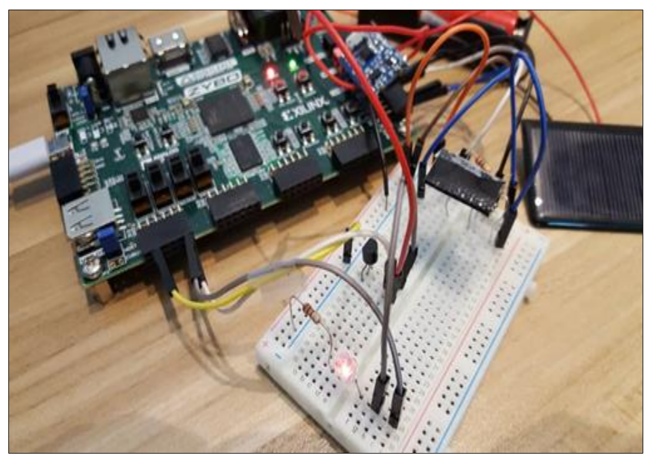

Fig. 8 LED street light is dimmer when no button is pressed

An efficient and successful energy-saving solution is demonstrated by the outcomes of the solar-powered LED street light system with movement detection and intensity control that was constructed using FreeRTOS on a Zybo board. The system maintains a low-power baseline state during periods of inactivity by prioritizing movement detection, which enables fast illumination adjustment when a vehicle or pedestrian is detected through task scheduling via FreeRTOS.

With a higher priority given to the button job, which simulates motion detection, and a lower priority given to the light detection task, which uses the Light Dependent Resistor (LDR), this method makes use of semaphores to manage task execution. Priority-based job scheduling combined with intensity management shows enhanced power efficiency by dynamically varying the light's brightness according to the current situation.

4.1. Comparison to State-of-the-Art Techniques

The suggested system exhibits increases in power efficiency and responsiveness when compared to state-of-the-art methods; nevertheless, there are a number of areas where additional modifications could produce even better outcomes. Conventional solar-powered street lighting systems frequently lack dynamic control based on real-time movement detection and instead rely on either set schedules or simple light sensors. Although these systems are efficient at saving energy, they are not able to precisely adjust the intensity in response to the presence of vehicles or pedestrians, which could result in energy waste during periods of low activity. This gap is filled by the suggested system's mix of movement detection and intensity management, which reduces energy usage without sacrificing safety by only raising brightness when needed.

However, a lot of contemporary systems have shifted to more sophisticated options that offer more flexibility and control, like smart grids and Wireless Sensor Networks (WSNs). Systems that use adaptive lighting in response to various environmental elements, like traffic volume, pedestrian density, and weather, have proven to be more effective in terms of energy conservation and public safety. To further increase efficiency, these sophisticated systems frequently include machine learning algorithms for predictive control, which makes sure that lighting settings are changed before movement is detected.

Additionally, a lot of modern systems use stronger wireless communication protocols for inter-light communication, which makes it possible for a coordinated and smooth response across whole networks of street lights. Even while the suggested approach works well for individual streetlights, it would be advantageous to implement networked communication in order to allow lights to "communicate" with one another and brighten ahead of time, improving user experience and saving energy.

5. Conclusion

A solar-powered LED streetlight with movement detection and intensity control is built for power saving. The solar energy used to power the system is renewable. The system consumes less power than conventional streetlights using the national grid as solar energy is used, and the LED streetlight is turned on-demand according to the situation. During daytime, with high light intensity, the LED streetlight is turned off. The LED streetlight is switched on during nighttime with intensity control. When movement detection of vehicles and pedestrians is triggered, the LED streetlight is brighter. On the other hand, when there is no vehicle or pedestrian, LED streetlights will be dimmer.

By optimizing the LED streetlight intensity, the power consumption of the system can be further reduced. In future work, vehicle detection sensors and laser detector sensors can be used for movement detection of vehicles and pedestrians to implement in the system in order to improve the accuracy of movement detection. In addition, image processing also can be one of the methods to detect vehicles and pedestrians with higher accuracy within the environment.

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