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Intelligent Arduino Streetlight System for Environmental Monitoring and Accident Detection

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Abstract

Smart urban infrastructure plays a significant role in improving the safety of the roads while also lowering the energy usage. In an ideal world, efficient accident detection systems in place, there is a timely response from an emergency service which would prevent loss of lives and properties during accidents, both in rural and urban areas. The aim of this project is to provide a solution to these problems by developing a system that is effective from a cost point of view and provides combination of environment monitoring in real time and impact of the accident. This paper presents an intelligent streetlight management system developed using Arduino Mega as a main controller along with environmental sensors including SHT31 temperature and humidity sensor, GL55 photoresistor (LDR), and ultrasonic sensor to help it monitor environmental conditions and only work when needed keeping it energy efficient. Real-time detection led to transfer of a model based on YOLOv8, which was built and trained using 1,807 photographs of individuals either being or not being hit; all this data was merged towards an ESP32 camera for on-the-go video analyses. They can then send accident data -- times, dates, GPS locations, whatever -- to a dashboard for instant response. Notably, the streetlight system operates solely under predetermined conditions, conserving energy, and the accident detection system reached a mAP@50 score of 0.6305 and a mAP@50–95 score of 0.4342, achieving a 60% accuracy when applied to video footage taken in real-world scenarios. These outcomes clearly show the viability of the integration of environmental observation and protection systems within a single low-cost unit. This project demonstrates how Arduino-based systems can help solve urban problems, generate energy savings, increase road safety, and identify sustainable solutions for urban growth.

1. Introduction

The Internet of Things is generally referring to cases where network connectivity and computing power is integrated into physical objects and everyday things that are not generally regarded as computers. This allows these devices to harvest, share and process data with little to no human intervention. The IoT is expanding exponentially and fundamentally altering urban life by network-enabling — with sensors, software and connectivity — a blast of diverse physical devices, appliances and objects in order to generate and share vital real-time data [1][2]. The evolution of this technology has brought "Smart Cities" in the picture, plan is to come up with applications inside smart grids, smart transportation, smart homes, smart buildings, and leading to a better urban life. Smart city development is spearheaded by major cities of London, Paris, Amsterdam, Rio de Janeiro, as well as the government of Malaysia, which through its Smart City Framework (MSCF) has dedicated efforts to develop smart city initiative, with smart transportation being a main theme. Accident detection and response systems are an integral part of smart transportation, which help to reduce the loss of lives and properties that can occur due to road accidents and contribute to the enhancement of road safety. In Malaysia, traffic-related accidents remain a major concern, often exacerbated by delayed reporting of accidents and calls for emergency response. Surveillance systems designed to detect accidents have been produced; however, their high cost and technical complexity may prohibit their accessibility. To tackle these issues, the current study proposes the establishment of an Intelligent Arduino Streetlight System that combines real-time environmental monitoring with accident detection. Are "smart" streetlights that lower energy consumption and dynamically improve the response time of emergency services whenever accident detected. This study proposed an economic solution that will help to achieve the ultimate goal of smart city in urban safety and efficiency prism.

IoT in Smart Cities plays an integral part in most aspects that contribute to the efficiency and sustainability of urban areas and the quality of services offered. With IoT technologies, urban metrics, and data such as temperature, traffic flow, and energy consumption are collected and analysed in real-time, allowing cities to operate more intelligently and responsively [3]. Smart transportation systems, which are used in Smart Cities, help optimize traffic management and minimize traffic congestion through the integration of real-time data from vehicles, traffic lights, and road sensors, improving road safety as well [4]. These systems do not only deal with traffic but also help the environment by facilitating green transportation solutions like EVs and driver-less vehicles. Medical IoT also allows for monitoring any chronically ill patients, even those with heart disease, from a distance. Real-time ECG and heart rate data are transmitted to healthcare providers via wearable devices, leading to the early detection of health issues [5]. These systems leverage machine learning algorithms to analyse the collected data and predict potential health risks, enabling proactive interventions. There are, however problems such as power the consumption and data privacy and solution like cloud storage is used to store Voluminous Data while considering data privacy [6].

With increasing urban populations and rising energy consumption, intelligent energy management is essential for optimizing energy consumption in urban environments. IoT facilitate smart grids which allows real time tracking of energy consumption, offering enhanced energy efficiency and sustainability. The incorporation of renewable energy sources and energy storage systems in these grids also supports sustainable infrastructure and minimizes the negative environmental impact [7].

In a world with constantly growing urban populations and energy consumption, it is only through intelligent energy management that we can achieve energy consumption optimization in an urban society. IoT helps in smarter grids providing a real time tracker for energy consumption thereby improving energy efficiency and sustainability. Integrating renewable energy sources and energy storage systems into these grids further contributes to sustainable infrastructure and reduces negative environmental impacts [7]. IoT technology is revolutionizing waste management too, by allowing smart waste collections systems which improve the monitoring and scheduling of waste collection. Efforts such as Smartbin [8] leverage sensor data to assess the fullness of bins so that garbage collection can be optimized to reduce operational costs and improve the environment. Toward this end, IoT Prototypes [9] utilizing spatio-temporal data or advanced algorithms help fine-tune the requirements needed for the estimates and ultimately improve overall activity efficiency; additionally, the adoption of LoRaWAN protocols provides the advantages of scalability, energy efficiency, and interoperability in urban waste systems. This would implement greener cities as well utilizing resources while decreasing carbon emission due to effective waste management. IoT is not just limited to transportation, healthcare, energy, waste management, etc. For example, IoT-based surveillance systems such as cameras, motion detectors and sensors detect suspicious activities like accidents or theft and notify emergency responders in real time. Not only do these systems help to strengthen public safety and ensuring to improve the emergency response times, but also to ensure urban security.

Intelligent Urban System for Environmental Monitoring and Accident Detection Environmental monitoring is necessary to set measures to monitor air quality, temperature, humidity and pollution levels to help authorities protect public health, reduce climate change, and exploit energy. It also serves as an essential utility in terms of disaster preparedness and resource management. But on the flip side, broadening the adoption of smart accident detection systems plays an important role to elevate road safety and emergency response in smart cities. These systems use real time data and AI-powered detection to quickly spot accidents and notify emergency personnel, resulting in shorter response times and possibly saving lives. With non-involved persons being less likely to call, automated accident detection minimizes reliance on witness reports for presenting correct information, speeding up and improving the process of helping out in the situation of an accident. Additionally, smart accident detection aids in traffic management, by rerouting vehicles from accident-prone areas, alleviating congestion, and helping to prevent secondary collisions. By analysing the data from these incidents, authorities can determine areas that exhibit high-risk tendencies, resulting in better road infrastructure, improved traffic regulations, and overall safety measures.

2. Method

The overall structure of intelligent streetlight and accident detection system designed. Based on these components, we have assembled a circuit with Arduino Mega as a microcontroller, and integrated the tools such as SHT31, GL55, Ultrasonic sensor & ESP32 camera. It generates and sends commands to the relay module that enables you to switch the streetlight on and off. In the case of an accident, the ESP32 camera will capture some image data and send it to a pre-train machine-learning model for processing to detect the accident. This architecture was designed to establish connections between the sensors, camera and central controller, enabling the system to react in response to real-time events and send data on an accident to a dashboard. The smart streetlight schematic diagram is shown in Fig. 1.

Component:

1. SHT 31 Temperature Sensor
2. GL55 Photoresistor
3. LCD Display
4. LED
5. Relay Module 5V
6. Neo 6M GPS
7. Ultrasonic Sensor
8. Arduino Mega 2560
9. ESP32 Cam
10. Jumper Wire
11. Breadboard

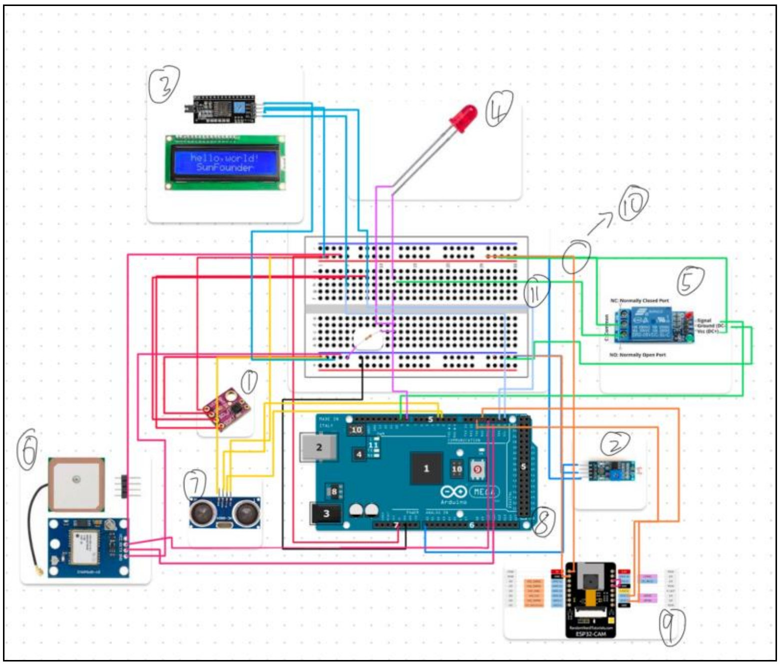

Fig. 1 Schematic Diagram Smart Streetlight System

Since the streetlight system is rather large, the control algorithms need to be designed. The Arduino Mega processes the value from the LDR and the ultrasonic sensors, and through this, the relay module is triggered, which turns on the streetlight if the value from the LDR is less than 900 and an object is within a distance of 50 cm from the ultrasonic sensor. The first one is where an ESP32 camera stream captured real-time images and send them to a machine learning model to detect any accident. After processing, the model provides an output that indicates an accident has or has not happened. This stage focused on developing the logic required for real-time decision-making for streetlight control as well as accident detection.

Attach the sensors, GPS, ultrasonic sensor, camera, and lightning sensor to the Arduino board and ensure that all components are interfaced according to Fig. 2, all set and calibrate for each of the hardware such as GPS module, ultrasonic sensor, Camera, lightning sensor, et cetera for respective task and use. Moreover, develop the Internet of things IoT communication modules to communicate between Arduino board and the external systems or devices, allowing real-time data transmission and remote monitoring features.

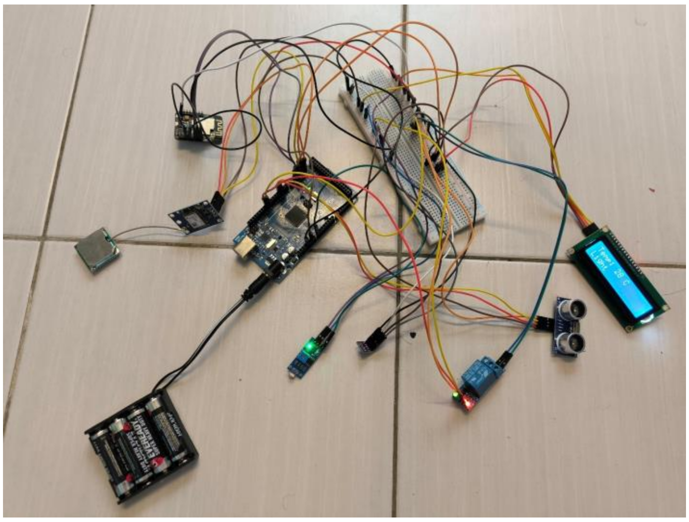

Fig. 2 Smart Streetlight System

All components were tested at system level to ensure the proper functioning of all sections. Sensor-specific testing methods were used to validate performance of each sensor for accuracy. To test the SHT31 temperature and humidity sensor the method was heat sht31 and check if whether or not the output values changed accordingly to ensure the changes in temperature and humidity was detected. In order to test the LDR sensor, the intensity of the surrounding light was adjusted in such a way that the readings would be checked whether they would react properly when testing between light and darkness. It was tested by moving the object in its detection range and checking whether the ultrasonic sensor maintains the presence of an object detected. The streetlight control logic was tested by ensuring that the LED light was activated only when the value of LDR was less than 900 and an object was present within 50 cm. Lastly check if the ESP32 camera module powered on & captured the image as one needed. The testing in this phase was to verify the working of each hardware component independently and make sure that they did what they were meant to do before putting them all in one system.

In this phase, the machine learning model for accident detection was developed; the goal was to train the models to correctly differentiate "car" from "accident". Using the LabelImg tool, we manually annotated a dataset of 1,807 images to ensure that each image in the dataset was labelled correctly as "car" or "accident." Accurate annotation like this is necessary to train the model to distinguish normal occurrences of vehicles from those on the scene of an accident. YOLOv8 was used as a model framework to implement a model with excellent object detection. Google Colab also use for the purpose of training and the annotated dataset needed to be pre-processed (e.g. to maintain consistent dimensions and image quality). It learns the patterns on which accidents have happened, so it learns so much about the real world, making sure that in the end it can recognize whether a car is about to crash or not. This phase was critical in setting the groundwork for integrating the trained model into the ESP32 camera, allowing for real-time collision detection in subsequent phases of development. With a carefully labelled dataset and a trained model, the goal was to create a system that would improve the reliability and accuracy of detecting traffic accidents. After that, attached all hardware & software together. The Arduino Mega controlled and integrated the sensors, relay module, and ESP32 camera. The purpose of the system was to trigger and turn on the streetlight given the real time sensor readings. To classify the images and detect the accidents, the accident detection model was injected into the system. The LCD showed the data from the sensors and sent an accident in case of detection to a dashboard to monitor. A complete system test was carried out to verify the proper functioning and operability in conditions close to the original. The performance of the streetlight control system was analysed in different lighting conditions to test its adaptability to ambient light variation and object detection. The accident detection system was tested with 10 real-world video samples, exploring its potential to correctly detect accidents. Additionally, Model performance was measured in terms of mean Average Precision (mAP) at two thresholds; mAP@50 and mAP@50-95, providing a method of detailed evaluation of detection accuracy.

3. Result & Discussion

This section describes the results and findings of the project organized by its objectives. First, it describes the design and implementation of the intelligent streetlight system focusing on the integration and functionality of real-time environmental monitoring sensors. It also investigates the implementation of the accident detection system using a machine learning model and tests its performance through accuracy metrics and actual testing environments.

3.1 Design and Implementation of a Streetlight Using Real-Time Environmental Monitoring Sensor

The smart streetlight system was designed and implemented using the Arduino Mega microcontroller as the central control unit. The system integrates multiple sensors for real-time environmental monitoring: SHT 31 Temperature and Humidity Sensor, GL55 Photoresistor (LDR) and Ultrasonic Sensors. SHT31 Temperature and Humidity Sensor captures the ambient temperature and humidity every second, GL5 Photoresistor (LDR) monitors the surrounding light intensity and Ultrasonic Sensor detects objects or movement. The change of result of the implemented system is shown in Fig. 3 and Fig. 4.

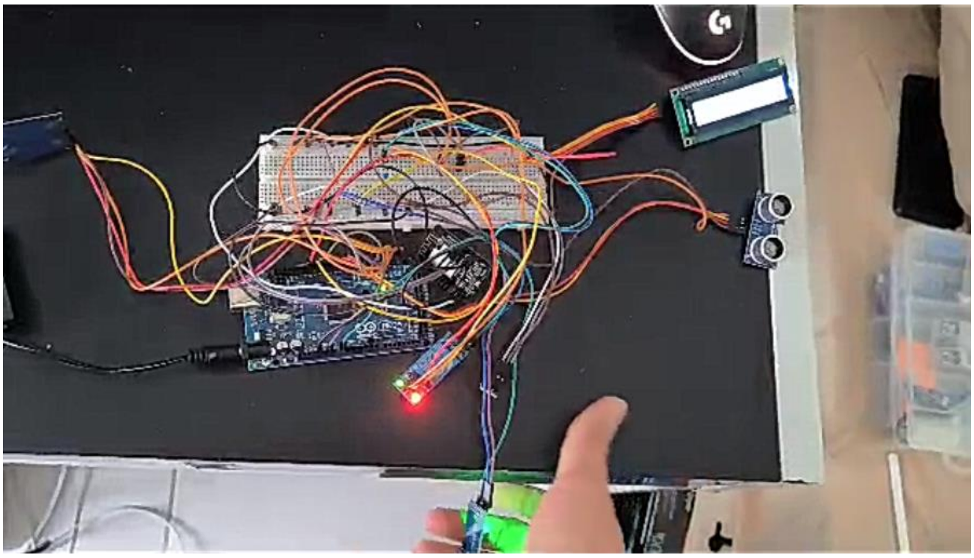

Fig. 3 Result with LDR high and no across ultrasonic sensor

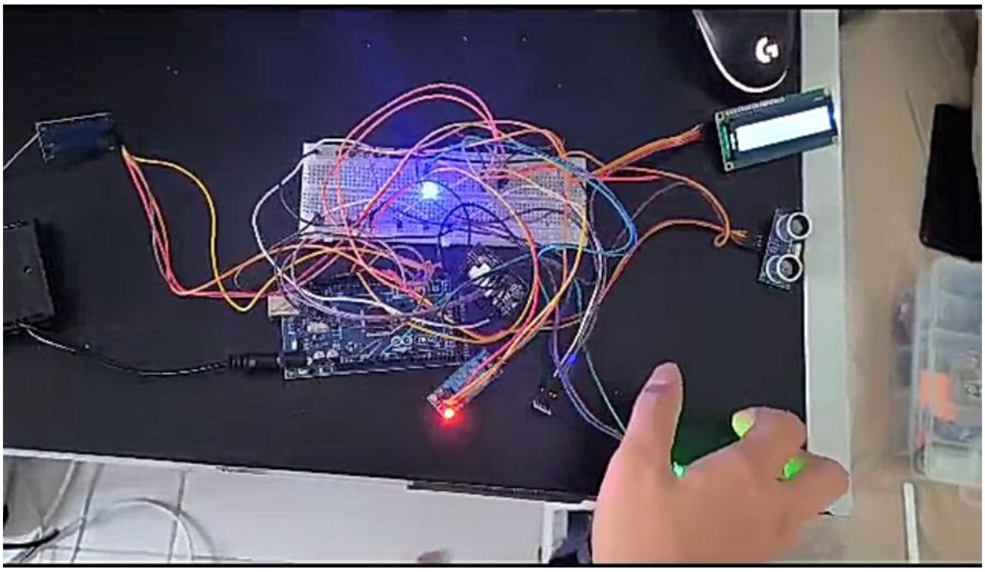

Fig. 4 Result with LDR low and across ultrasonic sensor

This system is also successful in reading the surrounding temperature, humidity, LDR value and the distance of the ultrasonic, the output as shown in Fig. 5. When the LDR value exceeds 900 (low light conditions) and the ultrasonic sensor detects an object within 50 cm, the Arduino sends a 5V signal to the relay module. The relay module activates the LED light around 5 seconds, illuminating in dark environments when necessary. Therefore, it will save energy when the road is not transportation at night or have transportation but in the morning. The LCD display will show real-time sensor readings, including temperature and current state of the surroundings and update it every seconds. If the LDR value > 900 it will show dark and LDR value <900 it will show light in the LCD. It is shown in Fig. 6.

```
09:26:01.089 -> Temp: 28.97 C, Humidity: 74.98 %, LDR: 771 Distance: 3 cm
09:26:01.288 -> Temp: 28.97 C, Humidity: 74.95 %, LDR: 773 Distance: 3 cm
09:26:01.459 -> Temp: 28.97 C, Humidity: 74.93 %, LDR: 770 Distance: 2 cm
09:26:01.659 -> Temp: 28.98 C, Humidity: 74.93 %, LDR: 772 Distance: 3 cm
09:26:01.820 -> Temp: 29.00 C, Humidity: 74.88 %, LDR: 770 Distance: 3 cm
09:26:02.012 -> Temp: 29.00 C, Humidity: 74.89 %, LDR: 771 Distance: 3 cm
09:26:02.212 -> Temp: 29.01 C, Humidity: 74.87 %, LDR: 770 Distance: 3 cm
09:26:02.372 -> Temp: 29.01 C, Humidity: 74.87 %, LDR: 770 Distance: 3 cm
```

Fig. 5 Arduino IDE Output System Smart Streetlight

Fig. 6 Display temperature detect

3.2 Development of an Intelligent Real-life Accident Detection System Using a Machine Learning Model

The accident detection system was developed using a machine learning model trained on 1,807 images. The dataset included accident and non-accident scenarios, labelled appropriately for binary classification labels by accident and car. The YOLOv8-based model was trained over 100 epochs, optimizing for mean Average Precision (mAP). The model is test by real time video as shown in Fig. 7 and Fig. 8.

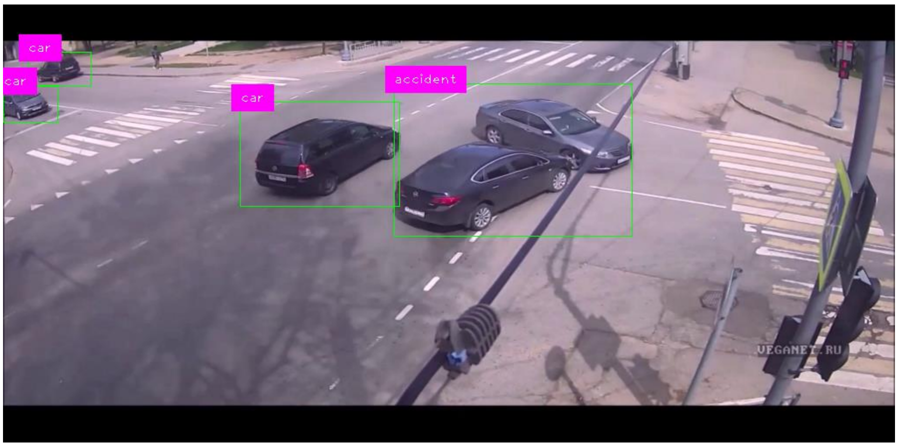

Fig. 7 Accident Detection by Video 1

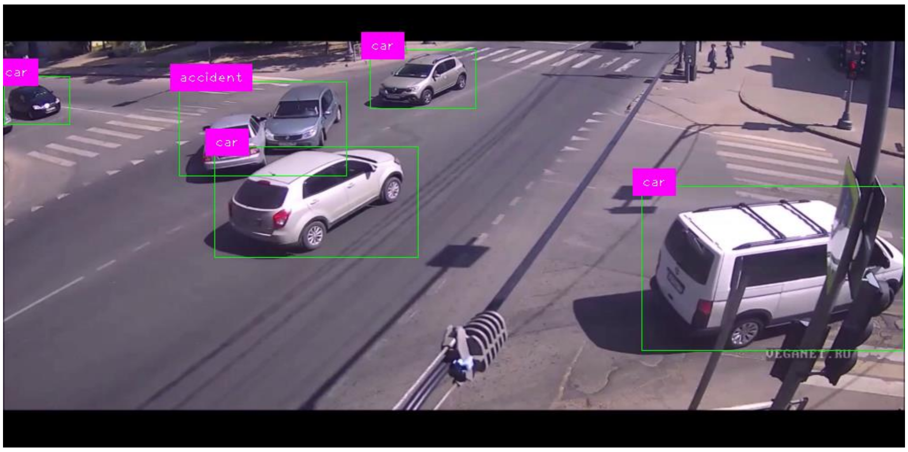

Fig. 8 Accident Detection by Video 5

After that, the ESP32 Camera was also integrated with Arduino Mega to provide real-time video for accident detection by toy cars as shown in Fig. 9 and Fig. 10.

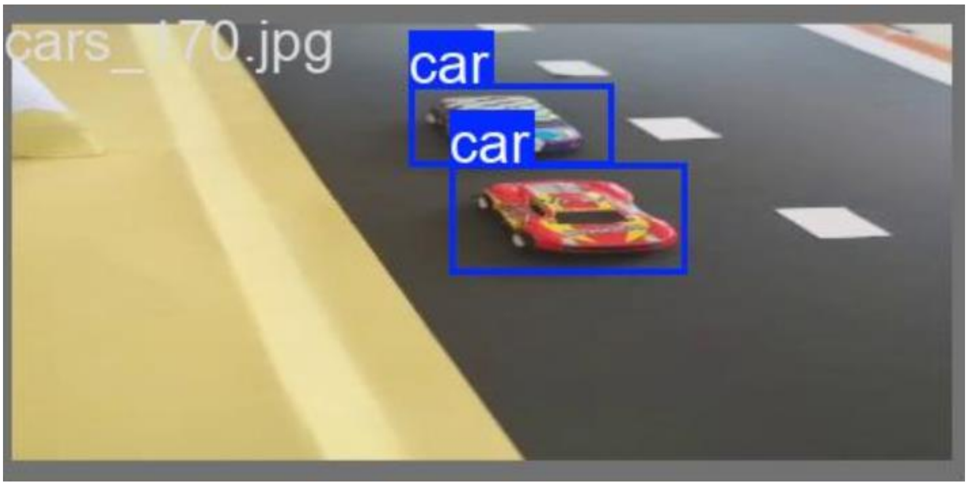

Fig. 9 Real-Time Detection With ESP32 Cam

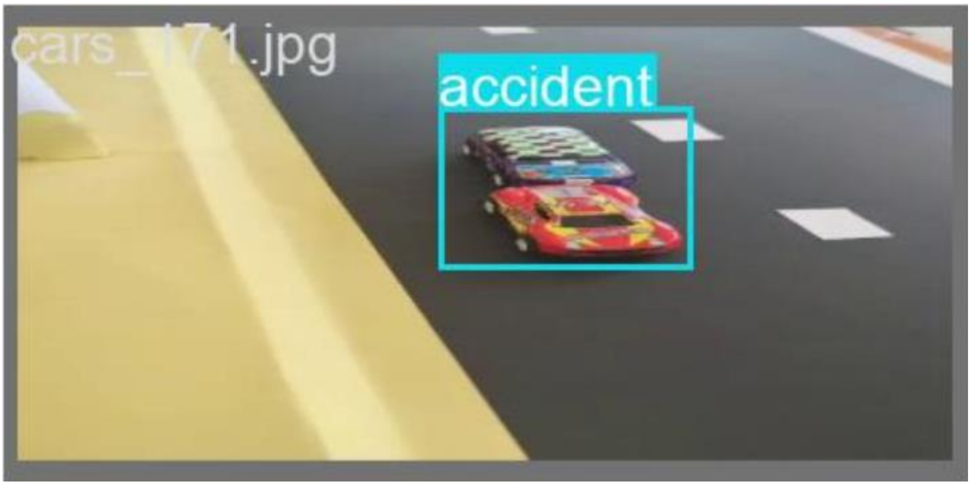

Fig. 10 Real-Time Detection With ESP32 Cam

So that it shows that the camera and the system can detect accident with truly. After that, if the accident is detected it will send to a dashboard with details such as time and date of detection and location based on GPS coordinates. The result as shown in Fig. 11 and Fig. 12.

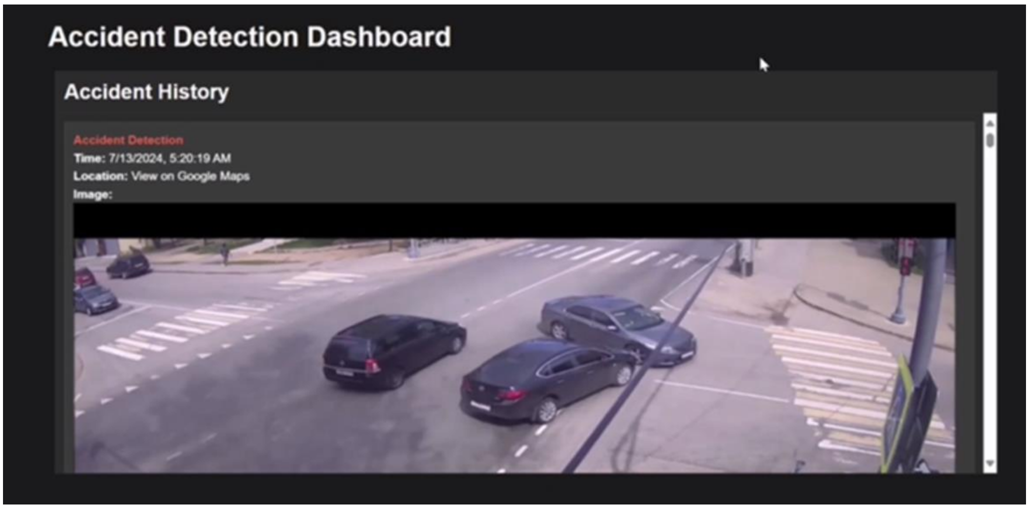

Fig. 11 Accident Detection Dashboard

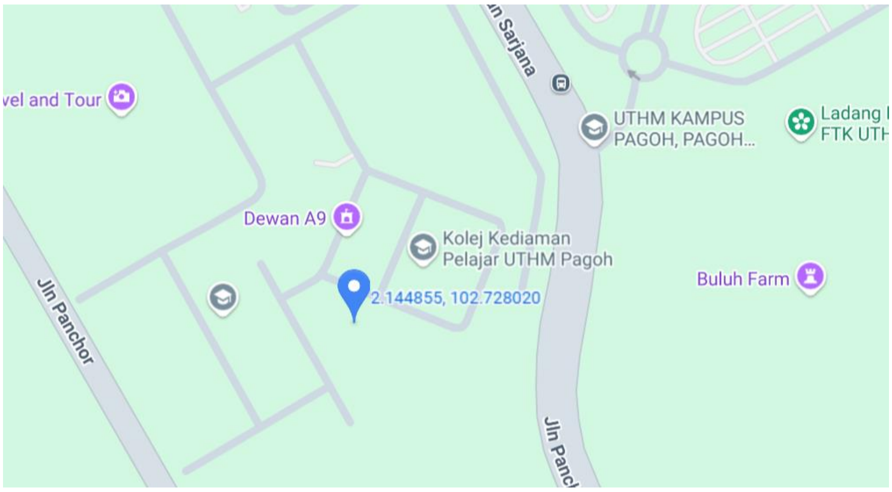

Fig. 12 Result view location

3.3 Measurement of Accident Detection Accuracy Using Real-Time Information

The accident detection system's performance was evaluated using two key metrics—mean Average Precision (mAP) at two thresholds—and testing it on real-life video scenarios. The results highlight the system's capability and limitations in detecting accidents effectively in real-time settings.

mAP Metrics and Their Significance

The model achieved the following mAP scores: **mAP@50: 0.6305** indicates that, at a confidence threshold of 50%, the model correctly identifies accidents with a precision of approximately 63%. This is a reasonably strong result, demonstrating that the model performs well in distinguishing accidents from other scenarios in relatively clear conditions. **mAP@50–95: 0.4342** reflects the average precision across confidence thresholds ranging from 50% to 95%. The lower value indicates that the model's performance decreases as the confidence threshold becomes stricter, suggesting challenges in identifying borderline cases or complex accident scenarios.

3.3.1 Real-Life Video Testing

When tested with real-life video inputs, the system correctly detected accidents in 6 out of 10 cases. However, 4 cases involved missed detection. This outcome reflects an accuracy rate of 60%. The result is shown in Fig. 13.

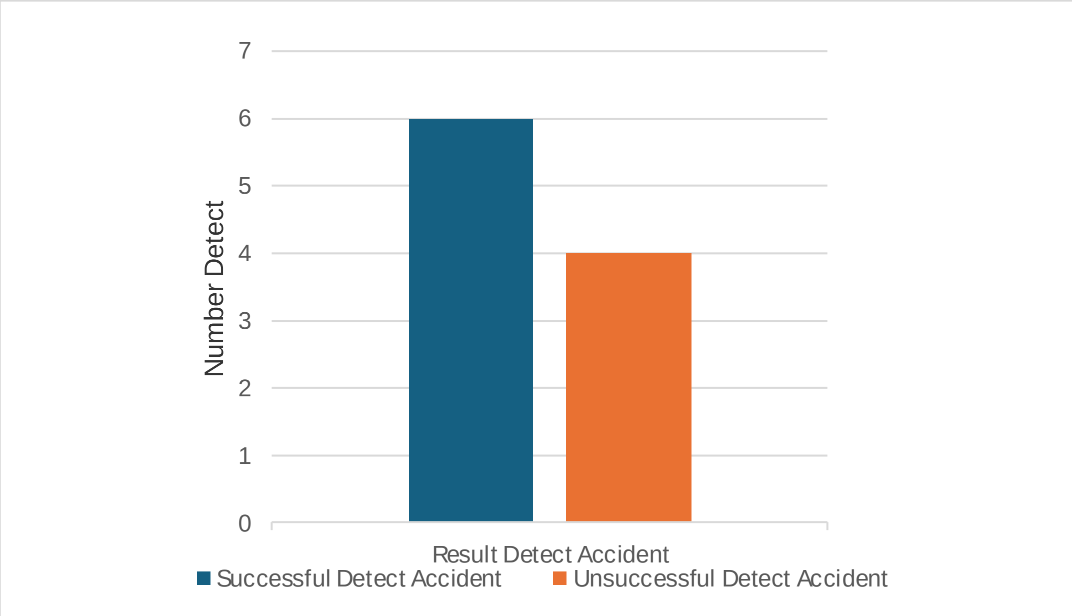

Fig. 13 Result Testing of Detection Accident

4. Conclusion

This study successfully proved the designing and implementation of Intelligent Arduino Streetlight system along with environment monitoring and accident detection. A real-time environmental monitoring system with an Arduino Mega, SHT31 temperature and humidity sensor, GL55 photoresistor, and ultrasonic sensor which showed that the system achieved its basic goals. These components worked together to control when the streetlight was turned on, based on the amount of ambient light in the vicinity and the presence of nearby objects, ensuring they were only used when needed, therefore saving electricity. Our system for detecting accidents was implemented using a machine learning model along with an ESP32 camera. The model reached mAP@50 of 63.05% (mAP@50-95 of 43.42%) with 1,807 images in training and a 60% accuracy of detecting video-based accidents: 6 out of 10 in real scenarios. Identified incidents were transmitted simultaneously to a dashboard containing date, time, and location information, allowing quick responses from emergency services. The findings demonstrate the feasibility of integrating environmental and road hazard monitoring in a single low-power Arduino system, providing insights into potential synergies between environmental sustainability and road safety in urban areas. That said, there are a number of tweaks that could improve the system. To make it more accurate, the accident detection dataset could be expanded – include more diverse representations, such as low-light condition and many things around. This would benefit by transferring to deep-learning architectures, such as Transformer-based models. This could involve cloud-based platforms for storing and analysing data, as well as monitoring it in real-time through mobile apps. Furthermore, adding solar panels provides sustainability through lower reliance on external electricity. The project, however, had its limitations, despite the success. While millimeter-level precision in the accident detection model works well for its applications, it faced challenges of complex real-world situations such as the environment, weather, population density, heavy traffic, and camera angle. Limited processing power and resolution, inaccurate detection speed, were limited by hardware, especially by ESP32 camera and Arduino Mega. Testing was primarily done in controlled conditions and with a narrow set of videos, which may not accurately capture the challenges of real-world videos. Also, dependence on specific sensors, such as the photoresistor and ultrasonic sensor, created vulnerabilities as there was no redundancy. To ensure the proposed system was accurate, reliable, and scalable for real-world deployments, these issues would need to be addressed through dataset expansion, hardware upgrades, and extensive testing in real-world environments.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Tan Tian Xian;* ***analysis and interpretation of results:*** *Tan Tian Xian, Ahmad Hassan Sallehudin Mohd Sarif;* ***draft manuscript preparation:*** *Tan Tian Xian, Ahmad Hassan Sallehudin Mohd Sarif. All authors reviewed the results and approved the final version of the manuscript.*

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