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Full Length Article

Calmnest: An IoT-Enabled Intelligent Zebra Crossing System With PIR Sensor And Camera-Based Pedestrian Counting

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Abstract:
The Smart Automated Zebra Crossing System operationalizes Passive Infrared (PIR) sensors and Internet of Things (IoT) technology with IP camera-based headcount capabilities to foster pedestrian safety. A data-driven control system protected pedestrian safety by integrating adaptive management structures and intelligent traffic methods. The system actively switches on its crossing systems only after PIR sensors detect approaching pedestrians.

Keywords: *Iot, zebra crossing, PIR Sensor, pedestrain detection, smart traffic.*

Introduction:

Rapid urbanization and the continuous growth in the number of vehicles have significantly increased the complexity of road traffic management across cities worldwide. While considerable attention has been devoted to improving vehicular traffic flow, pedestrian safety remains a major concern, particularly at unsignalized zebra crossings where pedestrians are often exposed to high accident risks. Conventional zebra crossings rely heavily on driver awareness and fixed traffic control mechanisms, which are unable to respond dynamically to real-time pedestrian movement. Consequently, there is a growing demand for intelligent pedestrian crossing systems capable of adapting to changing traffic conditions while ensuring safe and efficient road usage. Recent advancements in the Internet of Things (IoT) have created new opportunities for developing smart transportation infrastructures that integrate sensing technologies, real-time communication, and automated decision-making to improve pedestrian safety and traffic efficiency **[1]**.

The emergence of smart city initiatives has accelerated the adoption of IoT-based intelligent transportation systems that combine embedded sensors, cloud connectivity, and automated control algorithms. These systems continuously monitor road environments, collect real-time traffic information, and enable adaptive responses based on prevailing traffic conditions. Unlike conventional traffic management systems, IoT-enabled infrastructures facilitate seamless communication between sensing devices and traffic control units, allowing rapid decision-making with minimal human intervention. Such intelligent frameworks have demonstrated considerable potential in reducing traffic congestion, minimizing delays, and enhancing the overall safety of pedestrians and motorists **[1]**.

Pedestrian crossings require special attention because pedestrians are among the most vulnerable road users. Traditional signalized crossings generally operate using predefined timing intervals regardless of whether pedestrians are actually present. This fixed-time operation often results in unnecessary traffic delays or insufficient crossing time during periods of heavy pedestrian movement. Intelligent pedestrian crossing systems overcome these limitations by incorporating sensing technologies that detect pedestrian presence and activate crossing signals only when required. Smart vehicle crossing systems have demonstrated that adaptive signal control improves traffic efficiency while simultaneously enhancing pedestrian protection **[2]**.

Passive Infrared (PIR) sensors have become one of the most widely adopted sensing technologies for detecting human movement because of their low power consumption, affordability, reliability, and ease of deployment. PIR sensors identify variations in infrared radiation emitted by the human body, making them suitable for outdoor pedestrian detection under varying environmental conditions. When integrated with IoT-enabled controllers, PIR sensors provide immediate activation of pedestrian crossing mechanisms only upon detecting human presence, thereby reducing unnecessary signal activation and improving overall operational efficiency.

Although PIR sensors effectively detect pedestrian presence, they cannot estimate the number of pedestrians waiting to cross. Recent developments in computer vision and intelligent image processing have addressed this limitation through camera-based pedestrian counting systems. Image processing algorithms combined with deep learning techniques can accurately estimate pedestrian density by identifying and counting human heads or body features captured through IP cameras. Such information enables adaptive allocation of pedestrian crossing duration according to the actual crowd size, thereby improving both safety and traffic flow.

The integration of IoT communication, PIR sensing, and vision-based pedestrian analytics forms the foundation of next-generation intelligent transportation systems. These technologies collectively support dynamic decision-making by transmitting sensor information to cloud platforms or edge computing devices where real-time processing determines the most appropriate signal control strategy. Intelligent traffic light solutions developed for sustainable smart cities have demonstrated the effectiveness of combining sensing technologies with automated traffic management to enhance urban mobility while reducing congestion and improving pedestrian safety **[3]**.

Motivated by these technological advancements, this research proposes **Calmnest**, an IoT-enabled intelligent zebra crossing system that combines PIR sensor-based pedestrian detection with camera-based pedestrian counting to provide adaptive crossing control. The proposed system activates pedestrian signals only when required and dynamically adjusts crossing duration based on the number of pedestrians detected by the IP camera. By integrating low-cost sensors, IoT communication, and intelligent traffic control, the proposed framework aims to improve pedestrian safety, reduce unnecessary traffic interruptions, and contribute to the development of safer and smarter urban transportation infrastructure.

Literature Review:

Javaid et al. proposed an Internet of Things (IoT)-based smart traffic management system that integrated sensor networks and communication technologies to improve traffic flow and minimize congestion in urban areas. Their work demonstrated that real-time data acquisition from distributed sensing devices enables intelligent traffic control decisions, resulting in more efficient utilization of road infrastructure. The study established the importance of IoT architecture in developing adaptive transportation systems and highlighted its potential to improve pedestrian and vehicular safety through automated monitoring and control. **[1]**

Singh et al. introduced the Signaling and Vehicle Crossing with Smart Intelligent System (SVCSIS), which focused on improving road safety through intelligent traffic signal management. The proposed system utilized automated signal control mechanisms to regulate vehicle movement while reducing traffic conflicts at intersections. Their research emphasized that intelligent crossing systems can significantly enhance transportation efficiency by minimizing unnecessary waiting times and providing safer crossing opportunities for pedestrians. **[2]**

Jafari et al. presented an intelligent traffic light solution designed for sustainable smart cities by integrating modern sensing technologies with adaptive traffic signal control. Their work demonstrated that intelligent traffic management systems can dynamically respond to varying traffic conditions while improving energy efficiency and reducing congestion. The study further highlighted the role of automation in enhancing pedestrian safety and supporting environmentally sustainable urban transportation. **[3]**

Recent researchers in IoT-enabled transportation systems have emphasized that wireless sensor networks, cloud connectivity, and embedded controllers provide the technological foundation for intelligent traffic infrastructures. These studies indicate that IoT platforms enable continuous communication between field devices and centralized monitoring systems, allowing traffic signals to operate dynamically according to real-time traffic conditions rather than relying on fixed schedules. Such adaptive operation contributes significantly to safer and more efficient pedestrian crossing management. **[4]**

Researchers investigating computer vision-based pedestrian detection have demonstrated that camera-based monitoring systems can accurately identify pedestrians under diverse environmental conditions using deep learning and image processing algorithms. These intelligent vision systems provide higher detection accuracy than conventional motion sensors and can distinguish between pedestrians, vehicles, and surrounding objects, thereby improving decision-making in smart transportation applications. **[5]**

Studies focusing on PIR sensor applications have reported that Passive Infrared sensors offer an economical and reliable solution for detecting human presence in outdoor environments. Their low power consumption, simple hardware implementation, and rapid response characteristics make them suitable for intelligent pedestrian crossing systems where signal activation depends on actual pedestrian movement. The integration of PIR sensors with embedded microcontrollers further enhances automation while reducing unnecessary traffic signal operations. **[6]**

Researchers working on edge computing for intelligent transportation have highlighted the advantages of processing traffic data close to the sensing devices instead of relying entirely on cloud infrastructure. Edge computing significantly reduces communication latency, enabling real-time pedestrian detection and immediate signal control decisions. Such decentralized processing improves system responsiveness, reliability, and scalability in densely populated urban traffic environments. **[7]**

Vision-based pedestrian counting researchers have demonstrated that intelligent image analysis techniques can estimate pedestrian density by detecting individual heads or body features captured through surveillance cameras. Unlike simple motion detection, pedestrian counting enables adaptive allocation of crossing time according to the number of people waiting to cross. This capability improves pedestrian convenience while maintaining efficient traffic flow on busy urban roads. **[8]**

Researchers developing IoT-enabled smart pedestrian crossing systems have integrated sensing technologies, wireless communication, and automated traffic controllers to create intelligent crossing infrastructures capable of responding dynamically to pedestrian requests. These systems reduce unnecessary signal activation, improve crossing efficiency, and contribute to safer urban mobility by combining real-time sensing with adaptive traffic management algorithms. **[9]**

Recent studies on intelligent pedestrian safety systems have explored the integration of PIR sensors, IP cameras, artificial intelligence, and IoT communication into unified smart transportation platforms. These integrated systems perform pedestrian detection, crowd estimation, and adaptive signal control simultaneously, thereby offering a comprehensive solution for enhancing pedestrian safety while minimizing traffic congestion. Such research provides a strong technological foundation for the proposed **Calmnest** intelligent zebra crossing system. **[10]**

Calmnest: IOT Based Smart Cradle Using Controller BLE Sense

Calmnest An IoT-enabled intelligent zebra crossing system that integrates PIR sensors and camera-based pedestrian counting represents a modern approach to improving pedestrian safety and traffic efficiency. In traditional systems, zebra crossings operate on fixed timing or require manual input, which often fails to respond effectively to real-time pedestrian needs.

PIR sensors play an important role in these systems by detecting the presence of pedestrians based on body heat. They are widely used because they are cost-effective, consume very little power, and are easy to install. When a pedestrian approaches the crossing, the PIR sensor quickly identifies motion and sends a signal to the control unit. However, while PIR sensors are efficient for detection, they cannot accurately determine the number of pedestrians, especially in crowded situations, and may sometimes be affected by environmental conditions

Proposed System:

The proposed smart automated zebra crossing system uses PIR (Passive Infrared) sensors to detect pedestrian presence, an IoT-based control system to manage crossing signals, and an IP camera for real-time headcount. This data is processed to intelligently control traffic lights and alert vehicles, improving pedestrian safety and traffic efficiency. By integrating these technologies, the system provides a responsive, automated solution that enhances road safety and optimizes traffic flow d user-friendly solution.

The proposed smart pedestrian crossing system consists of an input block, a microcontroller, IoT connectivity, and output control units. The input block gathers real-time information from multiple sensors and devices, including a camera, PIR sensor, object sensor, and GPS module. The camera captures live images and video of the zebra crossing, enabling pedestrian detection and counting through image processing techniques. The PIR (Passive Infrared) sensor detects human presence based on body heat and helps identify when pedestrians arrive at the crossing. The object sensor is used to detect nearby vehicles, pedestrians, or obstacles, thereby enhancing safety and supporting efficient traffic signal control. The GPS module provides the geographical location of the system, allowing location tracking and monitoring of multiple crossings through IoT-based communication. All sensor data are transmitted to the microcontroller, which acts as the central processing unit of the system. The microcontroller analyzes the collected information, makes decisions regarding pedestrian crossing requests, and generates appropriate control signals. Through IoT connectivity, system data such as pedestrian counts, crossing status, and operational information are transmitted to the cloud for remote monitoring, analysis, and management. The processed outputs are then used to control traffic signals, including red and green lights, as well as alerts and indicators, ensuring safe and efficient pedestrian movement.

Block diagram:

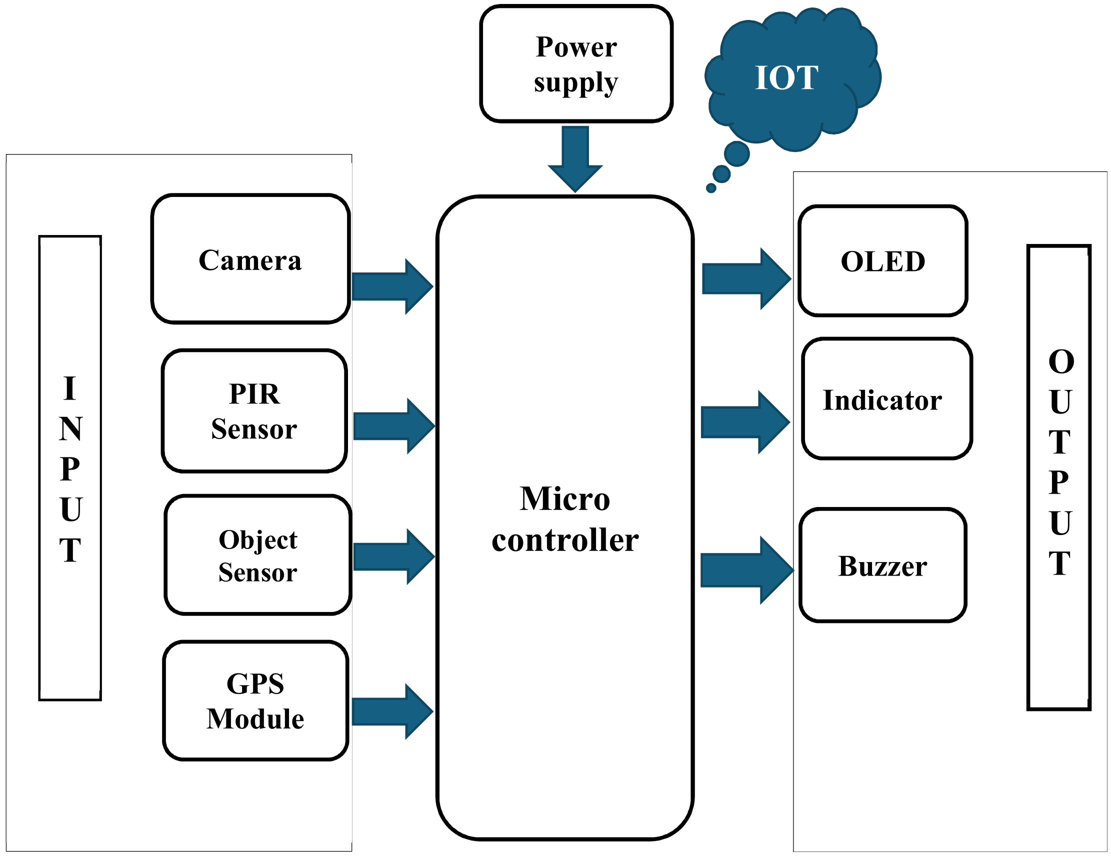

Fig 1; Block diagram

Working Process of the Proposed System

The proposed **Calmnest: An IoT-Enabled Intelligent Zebra Crossing System with PIR Sensor and Camera-Based Pedestrian Counting** is designed to improve pedestrian safety by integrating sensing technologies, image processing, and Internet of Things (IoT) communication. The system continuously observes the pedestrian crossing area and automatically manages the crossing operation whenever pedestrians are detected. Unlike conventional zebra crossings that operate with fixed timing or require manual intervention, the proposed system responds dynamically to real-time pedestrian activity. The complete operational sequence is described below.

Step 1: System Initialization

The operation begins when electrical power is supplied to the system. The regulated power supply energizes all hardware components, including the microcontroller, PIR sensor, IP camera, object sensor, GPS module, OLED display, buzzer, and indicator LEDs. During initialization, the microcontroller verifies the operational status of each connected device and establishes communication with the IoT platform through a wireless network. This initialization ensures that every module is functioning correctly before monitoring begins. The IoT connection enables remote supervision, data storage, and system diagnostics while supporting future analytical applications **[1]**.

Step 2: Continuous Pedestrian Monitoring

After initialization, the PIR sensor continuously monitors the zebra crossing area for pedestrian movement. The PIR sensor detects changes in infrared radiation produced by the human body. Whenever a pedestrian enters the sensing range, the sensor immediately transmits a detection signal to the microcontroller. Since the PIR sensor consumes very little power and responds quickly, it provides an efficient solution for continuous pedestrian monitoring without unnecessary energy consumption **[6]**.

Step 3: Camera-Based Pedestrian Counting

Once the pedestrian presence is confirmed, the IP camera is activated to capture images or short video sequences of the crossing area. The captured frames are processed using computer vision algorithms to identify individual pedestrians and estimate the total number of people waiting to cross. Head-counting techniques reduce counting errors caused by overlapping pedestrians and provide accurate crowd estimation even during moderate pedestrian traffic. This information enables the system to allocate an appropriate crossing duration based on the actual pedestrian demand rather than using predetermined timing intervals **[5]**.

Step 4: Decision-Making by the Microcontroller

The microcontroller receives data from both the PIR sensor and the camera module before making an operational decision. If no pedestrians are detected, the system remains in monitoring mode without interrupting vehicular traffic. However, when one or more pedestrians are identified, the controller initiates the pedestrian crossing sequence. The duration of the crossing signal is determined according to the number of pedestrians detected by the camera. A larger pedestrian group receives additional crossing time, whereas a smaller group is provided with a shorter but sufficient crossing interval. This adaptive approach improves traffic efficiency while ensuring pedestrian safety **[2]**.

Step 5: Traffic Control and Output Activation

After the decision-making process is completed, the controller activates the output devices. The OLED display presents informative messages such as *"Pedestrian Crossing Active"* or *"Please Wait."* Simultaneously, the traffic indicator changes to stop approaching vehicles and allow pedestrians to cross safely. The buzzer generates audible alerts that assist visually impaired individuals by indicating when it is safe to cross the road. Together, these output devices provide visual and audio guidance, making the crossing safer and more accessible for all pedestrians **[3]**.

Step 6: Vehicle Monitoring During Crossing

While pedestrians are crossing the road, the object sensor continuously monitors the crossing zone for approaching vehicles. If a vehicle attempts to enter the crossing area during the pedestrian phase, the system immediately detects its presence. Depending on the programmed control logic, the controller may generate an alert, extend the pedestrian crossing duration, or maintain the stop signal until the crossing area becomes safe. This additional monitoring layer further minimizes the possibility of pedestrian-vehicle collisions and enhances overall road safety **[7]**.

Step 7: IoT-Based Data Communication

Throughout the crossing operation, important operational data are transmitted to the IoT cloud platform. The uploaded information includes pedestrian count, crossing status, GPS location, activation time, and system health information. Cloud connectivity allows traffic authorities to monitor multiple zebra crossings remotely, maintain historical records, and analyze pedestrian movement patterns for future traffic planning. The stored information can also be used to evaluate crossing performance and support predictive maintenance of the installed infrastructure **[4]**.

Step 8: Crossing Completion and System Reset

When the allocated crossing time expires, the controller terminates the pedestrian crossing sequence. The pedestrian indicator and buzzer are switched off, while the vehicle traffic signal returns to its normal operating state. The OLED display updates the current system status, and the IoT platform records the completion of the crossing event. Finally, the controller resets all temporary variables and returns the system to continuous monitoring mode, allowing the next pedestrian request to be processed automatically **[9]**.

Step 9: Continuous Intelligent Operation

The entire process operates continuously without requiring manual supervision. Each time a pedestrian approaches the zebra crossing, the sensing, counting, decision-making, and traffic control sequence is repeated automatically. The integration of PIR sensing, camera-based pedestrian counting, IoT communication, and adaptive traffic management enables the proposed **Calmnest** system to provide reliable, efficient, and intelligent pedestrian crossing control. This coordinated operation reduces unnecessary vehicle delays, improves pedestrian safety, and supports the development of sustainable smart city transportation infrastructure **[10]**.

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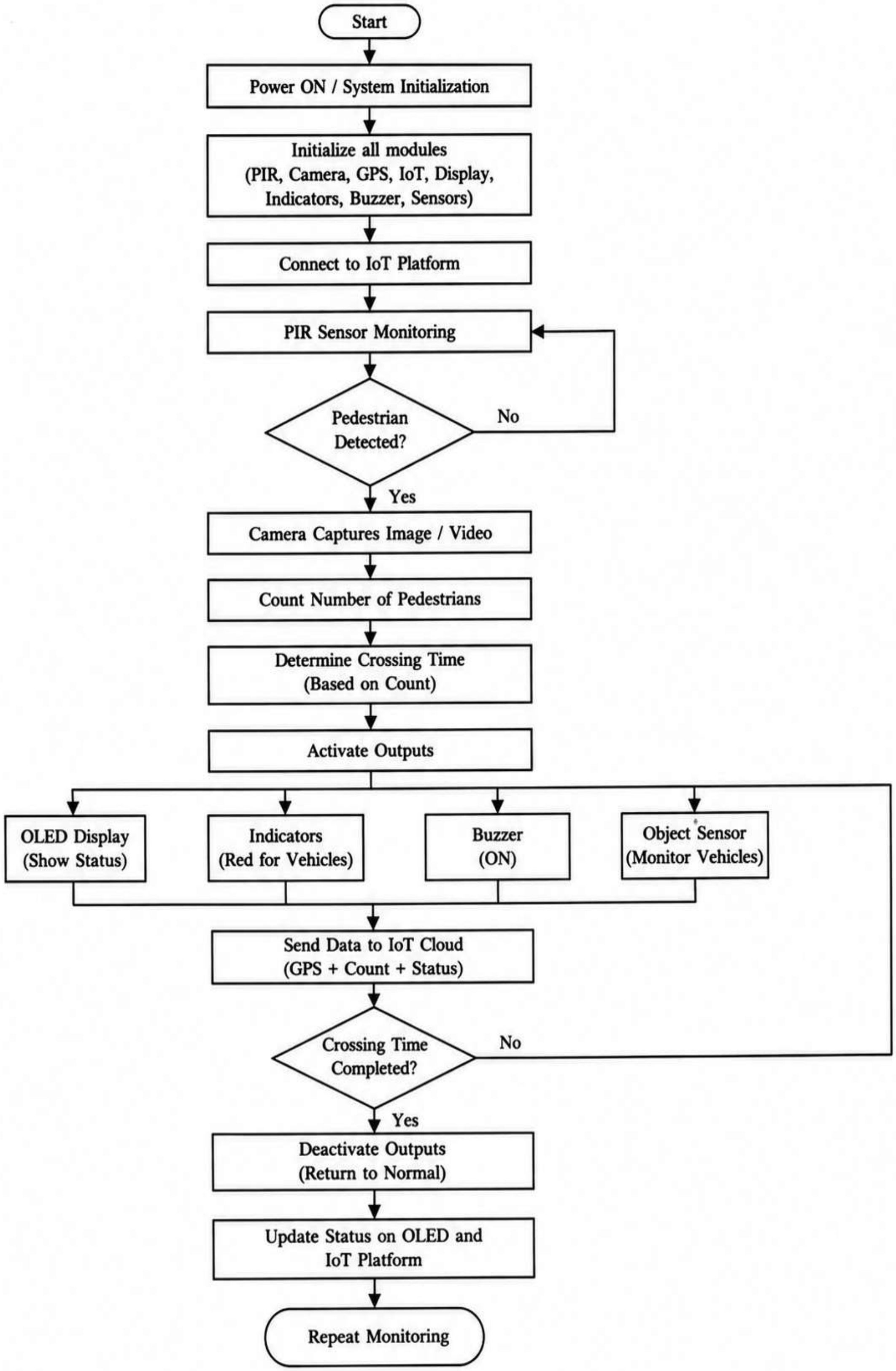

Figure 2 : Working Process

Schematic Diagram:

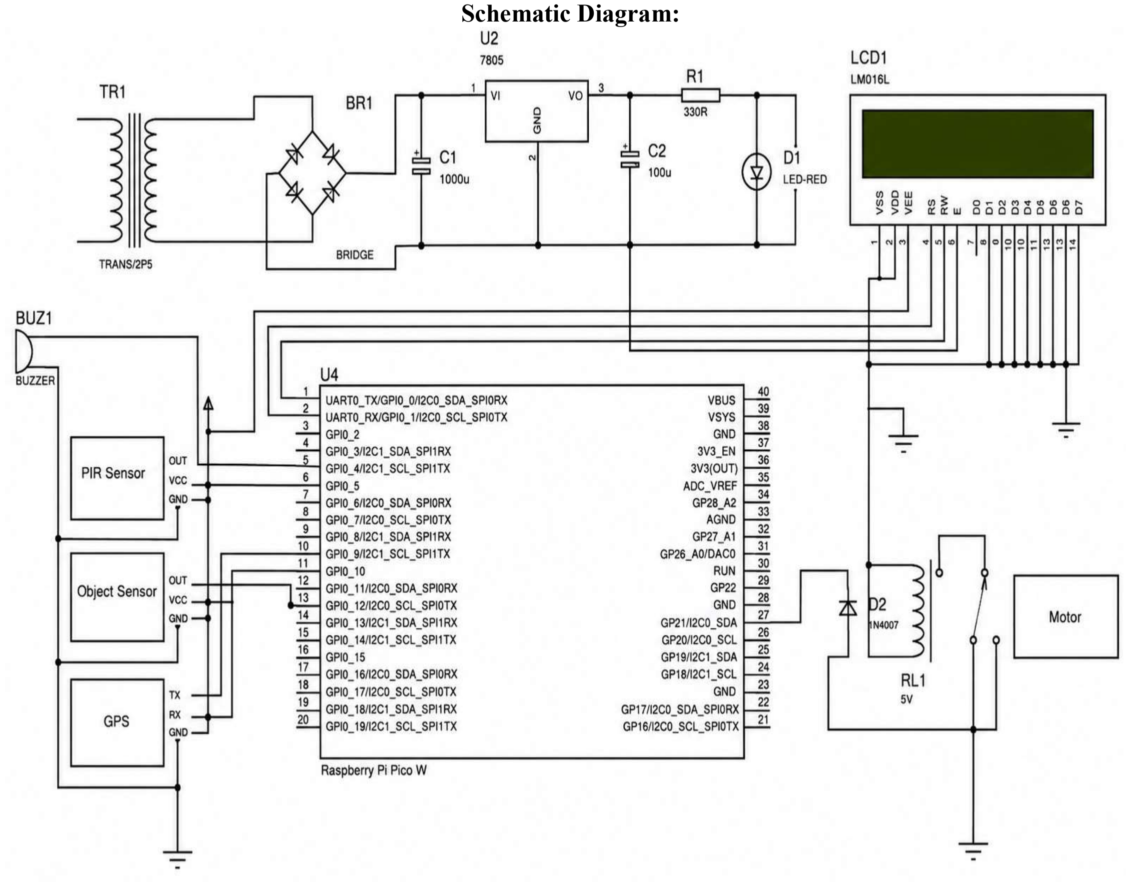

Figure 3: Schematic diagram

Result:

The proposed IoT-enabled intelligent zebra crossing system with PIR sensor and camera-based pedestrian counting successfully improves pedestrian safety and traffic efficiency by enabling real-time, automated signal control. The integration of the PIR sensor ensures reliable detection of pedestrian presence, while the camera module provides accurate pedestrian counting for dynamic signal timing based on crowd density.

The system effectively reduces waiting time for pedestrians and minimizes unnecessary traffic delays by adapting signal changes according to actual road conditions. The microcontroller processes sensor data efficiently and controls the traffic lights in real time, ensuring safe crossing operations.

Outputs:

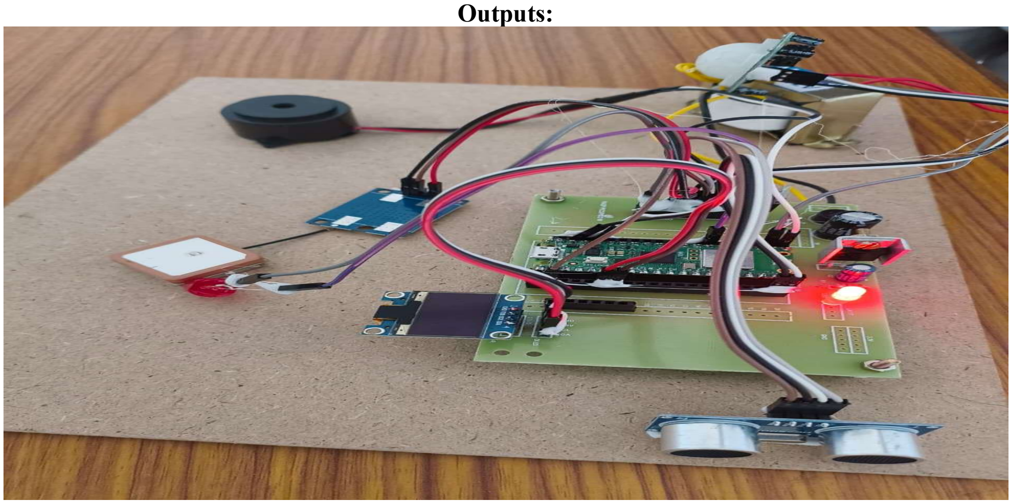

Figure 4: Hard ware kit

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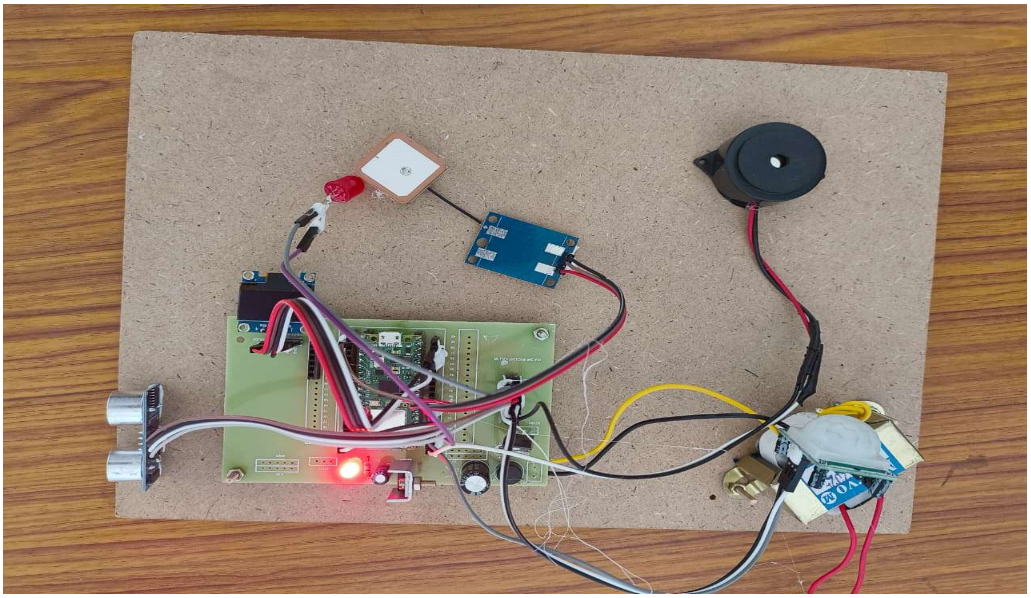

Figure 5: Hardware kit ON state

Figure 6: Outputs on OLED

Conclusion:

The IoT-enabled intelligent zebra crossing system with PIR sensor and camera-based pedestrian counting provides an effective solution for improving pedestrian safety and traffic management. By integrating multiple sensing technologies with IoT, the system enables real-time detection of pedestrians and adaptive control of traffic signals based on actual demand.This reduces the limitations of traditional fixed-timing zebra crossings, such as unnecessary vehicle delays and unsafe pedestrian crossing conditions. The use of PIR sensors ensures quick detection of human presence, while camera-based counting improves accuracy in assessing pedestrian density.

Future Scope:

An IoT-enabled intelligent zebra crossing system integrating PIR sensors and camera-based pedestrian counting has strong potential for future development in smart urban mobility.

In the future, the system can be enhanced using advanced AI and computer vision to detect pedestrians more accurately.

It can be extended to identify cyclists, elderly individuals, and people with disabilities for more inclusive crossing control.

Adaptive signal timing can be improved based on different user needs and safety priorities.

Integration with smart traffic management systems can enable centralized and efficient control of road networks.

Vehicle-to-Infrastructure (V2I) communication can allow direct interaction between traffic signals and connected vehicles.
This can improve response time and significantly reduce road accidents.
Real-time cloud connectivity and data analytics can help monitor pedestrian movement patterns.
Traffic authorities can use this data to optimize traffic flow and urban planning decisions. component of smart city ecosystems, significantly enhancing pedestrian safety, efficiency, and urban planning.

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