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Intelligent Power Management System Using AI for Optimized Energy Efficiency

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***Abstract*— Energy optimization in indoor environments has become a significant challenge due to the increasing use of electrical appliances and the limitations of conventional automation systems. Traditional power management approaches based on manual operation, timers, or motion sensors often fail to adapt to real-time occupancy and environmental conditions, leading to unnecessary energy consumption. This paper presents an AI-based Intelligent Power Management System that integrates computer vision with multi-sensor data to achieve context-aware automation. The proposed system utilizes the YOLO (You Only Look Once) object detection algorithm to detect human presence in real time and combines it with environmental sensors such as a Light Dependent Resistor (LDR), temperature and humidity sensor, and ultrasonic sensor through an ESP32 microcontroller. Based on the fusion of visual and sensor inputs, the system intelligently controls lighting and fan operation to optimize energy usage while maintaining user comfort. Experimental evaluation demonstrates accurate human detection, reliable automation, reduced false triggering, and improved energy efficiency, making the system suitable for smart home and intelligent building applications.**

***Keywords*— Intelligent Power Management, Computer Vision, YOLO, Smart Home Automation, ESP32, Energy Efficiency.**

I. Introduction

The rapid growth of smart infrastructure and increasing demand for electricity have intensified the need for energy-efficient power management solutions. In many residential and commercial buildings, electrical devices such as lights and fans are often left operational even when spaces are unoccupied, resulting in significant energy wastage. Conventional automation systems rely on manual switches, fixed timers, or basic motion sensors, which provide limited adaptability and intelligence [1]. Motion-based sensors such as Passive Infrared (PIR) sensors are prone to false triggering caused by environmental heat variations, pets, or background movements. Timer-based systems operate on predefined schedules and cannot respond dynamically to real-time occupancy or changing environmental conditions.

These limitations highlight the necessity for intelligent systems capable of accurately detecting human presence and adapting to contextual factors such as lighting, temperature, and proximity [2].

Recent advancements in Artificial Intelligence (AI), computer vision, and IoT technologies enable the development of smart automation systems with higher accuracy and autonomy. Vision-based human detection using deep learning models such as YOLO offers superior performance compared to traditional sensor-based methods. When combined with environmental sensing, such systems can make informed decisions that balance energy efficiency and user comfort. This research proposes an AI-driven intelligent power management system that integrates computer vision with multi-sensor fusion to overcome the shortcomings of conventional automation approaches [3].

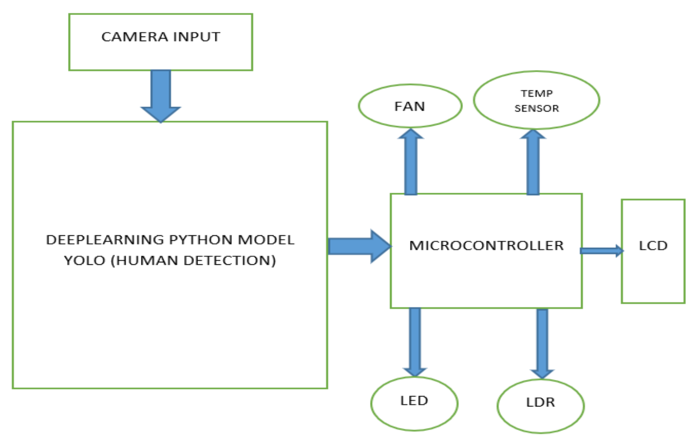

Figure 1. Overview of AI-Based Intelligent Power Management System

The rest of this paper is organized as follows. Section II presents a comprehensive literature survey on intelligent power management, artificial intelligence, and smart home automation systems. Section III describes the methodology adopted for integrating computer vision and multi-sensor data. The system modeling and analytical framework are discussed in Section IV, followed by implementation details in Section V.

Experimental results and discussion are presented in Section VI, while performance metrics used for evaluation are explained in Section VII. Section VIII provides detailed output observations and validation scenarios. Finally, Section IX concludes the paper, and Section X lists the references used in this study.

II. LITERATURE SURVEY

Recent advancements in smart home and intelligent building technologies have emphasized the importance of energy-efficient power management systems. Traditional energy management approaches rely on manual control, fixed schedules, or simple sensor-based automation, which often result in inefficient energy usage. To overcome these limitations, researchers have explored Artificial Intelligence (AI), Internet of Things (IoT), and data-driven techniques for intelligent energy optimization.

Ahmed et al. investigated the role of advanced energy management technologies in cyber-resilient smart homes, highlighting how intelligent monitoring and automation can significantly improve energy efficiency and sustainability in urban environments [1]. Their study emphasizes the integration of smart sensing and control mechanisms to reduce unnecessary power consumption while maintaining system reliability.

Khan et al. proposed a transfer reinforcement learning framework for smart home energy management systems, where AI models dynamically adapt to changing user behavior and environmental conditions [2]. Although reinforcement learning improves long-term energy optimization, the approach requires extensive training data and computational resources, making real-time deployment challenging in low-cost embedded systems.

Another study by Khan et al. reviewed the combined use of Artificial Intelligence and blockchain technology for secure smart grid and power distribution automation [3]. The authors demonstrated that AI-based decision-making improves energy distribution efficiency; however, their work primarily focuses on grid-level automation rather than indoor, room-level energy management.

Patel and Shah presented an IoT-based smart home automation system using machine learning techniques to enhance energy efficiency [4]. Their work showed improved appliance control based on sensor data, but the system relied mainly on environmental sensing and lacked accurate human presence detection, which can lead to false triggering.

Rashid and Singh developed an IoT-based smart home automation system using sensors and actuators to control appliances automatically [5].

While the system achieved basic automation, it depended on conventional motion and threshold-based sensors, limiting its ability to distinguish actual human presence from background movement.

With the emergence of computer vision, object detection algorithms such as YOLO have gained significant attention for real-time applications. Redmon et al. introduced the YOLO algorithm, which performs object detection as a single regression problem, enabling fast and accurate detection suitable for real-time systems [6]. YOLO's ability to detect humans reliably makes it a strong candidate for occupancy-based automation.

Wang et al. explored intelligent monitoring and control of power systems using AI techniques, demonstrating improved system performance and adaptive control capabilities [7]. Similarly, Zhao et al. provided a comprehensive overview of AI applications in power electronics, highlighting how machine learning enhances efficiency, fault detection, and control strategies [8]. However, these studies primarily address large-scale power systems rather than localized indoor energy management.

From the literature, it is evident that while AI and IoT-based energy management systems have shown promising results, many existing solutions either lack accurate real-time human detection or do not effectively integrate vision-based methods with environmental sensing. This research addresses these gaps by combining YOLO-based human detection with multi-sensor fusion to achieve a cost-effective, real-time, and context-aware Intelligent Power Management System.

III. METHODOLOGY

The methodology adopted in this research combines AI-based computer vision with sensor-driven environmental monitoring to enable intelligent power management. The system follows a structured workflow that begins with real-time video acquisition and ends with automated control of electrical appliances based on fused inputs.

The camera continuously captures live video frames, which are processed using the YOLO object detection algorithm to identify human presence. In parallel, the ESP32 microcontroller collects real-time data from multiple sensors, including an LDR for ambient light measurement, a temperature and humidity sensor for environmental monitoring, and ultrasonic sensor for proximity detection. As shown in below Figure 2 presents the UML representation of the proposed system, clearly depicting the interaction between the vision module, sensor module, ESP32 controller, and actuator components.

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This diagram highlights the logical flow of data from human detection and sensor acquisition to decision-making and device control.

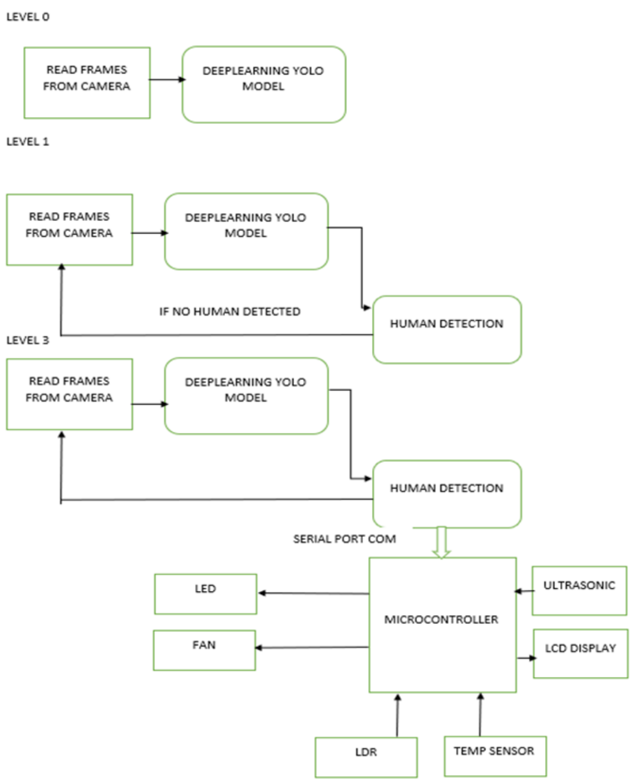

Figure 2. UML Representation of the Proposed Intelligent Power Management System

A. Human Detection Using YOLO

YOLO is a real-time object detection algorithm that formulates object detection as a single regression problem. It predicts bounding boxes and class probabilities directly from full images, enabling fast and accurate detection. In the proposed system, YOLO is trained to detect the "person" class, ensuring that automation decisions are triggered only when a human is present [4]. As illustrated in below Figure 3, the YOLO-based detection architecture processes the input image through multiple convolutional layers to extract spatial features and predict bounding boxes along with class probabilities, enabling real-time and accurate human detection.

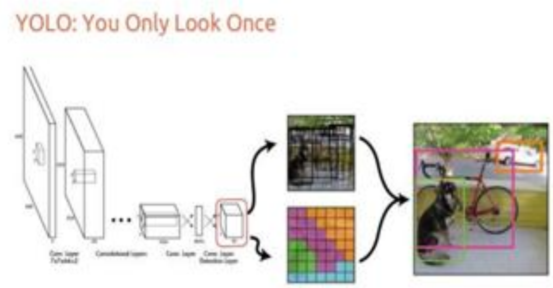

Figure 3. YOLO-Based Human Detection Model Architecture

B. Sensor-Based Environmental Monitoring

The LDR sensor measures ambient light intensity to determine whether the room is dark or bright. Temperature and humidity sensors monitor environmental comfort levels, while the ultrasonic sensor measures the distance between the user and the system. These sensor readings provide contextual awareness required for intelligent decision-making [1], [2].

IV. Modeling & Analysis

The proposed system model integrates computer vision outputs with sensor data to control electrical appliances intelligently. The ESP32 microcontroller acts as the central processing unit, coordinating communication between the Python-based AI module and hardware components.

A. System Architecture

The architecture consists of four main layers: a vision layer for human detection, a sensor layer for environmental data acquisition, a processing layer for decision-making, and an actuation layer for device control. This layered architecture ensures modularity, scalability, and reliable system operation.

The architecture consists of four layers:

1. *Vision Layer:* Captures video and detects human presence using YOLO
2. *Sensor Layer:* Collects environmental data (light, temperature, humidity, proximity)
3. *Processing Layer:* ESP32 processes fused inputs
4. *Actuation Layer:* Controls lights, LEDs, fan, and LCD display

B. YOLO Grid and Bounding Box Modeling

YOLO divides the input image into a grid of equal-sized cells, where each cell is responsible for detecting objects whose center lies within it. Each grid cell predicts bounding box coordinates, confidence scores, and class probabilities. As illustrated in below Figure 4 demonstrates the grid-based division of the input image used by the YOLO algorithm, where the image is split into equal-sized cells, each responsible for predicting object presence and bounding box parameters.

Figure 4. Image Grid Division Used in YOLO Object Detection

Bounding box regression predicts the width, height, and center of detected objects. This enables precise localization of humans within the frame. As shown in Figure 5, YOLO performs bounding box regression to predict the precise location of detected humans by estimating the width, height, and center coordinates of bounding boxes within each grid cell.

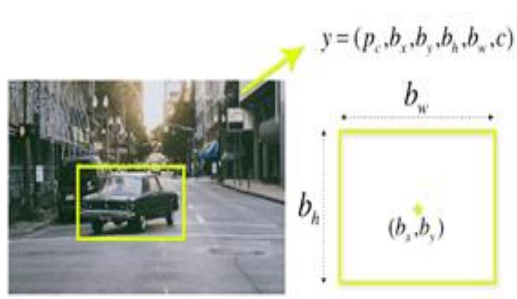

Figure 5. Bounding Box Regression in YOLO for Human Detection

C. Intersection over Union (IoU)

Intersection over union (IOU) is a phenomenon in object detection that describes how boxes overlap. YOLO uses IOU to provide an output box that surrounds the objects perfectly. Each grid cell is responsible for predicting the bounding boxes and their confidence scores. The IOU is equal to 1 if the predicted bounding box is the same as the real box. This mechanism eliminates bounding boxes that are not equal to the real box. As shown in below Figure 6 illustrates the concept of Intersection over Union (IoU), which quantifies the overlap between the predicted bounding box and the ground truth box. This metric is used by the YOLO model to evaluate detection accuracy and eliminate redundant or inaccurate bounding box predictions.

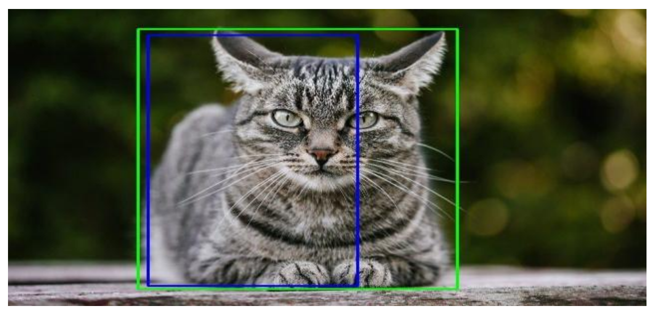

Figure 6. Intersection over Union Between Predicted and Actual Bounding Boxes

V. IMPLEMENTATION

The system implementation integrates Python-based computer vision with ESP32 firmware for sensor handling and device control. Serial communication enables real-time data exchange between the two components.

A. Software Implementation

YOLO is implemented using Python and OpenCV for real-time video processing. Pre-trained YOLO weights are used to detect the "person" class in Figure 7. Sensor data is received from the ESP32 and processed alongside vision outputs to determine control actions

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Figure 7. Object Classes Used for YOLO-Based Detection

B. Hardware Components

Table I

Component	Description
ESP32 Microcontroller	Central control and communication unit
Camera	Real-time video capture for YOLO
LDR Sensor	Ambient light detection
DHT11/DHT22	Temperature and humidity sensing
Ultrasonic Sensor	Proximity detection
LEDs	Intelligent lighting control
DC Fan	Automatic thermal regulation
LCD Display	Real-time system status display

VI. RESULTS & DISCUSSION

The results demonstrate that the proposed Intelligent Power Management System accurately detects human presence using the YOLO model and responds in real time. Lighting and fan operations are correctly controlled based on ambient light, temperature, and proximity conditions. The system effectively reduces unnecessary power consumption by turning devices OFF when no human is detected. Sensor readings and device responses remain stable during continuous operation. Overall, the system achieves improved energy efficiency, reliability, and user comfort.

A. Output Screens

The output screens display the real-time functioning of the Intelligent Power Management System. The YOLO output screen shows live camera feed with human detection results, confirming accurate occupancy recognition. Sensor outputs are reflected through the activation of lights, LEDs, and fan based on environmental conditions. The LCD output screen displays real-time system status, including light and fan operation, temperature, and humidity. These outputs collectively validate the correct and efficient operation of the proposed system. As depicted in Figure 8, the system operates in a no-human-detection state where the camera does not identify any person in the frame. In this condition, the control logic ensures that lights and fan remain switched OFF to conserve energy.

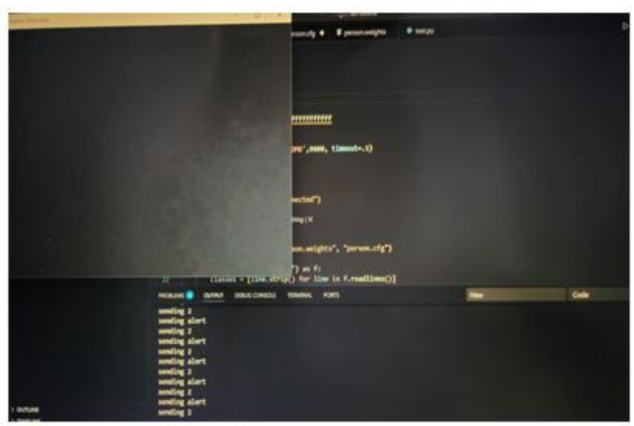

Figure 8. The camera does not detect any person in the frame.

As shown in below Figure 9 demonstrates the automatic activation of lighting when a human is detected by the YOLO-based vision system, confirming the correct functioning of occupancy-based automation in real time.

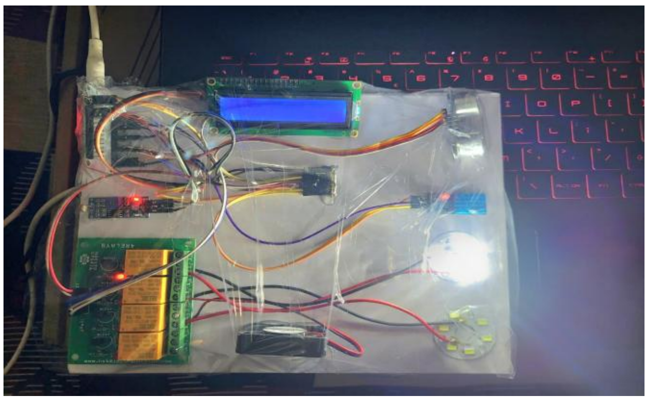

Figure 9. Light glows automatically when a human is detected.

VII. PERFORMANCE METRICS

The performance metrics illustrate the effectiveness and reliability of the YOLO model used for human detection in the Intelligent Power Management System. During training, the bounding box loss (Box) shows a consistent decrease, indicating improved accuracy in localizing humans within the video frames. The objectness loss also reduces steadily, confirming that the model learns to correctly distinguish between regions containing humans and background regions. Similarly, the classification loss decreases over epochs, demonstrating accurate identification of the "person" class. As shown in the above Figure 10 presents the performance metrics of the YOLO model, including bounding box loss, objectness loss, and classification loss during training. The decreasing loss curves indicate effective learning, while the increasing precision and recall curves demonstrate reliable and accurate human detection.

The precision curve increases gradually, showing that the model produces fewer false positives as training progresses. The recall curve also rises significantly, indicating the model's ability to detect most human instances present in the scene. High recall is especially important for automation systems to avoid missing human presence.

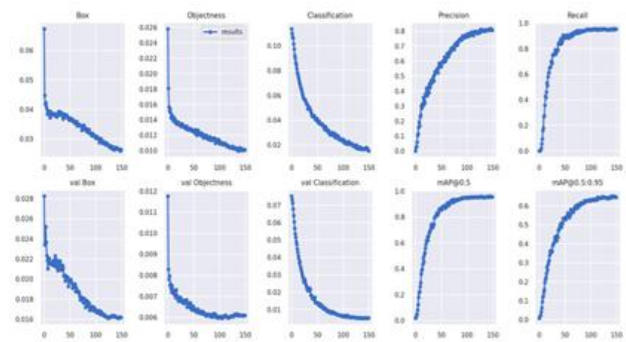

Figure 10. This shows the Performance.

VIII. OUTPUT OBSERVATIONS

To evaluate the correctness, reliability, and real-time responsiveness of the proposed Intelligent Power Management System, a comprehensive testing and validation procedure was conducted under multiple operating scenarios. The system was tested for different combinations of human presence, ambient lighting conditions, temperature thresholds, and user proximity to assess its decision-making accuracy. Each test case was designed to verify whether the system correctly interprets visual and sensor inputs and triggers the appropriate control actions for lighting and fan operation. The observed outputs were compared against the expected system behavior to identify deviations, delays, or inconsistencies. This testing process ensures that the system performs reliably under practical indoor conditions and highlights areas requiring further optimization.

Table II
Representation of Test Cases and Scenarios

Test Case ID	Description	Input Condition	Expected Output	Actual Output	Status
TC-01	Human detection in dark room	Room dark, human present	Main light ON	Light turned ON	**PASS**
TC-02	Human detection in bright room	Room bright, human present	Light OFF	Light remained OFF	**PASS**
TC-03	No human in dark room	Dark room, no presence	Lights OFF	Lights OFF	**PASS**
TC-04	Human entering & leaving room	Enter → ON, Exit → OFF	Light ON → OFF	Exit delay observed (1–2 sec)	**FAIL**
TC-05	Fan control on high temperature	Temp > 31°C	Fan ON	Fan turned ON	**PASS**
TC-06	Fan control on normal temperature	Temp ≤ 31°C	Fan OFF	Fan flickered once before OFF	**FAIL**
TC-07	Proximity – person near	Distance < 50 cm	Both LEDs ON	Both LEDs ON	**PASS**

IX. CONCLUSION

This paper presented an AI-based Intelligent Power Management System that integrates computer vision and multi-sensor fusion to optimize energy usage in indoor environments. The use of YOLO for human detection combined with environmental sensing enables accurate, context-aware automation. Experimental results confirm improved energy efficiency, reduced false triggering, and enhanced user comfort. The system is scalable, cost-effective, and suitable for smart home and intelligent building applications. Future work may include multi-room expansion, cloud integration, and mobile application support.

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