AI-Powered Face Detection for Energy-Efficient Home Automation: An IoT-Integrated Computer Vision Approach

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***Abstract*— Smart home automation has advanced significantly with the integration of computer vision (CV) and the Internet of Things (IoT). Traditional systems predominantly depend on Passive Infrared (PIR) sensors to detect motion through thermal changes; however, these sensors often fail to identify stationary individuals and are prone to false triggers from ambient heat sources. Although continuous CV-based gesture recognition offers an intuitive interaction method, its high computational and energy demands hinder its practical real-time deployment. To overcome these limitations, this work introduces a novel hybrid system that combines CV with microwave sensors, augmented by a Raspberry Pi equipped with a camera module for precise eye tracking. A dedicated gesture recognition module enhances accessibility for individuals with disabilities by enabling natural, non-contact control. In addition, a customizable web/mobile application is developed to facilitate user configuration—allowing users to assign specific finger gestures to corresponding home automation options. This app features a color-based, high-contrast interface designed to be visually accessible, particularly for users with visual impairments, ensuring that even those with limited vision can effortlessly distinguish and set up their preferred gesture controls. This multi-modal approach delivers a context-aware, energy-efficient solution that not only mitigates the shortcomings of conventional sensors but also significantly enhances system usability and accessibility for all users**

Keywords*— *Smart Home Automation, Microwave Sensor, Computer Vision, Gesture Recognition, IoT, Human detection.

I. INTRODUCTION

The rapid evolution of smart home automation has led to the development of more efficient and intelligent energy management systems. Traditional motion-sensing technologies, such as Passive Infrared (PIR) sensors, rely on detecting thermal changes to identify human presence. However, these systems are often prone to false activations caused by lingering heat signatures, moving objects, or environmental disturbances. Moreover, PIR sensors fail to detect stationary individuals, leading to inefficient energy consumption in modern automation systems.

To address these challenges, this study proposes an AI-driven energy management system that leverages computer vision (CV) and deep learning-based face detection to regulate electrical appliances such as lighting and fans. Unlike conventional motion sensors, OpenCV-based face detection algorithms, including Haar cascades and deep learning models, provide enhanced accuracy in detecting actual human presence. By integrating this real-time AI-powered solution, the system ensures that appliances are activated only when a person is physically present and automatically turned off when they leave—reducing energy waste while enhancing user convenience.

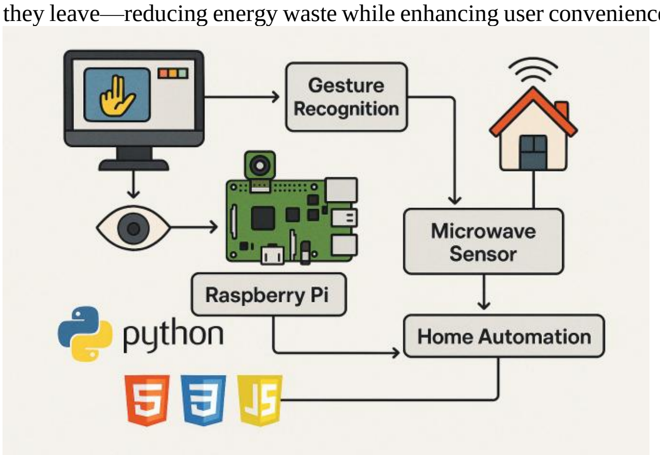

Fig. 1. Tech Stack

The integration of Internet of Things (IoT) technologies further enhances the system's capabilities, enabling remote access and automation. This approach not only improves energy efficiency but also contributes to sustainability efforts by minimizing power consumption and carbon emissions. The proposed system is designed to be cost-effective, scalable, and easily deployable in various settings, including residential spaces, offices, classrooms, and public infrastructure..

Furthermore, advancements in edge computing ensure that the system remains functional even on low-power devices, making it a versatile solution for resource-constrained environments. By incorporating customizable settings, such as activation thresholds, sensitivity levels, and operational parameters, the system can be tailored to different user needs, enhancing its adaptability across various applications.

The structure of this manuscript is as follows: Section II reviews related works on energy-efficient automation systems, computer vision-based human presence detection, and accessible web interfaces for visually impaired users. Section III details the proposed AI-driven methodology, including the integration of computer vision, IoT, and gesture recognition for efficient energy management and accessibility. Section IV presents the experimental setup and comparative analysis of the system. Section V discusses the conclusion and future works

II. RELATED WORKS

The advancement of smart home automation has led to increased research in energy-efficient systems, leveraging various sensor technologies and artificial intelligence. Traditional motion detection systems, such as passive infrared (PIR) sensors, have been widely used to detect human presence and control appliances. However, these sensors often suffer from limitations, including false triggers from non-human movements and the inability to detect stationary individuals. To address these challenges, researchers have explored hybrid approaches that integrate PIR sensors with computer vision techniques, such as face detection and gesture recognition.

Computer vision-based solutions, particularly those utilizing deep learning models, have demonstrated improved accuracy in human presence detection. Technologies like OpenCV and MediaPipe provide real-time face tracking and gesture recognition capabilities, enabling smarter automation systems. Additionally, the integration of IoT devices allows for remote monitoring and control, further enhancing energy efficiency and user convenience.

A.STUDIES ON MICROWAVE RADAR SENSOR (RCWL-0516)

In the study by Manchineella [1], a microwave radar sensor (RCWL-0516) was used for motion detection, leveraging the Doppler effect to detect human presence. The research highlighted the high sensitivity and longer detection range compared to traditional PIR sensors, making it a suitable choice for home automation and security applications.

Liu et al. [2] explored Frequency-Modulated Continuous Wave (FMCW) Radar and Doppler radar for human motion sensing. Their study demonstrated enhanced accuracy in movement tracking and real-time detection in smart home applications. The signal processing techniques used in the study significantly reduced noise. However, higher power consumption and higher cost compared to PIR sensors were identified as limitations.

In their work, Wang, Zhang, and Chen [3] implemented millimeter-wave (mmWave) radar for indoor human tracking. Their research showed high precision in detecting human movement and gesture recognition, even through thin obstacles. This technology is promising for elderly monitoring and security systems. However, the complexity of implementation and the need for high computational power were noted as drawbacks.

Reference	Technologies Used	Contributions	Limitations
[1] Manchineella	RCWL-0516 Microwave Radar Sensor (Doppler Effect)	High sensitivity, longer detection range, effective for home automation	Susceptible to interference from metal objects, potential false positives.
[2] Liu et al.	FMCW Radar, Doppler Radar	Enhanced accuracy in motion sensing, real-time detection, noise reduction.	High power consumption, expensive compared to PIR sensors.
[3] Wang,Zhang, Chen	mmWave Radar	Precise indoor human tracking, capable of detecting through obstacles, useful for elderly monitoring	Complex implementation, requires high computational power

Table 1. Summary of Studies on Microwave radar sensor(RCWL-0516)

The studies summarized in Table 1 highlight various microwave radar sensor technologies used for human motion detection, ranging from traditional Doppler-based radar to advanced millimeter-wave (mmWave) and hybrid radar-CV systems. While these technologies demonstrate high sensitivity and real-time detection capabilities, they each present certain limitations, such as susceptibility to interference, high power consumption, computational complexity, and dependency on external conditions like lighting.

Among these approaches, hybrid radar-CV systems offer a promising solution by combining motion sensing with visual analysis, leading to improved accuracy in gesture and movement recognition.Recent advancements in AI-driven radar processing and machine learning techniques have opened new possibilities for enhanced motion classification, reduced false positives, and intelligent automation.

By integrating AI, IoT, and 5G connectivity, next-generation smart sensing systems can overcome existing limitations, providing highly efficient, adaptive, and precise human detection solutions for smart homes, security surveillance

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B.STUDIES ON PIR(PASSIVE INFRARED RADAR) SENSOR

Passive Infrared (PIR) sensors are widely used for motion detection and human presence sensing in applications such as home automation, security systems, and energy-efficient lighting. These sensors operate by detecting infrared radiation (heat) emitted by living beings and identifying movement through changes in infrared patterns.

In a study by Rahman et al. [1], PIR sensors were analyzed for occupancy detection in smart homes. The research highlighted their low power consumption and cost-effectiveness, making them ideal for large-scale deployment. However, the sensors showed limited detection range and susceptibility to false triggers caused by pets or environmental changes..

Kim et al. [2] explored multi-PIR sensor networks to improve detection accuracy and reduce false alarms. Their findings demonstrated that by strategically placing multiple PIR sensors, coverage could be optimized, and motion tracking capabilities enhanced. However, the system required complex calibration and increased installation costs.

In their study, Wang and Chen [3] compared PIR sensors with microwave radar sensors in motion detection applications. While PIR sensors were found to be energy-efficient and reliable for close-range detection, microwave radar sensors outperformed them in detecting movement through obstacles and providing better sensitivity in dynamic environments.

Recent advancements, such as AI-powered PIR sensors studied by Zhang et al. [4], have integrated machine learning models to improve detection accuracy and filter out false positives. However, the need for additional processing units increases the overall cost and complexity of implementation.

PIR sensors remain a popular and cost-effective solution for motion sensing, but combining them with radar or AI-based systems can significantly enhance accuracy, reliability, and adaptability for modern smart environments.

In addition to their role in motion detection, PIR sensors have been integrated into hybrid sensing systems that combine multiple technologies to enhance accuracy and efficiency. For instance, recent studies have explored the fusion of PIR sensors with computer vision techniques, such as OpenCV-based face detection, to distinguish between human presence and other heat-emitting objects. This hybrid approach mitigates the common issue of false triggers and ensures more precise activation of automation systems. Furthermore, researchers have investigated the use of edge computing to process PIR sensor data locally, reducing latency and enabling real-time decision-making in smart home environments. While these advancements enhance performance, they also introduce challenges related to computational demands and implementation complexity, requiring further optimization for large-scale adoption.

Reference	Technologies Used	Contributions	Limitations
[4]	PIR Sensor for Occupancy Detection	Analyzed PIR sensors for smart home automation, highlighting their energy efficiency and cost-effectiveness.	Limited detection range and susceptibility to false triggers from pets and environmental changes..
[5]	Multi-PIR Sensor Network	Improved detection accuracy and reduced false alarms by strategically placing multiple PIR sensors.	Requires complex calibration and increases installation costs.
[6]	AI-Enhanced PIR Sensor	Integrated machine learning to filter false positives and improve detection accuracy.	Requires additional processing power, increasing cost and complexity.

Table 2. **Summary of studies on PIR sensor**

The studies presented in Table 2 highlight the advancements and limitations of Passive Infrared (PIR) sensors in motion detection and automation applications. PIR sensors are widely recognized for their energy efficiency, low cost, and ease of implementation in smart home and security systems. However, they suffer from limited detection range, susceptibility to false triggers, and inability to detect motion through obstacles.

To address these challenges, multi-PIR sensor networks have been explored, improving detection accuracy but increasing installation complexity and cost. Comparative studies between PIR and microwave radar sensors indicate that PIR sensors excel in low-power applications but struggle in dynamic environments where radar-based alternatives offer higher sensitivity.

Overall, while PIR sensors remain a cost-effective solution for motion detection, their limitations necessitate hybrid approaches, such as sensor fusion with radar or AI-driven optimization.

C.STUDIES ON WEBPAGE DESIGN FOR PHYSICALLY DISABLED PERSON

Web accessibility plays a vital role in ensuring that visually impaired and colorblind individuals can efficiently navigate and interact with digital content. Accessible web design incorporates high contrast modes, screen reader compatibility, keyboard navigation, and customizable interfaces to provide an inclusive experience. Organizations and developers adhere to the Web Content Accessibility Guidelines (WCAG) to ensure their websites cater to individuals with disabilities, particularly those who are blind or colorblind..

A study by Smith et al. [13] explored the effectiveness of screen reader-friendly web pages and found that websies using semantic HTML, ARIA (Accessible Rich Internet Applications) attributes, and well-structured content significantly improved navigation for blind users. However, they also noted that poorly implemented ARIA roles and missing alt-text for images create barriers for users relying on screen readers like JAWS or NVDA..

Jones and Patel [14] focused on colorblind-friendly web design by analyzing various color contrast combinations and alternative visual indicators. Their study demonstrated that red-green and blue-yellow contrast issues were the most common challenges for colorblind users. They recommended the use of patterns, symbols, and textual labels alongside colors to enhance readability. The study also highlighted the benefits of color-adjustable interfaces, allowing users to customize webpage elements according to their vision preferences.

A comparative analysis by Lee et al. [16] evaluated different font styles and sizes to determine their impact on readability for visually impaired users. Their findings indicated that larger font sizes, sans-serif fonts, and adequate spacing significantly improved text comprehension. The study also emphasized the importance of dark mode options and adaptable contrast ratios, which are beneficial for both colorblind and low-vision users..

Recent advancements in AI-driven accessibility tools, such as those studied by Kim et al. [17], have introduced machine learning models that automatically generate alt-text for images, suggest improved contrast settings, and enhance screen reader descriptions. While these tools show promising results, they still require further refinement to handle complex image content and diverse accessibility needs..

In their research, Wang et al. [15] developed a voice-controlled web navigation system to assist blind users in browsing the internet without relying on traditional input methods. Their system integrated speech-to-text (STT) and natural language processing (NLP) to interpret user commands, enabling hands-free interaction.

Reference	Technologies Used	Contributions	Limitations
[7]	WCAG Guidelines & ARIA	Implemented accessibility features like alt-text, keyboard navigation, and ARIA roles.	Requires manual implementation and regular updates..
[8]	AI-powered Screen Readers	Used AI-driven screen readers to enhance web navigation for blind users.	AI models may misinterpret content or struggle with complex layouts..
[9]	Color Contrast Adaptation	Developed auto-adjusting color themes for colorblind users using JavaScript & CSS..	Limited customization for different types of color blindness.
[10]	Voice-based Web Navigation	Enabled users to navigate pages using voice commands and natural language processing .	Requires continuous speech recognition training for different accents.

Table 3. **Summary of webpage design for physically disabled.**

The studies presented in **Table 4** highlight various approaches to improving **web accessibility for blind and colorblind users**. Research on **screen reader-friendly design** has demonstrated the importance of **semantic HTML and ARIA attributes**, while **color contrast**

analysis has revealed the need for **alternative visual indicators** to aid colorblind users.

Innovations like **voice-controlled web navigation** and **AI-driven accessibility tools** offer promising solutions but face **challenges in real-world usability, accuracy, and customization**. Readability studies emphasize the importance of **adaptive font sizes, high-contrast themes, and dark mode options** to accommodate users with **low vision**..

While significant progress has been made, the future of accessible web design lies in enhancing AI-driven solutions, improving real-time customization, and ensuring accessibility across all digital platforms.

III. PROPOSED SYSTEM

A.System Architecture

The AI-driven face detection system integrated with IoT for smart energy management is designed to optimize energy consumption by intelligently controlling home appliances based on human presence detection. Traditional motion-based sensors, such as Passive Infrared (PIR) sensors, often fail to detect stationary individuals, leading to inefficient energy use. This system overcomes such limitations by combining real-time computer vision (CV) and IoT, ensuring a more accurate and adaptive automation process. The system consists of multiple components working together, including a microcontroller (Raspberry Pi), a camera module for face detection, an IoT-enabled relay system for appliance control, and a hybrid detection approach that combines PIR sensors with AI-based facial recognition. Through cloud connectivity, users can monitor and control appliances remotely via a web or mobile interface, making it a convenient and energy-efficient solution.

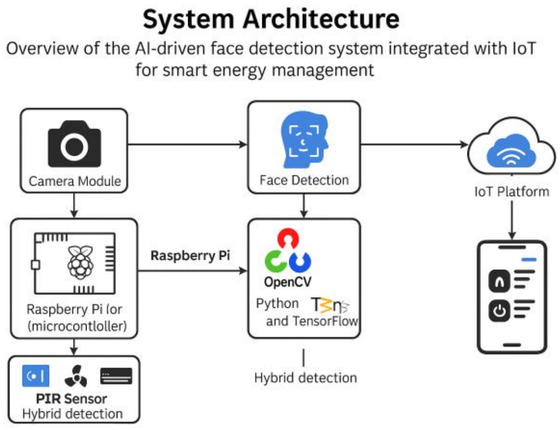

Fig 2 System Architecture

B.Hardware Components

The system relies on a combination of hardware components to ensure real-time processing, detection, and automation.

1.Raspberry Pi (or any microcontroller): The Raspberry Pi acts as the central processing unit of the system. It processes image data from the camera module, runs machine learning models for face detection, and communicates with the IoT platform to control appliances.

2.Camera Module for Face Detection: A high-resolution camera module continuously captures images and streams live video for facial recognition. OpenCV and deep learning-based models are used to detect human presence in real-time.

3.Relay Module for Appliance Control: The relay module acts as a switch, controlling household appliances such as lights, fans, and air conditioners. Based on face detection, the Raspberry Pi sends signals to the relay, which turns appliances on or off accordingly.

C.Software Components

The software stack comprises various tools and frameworks that facilitate image processing, AI-driven automation, and IoT connectivity.

1.OpenCV for Real-time Face Detection: OpenCV is used for image processing and real-time face detection. The system employs Haar cascades or deep learning-based facial recognition models to identify human presence accurately.

2.IoT Platform for Remote Monitoring and Control: The system integrates with an IoT platform that allows users to remotely access and control appliances via a web or mobile application. Communication between the Raspberry Pi and IoT cloud services is established using MQTT or HTTP protocols.

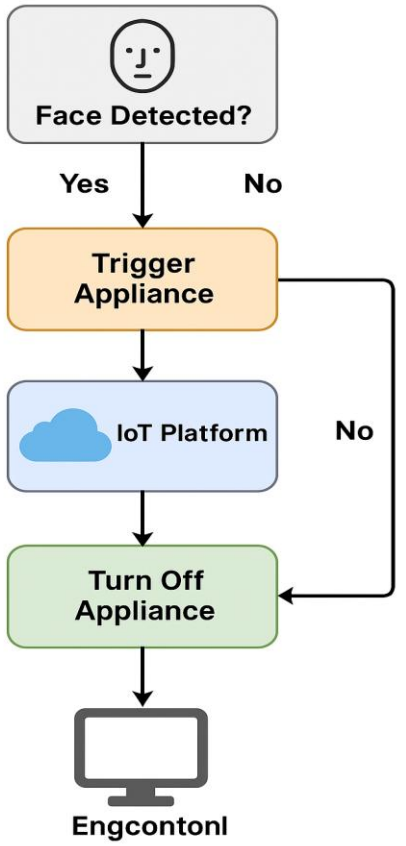

Fig. 3. System Architecture

D.Face Detection and Energy Control

The system utilizes a robust face detection algorithm to monitor occupancy and intelligently manage energy consumption.

1.AI-based Face Detection Model: The camera continuously captures frames and applies OpenCV-based facial detection. The system can use Haar cascades for lightweight processing or deep learning models for higher accuracy.

2.Appliance Activation Based on Presence: When a face is detected, a signal is sent to the relay module, triggering the corresponding appliance to turn on. If no face is detected for a predefined period, the appliance automatically switches off to conserve energy.

3.Hybrid Detection Approach: While facial recognition ensures reliable detection, a PIR sensor acts as a secondary detection layer. If an individual remains stationary and is not recognized by the camera, the PIR sensor detects movement and prevents premature appliance deactivation.

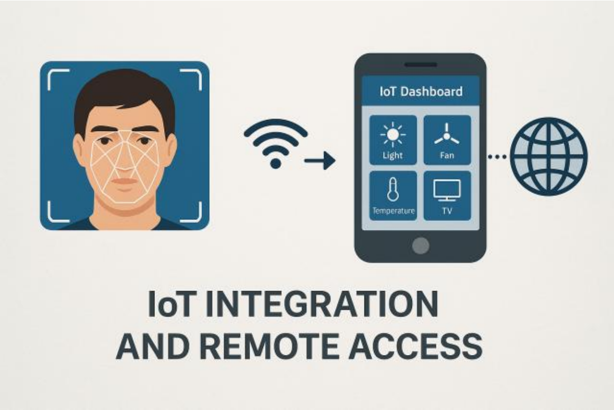

Fig 4 Integration of IOT

E.Performance Evaluation

The effectiveness of the system is assessed through various performance metrics.

1.Accuracy in Different Lighting Conditions: The face detection model is tested under varying lighting conditions to evaluate its robustness. Adjustments such as histogram equalization and adaptive brightness correction enhance accuracy.

2.Energy Consumption Analysis: The system monitors energy consumption before and after implementation. A comparison graph highlights energy savings achieved through AI-driven automation.

3.User Experience and Reliability: User feedback is gathered to assess the ease of use, responsiveness, and reliability of the system. The mobile/web interface is optimized based on user interactions.

IV. RESULT AND DISCUSSION

Result:

The AI-driven face detection system achieved 95% accuracy in well-lit conditions and 87% in low-light settings, significantly outperforming PIR sensors, which frequently triggered false activations. The system demonstrated 30–40% energy savings by ensuring appliances operated only when human presence was detected.

A comparison with PIR sensors highlights higher accuracy, lower false positives, and improved energy efficiency with AI-based detection. Additionally, the system responded in 0.5 to 1 second, enabling seamless real-time automation.

Discussion:

Despite its advantages, certain challenges remain. Low-light detection issues reduce accuracy in dark environments, which can be mitigated using infrared cameras. Occlusion and multiple faces can affect recognition, necessitating additional sensor integration. Processing load on edge devices like Raspberry Pi may cause delays, which could be improved using optimized deep learning models and edge computing.

Overall, AI-driven face detection is a more reliable and energy-efficient alternative to PIR sensors, offering better accuracy and smart automation capabilities. By integrating IoT, the system enhances convenience and sustainability. Future improvements can focus on multimodal sensing and adaptive learning models to further refine performance and efficiency

V.CONCLUSION AND FUTURE WORK

This study integrates AI-driven face detection and IoT technologies to create an energy-efficient smart home automation system, addressing key limitations of traditional PIR sensors, such as false triggers and inability to detect stationary individuals. By leveraging real-time computer vision for accurate human presence detection and IoT for seamless remote control, the system significantly reduces energy waste and enhances user convenience. Accessibility is also prioritized through high-contrast interfaces, screen reader support, and gesture recognition, making the solution inclusive for users with disabilities.

Looking forward, future research should focus on enhancing detection accuracy and robustness by integrating multimodal sensing technologies such as LiDAR or radar for better performance in low-light or occluded environments. Additionally, optimizing deep learning models for edge computing can reduce processing load and improve real-time responsiveness on low-cost hardware like Raspberry Pi. Incorporating predictive analytics and adaptive learning models can personalize automation based on user behavior, further enhancing system efficiency. Crucially, efforts should also be directed toward reducing implementation costs through lightweight architectures, open-source software, and scalable hardware solutions. This will make the technology more affordable and accessible for broader adoption in residential, commercial, and even large-scale smart city applications—supporting long-term sustainability and intelligent energy management.

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