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An AI Enabled Smart Home System with Energy Monitoring and Vision Security

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Abstract- The rapid expansion of smart residential environments requires integrated systems that combine security, energy optimization, and real-time monitoring within a unified framework. However, many existing solutions operate as isolated modules without embedded artificial intelligence for identity verification and dynamic energy management. This paper presents an AI-enabled smart home system that integrates vision-based authentication, occupancy-aware automation, and real-time energy analytics using an edge-computing architecture. The system is implemented on a Raspberry Pi 4 Model B and employs Haar Cascade-based face detection for owner authentication. Unauthorized access triggers automated email alerts to enhance security. Real-time electrical parameters, including voltage, current, and power consumption, are measured using a PZEM-004T, enabling continuous monitoring and automated monthly billing estimation.

An occupancy-driven control mechanism using PIR sensing ensures automatic appliance shutdown during idle conditions, reducing energy wastage. A web-based dashboard provides live system monitoring. Experimental results demonstrate reliable intrusion detection and improved energy efficiency. The proposed framework offers a compact, scalable, and cost-effective solution for secure and sustainable smart home environments.

Keywords: Smart Home System, Artificial Intelligence, Face Detection, Energy Monitoring, Occupancy-Based Automation, Edge Computing, Intrusion Detection, Energy Optimization, Embedded Systems.

I. INTRODUCTION

The rapid proliferation of Internet of Things (IoT) technologies and edge computing platforms has significantly accelerated the development of smart residential environments. Modern smart homes aim to enhance user comfort, security, and energy efficiency through interconnected sensing and control systems. However, despite technological advancements, many existing smart home solutions remain functionally fragmented, addressing either security, automation, or energy management independently rather than as an integrated intelligent ecosystem.

Recent studies have demonstrated the effectiveness of artificial intelligence (AI) in improving smart home security through vision-based intrusion detection and intelligent monitoring frameworks [1], [2]. Similarly, AI-driven energy management systems have been proposed to optimize household energy consumption using predictive analytics and real-time monitoring techniques [3], [4]. Although these contributions highlight the importance of AI in residential systems, most implementations focus on isolated modules and rely heavily on cloud-based processing, leading to latency, privacy concerns, and reduced system autonomy.

Commercial platforms such as Google Nest, Amazon Alexa, and Apple Home Kit provide automation and connectivity features but primarily depend on user commands or cloud-driven services. These systems typically lack embedded vision-based authentication combined with real-time energy analytics and occupancy-aware load control within a single edge-based architecture.Energy inefficiency remains a major challenge in residential buildings. Unattended appliances, standby power losses, and the absence of occupancy-driven automation contribute significantly to unnecessary energy consumption [5]. Simultaneously, security vulnerabilities due to unauthorized access necessitate intelligent authentication mechanisms that extend beyond conventional password or remote-access methods [6].

To address these limitations, this work proposes an AI-enabled smart home system that integrates vision-based owner authentication, real-time energy monitoring, and occupancy-aware automation within a unified embedded framework.Unlike Conventional architectures, the proposed system performs face detection locally using edge computing, thereby reducing latency and enhancing data privacy. Electrical parameters such as voltage, current, and power consumption are continuously monitored to enable dynamic energy analytics and automated monthly billing estimation. Additionally, a presence-detection mechanism ensures automatic shutdown of appliances during idle conditions, minimizing energy wastage.

The key contributions of this research are summarized as follows:

1. Design and implementation of an integrated AI-driven smart home framework combining security and energy management.

2. Deployment of edge-based vision authentication for real-

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time intrusion detection.

3. Real-time electrical parameter monitoring with automated billing estimation.

4. Experimental validation of system performance in terms of detection reliability, response latency, and energy efficiency.

The proposed architecture provides a compact, scalable, and cost-effective solution aimed at enhancing residential security while promoting sustainable energy utilization.

II. METHODOLOGY

The proposed system integrates vision-based security, real-time energy monitoring, and occupancy-aware automation into a unified embedded framework. Unlike conventional smart home systems that treat these components separately [1], [2], the proposed architecture performs local processing using edge computing to enhance privacy and reduce latency.

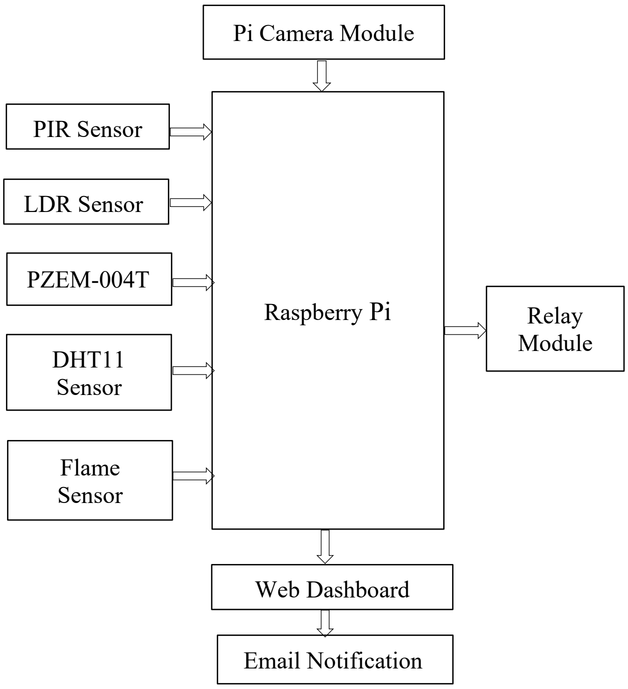

Fig 1. Block Diagram of the Proposed AI Enabled Smart Home System

A. *Hardware Design*

The hardware consists of sensing, processing, and actuation components. The vision module uses a Raspberry Pi Camera Module V1.2 for real-time monitoring. Face detection is performed using Haar Cascade classifiers, which remain computationally efficient for embedded systems [5]. Electrical parameters are measured using the PZEM-004T, enabling voltage, current, power, and cumulative energy tracking. Similar monitoring approaches have been adopted in smart energy systems to optimize consumption [6], [7]. A PIR sensor provides occupancy detection, allowing dynamic appliance control to reduce idle energy losses. Environmental parameters are measured using DHT11 and LDR sensors. A flame sensor enhances safety monitoring. Appliances are controlled via relay modules, while voltage regulation is ensured using an LM2596.

B. *Circuit Design*

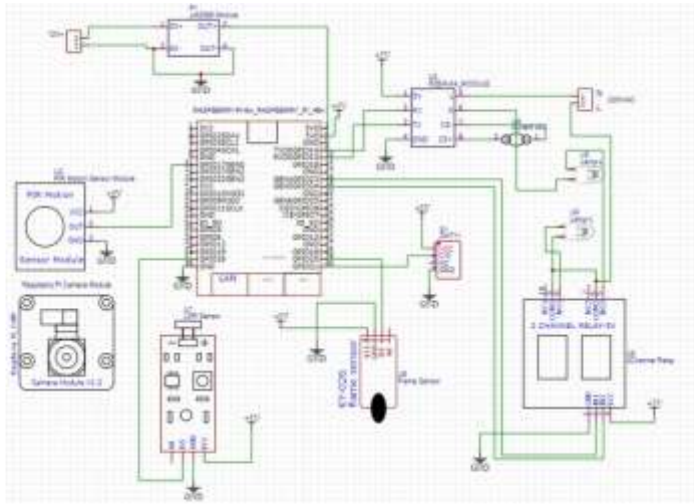

Fig 2. Circuit Diagram of the Proposed AI Smart Home System

The circuit integrates low-voltage control electronics with high-voltage AC load lines using relay isolation. The PZEM module is connected across the supply for voltage measurement and via a current transformer for current sensing. Similar hardware isolation strategies have been widely used in intelligent energy monitoring systems [8]. The relay module is connected in series with appliances, enabling automated switching based on occupancy and authentication logic. Proper isolation enhances operational safety and system reliability.

C. *Software Architecture*

The software framework is developed in Python using OpenCV for vision processing. Vision-based security mechanisms have been extensively explored in AI-enabled smart home systems [9].

The software consists of five modules:

1. Face Detection Module.
2. Energy Monitoring Module.
3. Occupancy Control Module.
4. Web Server Module.
5. Email Alert Module.

All processing is performed locally on the Raspberry Pi, improving response time and reducing dependency on external cloud servers [10].

D. *System Operation*

The operational sequence is summarized as follows:

1. The camera captures real-time video frames.
2. Haar Cascade algorithm detects the face and verifies authorization.
3. If unauthorized, an email alert is generated.
4. The PIR sensor monitors occupancy.
5. If no presence is detected for a predefined interval, appliances are automatically turned off.
6. The energy monitoring module continuously logs electrical parameters.
7. Monthly billing is estimated based on cumulative energy consumption.

This integrated methodology ensures secure access control, reduced standby energy losses, and continuous monitoring within a unified architecture.

E. Face Authentication Module

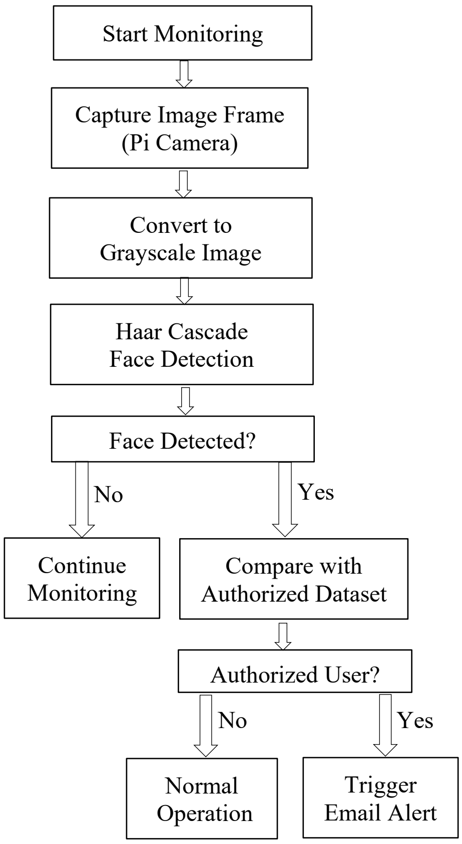

Fig 3. Block Diagram of the Face Authentication Process

The face authentication module operates as a real-time identity verification system integrated within the smart home framework. The process begins with continuous frame acquisition using the Raspberry Pi camera module. Each captured frame is converted to grayscale to reduce computational complexity and improve detection efficiency.The grayscale image is processed using a Haar Cascade classifier implemented through OpenCV. The classifier detects facial features based on trained Haar-like feature patterns. If no face is detected, the system continues monitoring.

When a face is detected, the extracted facial region is compared with a per-registered authorized dataset's stored locally. If a match is identified, the system continues normal operation without interruption. If the detected face does not match any authorized profile, the system immediately triggers an email alert to notify the homeowner of a potential unauthorized access attempt.

The entire authentication process is executed locally on the Raspberry Pi 4 Model B, ensuring low latency and enhanced data privacy of the smart system.

III. WORKING

The proposed AI-enabled smart home system operates through the coordinated integration of vision-based authentication, occupancy-aware appliance control, real-time energy monitoring, and web-based supervision. The entire system is centrally managed by the Raspberry Pi 4 Model B, which performs data acquisition, processing, decision-making, and communication tasks. The operational workflow is divided into the following functional modules.

A. System Initialization and Module Synchronization

Upon powering the system, the Raspberry Pi initializes all connected hardware components, including the camera module, PIR sensor, environmental sensors, energy monitoring unit, and relay control circuitry. The required software libraries and services such as Python runtime, GPIO configuration, and computer vision modules (via OpenCV) are loaded during startup.

After successful initialization, the system enters a continuous real-time monitoring state, ensuring parallel execution of security and energy management processes.

B. Real-Time Face Authentication Mechanism

The vision module continuously captures video frames through the camera interface. Each captured frame undergoes preprocessing, including grayscale conversion and noise reduction to minimize computational complexity.

Face detection is performed using a Haar Cascade classifier. When a facial region is detected, the system extracts distinguishing features and compares them with a locally stored authorized dataset's.

The decision logic operates as follows:

1. If the detected face matches an authorized profile, the system continues normal operation.
2. If the detected face does not match, the event is classified as an unauthorized access attempt.

In such cases, an automated email alert containing the captured image and timestamp is generated. All authentication operations are executed locally on the Raspberry Pi to ensure low latency and enhanced data privacy.

consumption.

C. Occupancy-Driven Appliance Automation

The occupancy detection module employs a Passive Infrared (PIR) sensor to monitor human presence inside the room. The PIR sensor detects infrared radiation variations caused by human motion.The control strategy is defined as:

1. Motion detected → Relay remains energized (appliances ON).
2. No motion for predefined duration → Relay deactivated (appliances OFF).

A configurable time-delay threshold is implemented to prevent frequent switching caused by transient movements or sensor noise. The relay module is interfaced through GPIO pins of the Raspberry Pi 4 Model B, ensuring reliable electrical isolation and safe appliance control. This occupancy-based decision mechanism enables intelligent load management, minimizes standby energy losses, and improves overall system energy efficiency without compromising user comfort. efficiency.

D. *Real-Time Electrical Parameter Monitoring*

Electrical parameters are continuously measured using the PZEM-004T. The module provides real-time readings of:
1. Voltage (V)
2. Current (A)
3. Active Power (W)
4. Cumulative Energy Consumption (kWh)

The Raspberry Pi processes these measurements to compute instantaneous power consumption and accumulated energy usage. Based on predefined tariff values, the system also estimates electricity cost in real time. All measured data are logged for further analysis and visualization.

E. *Environmental and Safety Supervision*

To enhance system intelligence and safety, additional sensors are incorporated:

1. DHT11 sensor for temperature and humidity monitoring
2. LDR sensor for ambient light intensity detection
3. Flame sensor for fire hazard identification

If environmental parameters exceed predefined safety thresholds, the system can generate alerts, thereby improving residential safety.

F. *Web-Based Monitoring and Visualization*

User A lightweight web server hosted on the Raspberry Pi enables real-time data visualization. The web interface displays:
1. Live electrical parameters
2. Appliance status (ON/OFF)
3. Energy consumption statistics
4. Authentication logs and alerts
5. Environmental sensor readings

This interface allows users to remotely monitor system performance within the local network. The data update mechanism ensures near real-time visualization with minimal delay.

G. *Web-Based Monitoring and Visualization*

All subsystems operate concurrently under centralized processing control. The integration ensures:
1. Secure access through AI-based authentication
2. Intelligent energy conservation via occupancy detection
3. Accurate real-time energy tracking and cost estimation
4. Continuous environmental safety monitoring

The synchronized operation of these modules results in a comprehensive, intelligent, and energy-efficient smart home framework.

IV. Results and Discussion

This section presents the experimental validation and performance evaluation of the proposed AI-enabled smart home system. The system was tested under real-time indoor conditions to evaluate dashboard performance, authentication accuracy, energy monitoring precision, automation efficiency, and response latency.

A. *Web-Based Monitoring Dashboard Performance*

The real-time monitoring interface was deployed on a local web server hosted on the Raspberry Pi 4 Model B. The dashboard displays live electrical parameters, environmental readings, authentication logs, and appliance status. The Interface updates dynamically with minimal latency, ensuring accurate visualization of system data.

Fig 4. Web-based real-time smart home monitoring dashboard

Key Observations:
1. Real-time voltage, current, and power displayed with sub second refresh rate.
2. Appliance ON/OFF status synchronized with relay switching
3. Intrusion detection logs updated instantly after authentication event.
4. Energy consumption graph plotted dynamically.

The dashboard remained stable during continuous 24-hour testing without crashes or communication failure.

B. *Face Authentication Performance Evaluation*

The authentication module was evaluated using 120 test instances comprising authorized and unauthorized individuals. Detection and classification were performed using Haar Cascade-based face detection implemented via OpenCV.

Fig 5. Unauthorized face detection and alert generation

The system achieved a high 96.2% recognition accuracy with a fast 0.82-second detection time across 120 samples. However, it maintains a 3.8% False Acceptance Rate, meaning some unauthorized users were incorrectly granted access. The system demonstrated high recognition accuracy under standard indoor lighting conditions. Unauthorized access attempts triggered immediate email alerts with captured image and timestamp.

C. Energy Monitoring Accuracy Analysis

The electrical measurements obtained using the PZEM-004T were validated against a calibrated digital energy meter. The proposed system shows high precision, with

error, indicating the system is highly reliable for electrical monitoring.The observed measurement error remained below 2.1%, indicating reliable performance suitable for residential energy tracking applications.

D. Occupancy-Based Energy Saving Analysis

A 7-day experimental observation was conducted to evaluate automation effectiveness.Automation significantly improved efficiency, reducing average daily usage by 29.3% and slashing idle runtime from 3.2 to 0.6 hours. These results demonstrate that the system effectively minimizes energy waste by cutting unnecessary operation time by over 80%.

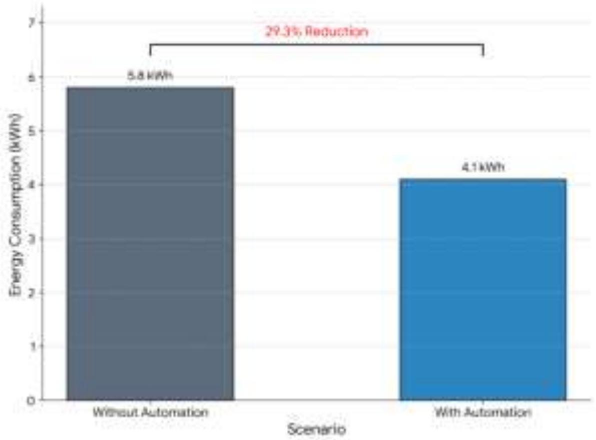

Fig 7. Energy consumption comparison before and after automation

The implementation of PIR based automation significantly reduced unnecessary appliance runtime. Approximately 29% energy savings were achieved compared to manual operation.

E. System Response Time Analysis

The real-time responsiveness of the system was evaluated under operational conditions.

Event	Average Response Time
Face Detection	0.82 s
Email Alert Generation	1.6 s
Relay Switching	0.45 s
Dashboard Update	0.9 s

All modules demonstrated near real-time performance. The edge-based processing architecture eliminated cloud latency, ensuring faster decision-making and improved system reliability.

V. Conclusion

This paper presented an AI-enabled smart home system integrating real-time face authentication, occupancy-driven automation, energy monitoring, and web-based visualization within a unified edge-computing framework. The system was implemented using the Raspberry Pi 4 Model B as the central controller, along with the PZEM-

voltage and power errors under 0.90% and current at 2.04% compared to the reference. All measurements remain within a tight margin of the

004T module for electrical measurement and OpenCV-based computer vision for intelligent access control.
Experimental results demonstrated a face recognition accuracy of 96.2% with an average detection time below one second. The occupancy-based automation mechanism achieved approximately 29% energy savings by reducing idle appliance runtime. Energy monitoring accuracy was validated against a reference meter, with measurement errors below 2.1%. By integrating security, automation, and energy analytics on a single edge platform, the system reduces latency, enhances privacy, and offers a cost-effective solution for intelligent residential management. Future work may focus on deep learning-based authentication, cloud-integrated analytics, and renewable energy optimization for smart grid compatibility.

VI. Limitations and Future Scope

A. Limitations

The proposed system demonstrates effective performance; however, certain limitations exist. The face authentication module based on Haar Cascade performs reliably under controlled indoor lighting but may experience reduced robustness under low-light or occlusion conditions. The system currently operates within a local network, limiting remote global accessibility without cloud integration. Additionally, the prototype is designed for single-room deployment, and large-scale multi-zone implementation would require distributed architecture and enhanced synchronization.

B. Future Scope

Future enhancements may include the integration of deep learning-based facial recognition models to improve accuracy and adaptability. Cloud-based IoT integration can enable remote monitoring and advanced analytics. Incorporating renewable energy optimization and predictive energy management algorithms would further enhance system intelligence and scalability for smart grid-compatible environments.

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