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Ai BAsed INtelligent Home APpliances With IOT INtegration For Zero Energy Wastage And Comfort Optimization

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Abstract: This paper proposes a hybrid hardware & software based intelligent monitoring system for conventional household appliances by integrating Internet of Things (IoT) architecture with data-driven fault detection and energy analysis. The system is designed using a dual-layer framework, where an ESP32 microcontroller performs real-time data acquisition, while a Raspberry Pi handles centralized processing and decision-making tasks. Key electrical and thermal parameters such as voltage, current, and temperature are continuously monitored to establish an adaptive baseline representing normal operating conditions. Any deviation from this baseline is analyzed using a machine learning based anomaly detection technique, enabling classification of appliance states into normal, warning, and critical categories. Unlike traditional threshold-based approaches, the proposed system incorporates trend aware analysis to detect gradual performance degradation and respond accordingly through user alerts or automatic power isolation using relay control. Additionally, real-time power and energy consumption are evaluated to assess appliance efficiency and identify abnormal usage patterns. Experimental validation on a household fan setup confirms effective detection of faults such as overheating, overcurrent, and voltage variations, while significantly reducing false alarms compared to conventional method.

Keywords: Internet of things, Intelligent Monitoring System, Fault Detection, Energy Efficiency, Anomaly Detection, Smart Home.

I. INTRODUCTION

The rapid growth of electrical appliance usage in residential environments has significantly increased household energy consumption and raised concerns related to operational safety and maintenance.

Despite the growing adoption of smart home systems, most existing solutions mainly focus on automation and remote operation, offering limited capability for monitoring appliance health or detecting abnormal conditions.

Consequently, faults and inefficiencies in traditional household appliances frequently go unnoticed until they cause performance issues or safety concerns.

Existing residential energy monitoring systems generally focus on consumption visualization and employ static thresholds to identify abnormal real time behaviour. Such approaches lack adaptability to changing appliance characteristics caused by aging, environmental variation, or usage patterns.

On the other hand, advanced fault detection techniques reported in the literature are predominantly developed for industrial systems, where large datasets, high computational resources, and complex models are feasible. These constraints limit their direct applicability in low cost, real time residential environments, particularly for traditional appliances that are not designed to be smart.

In response to these limitations, this paper presents an intelligent appliance monitoring framework that enables fault detection, fault prevention, and energy consumption analysis for conventional household appliances through a retrofit based approach. The proposed system employs a dual layer architecture, where an ESP32 microcontroller handles real time data acquisition and a Raspberry Pi performs adaptive baseline learning and anomaly evaluation.

By continuously learning normal operating behaviour from electrical and thermal parameters, the system identifies deviations and executes an appropriate response, ranging from user notification to

automated power isolation. This approach provides a practical pathway for transforming traditional homes into intelligent energy aware environments without incurring the high cost of appliance replacement.

The main contributions of this work are outlined below:

Development of a low cost, retrofit compatible monitoring system that enhances conventional household appliances awareness.

1. Introduction of an adaptive baseline based anomaly detection strategy that eliminates the need for predefined fault models or extensive labelled training data.

2. Design of a two level fault response mechanism that balances user awareness and automated protection based on fault severity.

3. Unified integration of fault detection and energy consumption analysis within a single edge based framework.

4. Experimental validation of the proposed approach using a practical household appliance setup, demonstrating its suitability for real world residential deployment.

II. LITERATURE REVIEW

Various studies have explored IoT-based home automation systems to enable remote monitoring and control of household devices through mobile and web based interfaces. These systems mainly focus on convenience and automation but do not incorporate intelligent fault detection or appliance health monitoring mechanisms [1], [2].

Several studies have proposed residential energy monitoring systems using electrical parameters such as voltage, current, and power consumption to help users understand energy usage patterns. However, most of these approaches rely on fixed or manually defined thresholds, which are not adaptive to changing appliance behaviour over time [3], [4].

Machine learning approaches are widely used for fault detection and predictive maintenance, especially in industrial environments such as motors, transformers, and manufacturing systems. Although these techniques demonstrate reliable detection performance under tested conditions, they typically require large datasets and significant computational resources, making them unsuitable for low cost household applications [5], [6].

Smart appliance solutions that integrate sensing and intelligence directly into appliance hardware have also been reported. While effective, such approaches increase device cost and reduce flexibility, as each appliance must be independently equipped with intelligent hardware modules [7].

Home energy management systems low cost have primarily focused on load scheduling, peak demand reduction, and overall energy optimization at the building level. These systems provide limited support for appliance level fault prevention, where abnormal operation can lead to safety risks and energy wastage [8].

The literature indicates a clear need for a cost-effective and adaptive system capable of performing fault detection and energy analysis in conventional household appliances by developing a low cost, adaptive, and retrofit-compatible system that can simultaneously perform fault detection, fault prevention, and energy consumption analysis for conventional household appliances [9].

The proposed work addresses this gap by implementing an edge-based intelligent monitoring framework that learns normal operating behaviour, detects anomalies using adaptive baselines, and applies a two-stage fault response mechanism suitable for residential environments.

III. METHDOLOGY

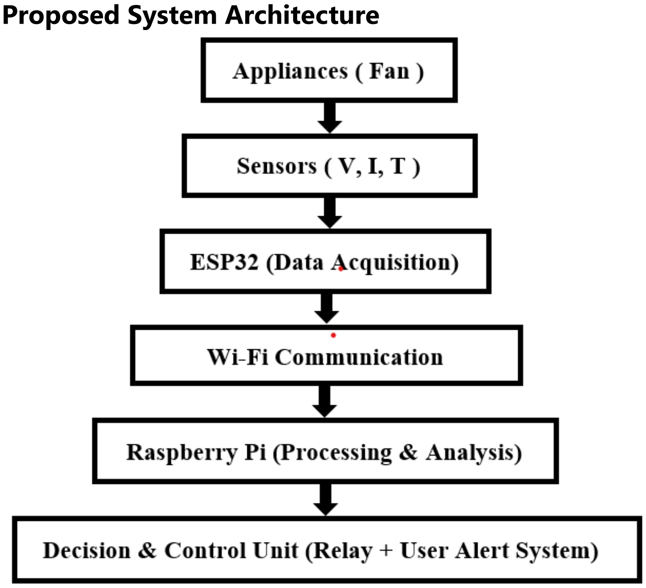
The system is implemented using a dual-layer architecture consisting of an ESP32 data acquisition and a Raspberry Pi for intelligent processing.

A conventional household fan is selected as the test appliance, and its electrical behavior is monitored using current, voltage, and temperature sensors. The ESP32 interfaces directly with these sensors to perform periodic sampling, basic signal conditioning, and wireless data transmission to the Raspberry Pi, ensuring reliable and continuous data flow.

An initial learning phase is carried out in which the Raspberry Pi observes the appliance operation over multiple usage cycles to establish a stable reference model of normal behavior. Mean and variance values of the sensed parameters are computed and stored as baseline operating conditions. During real-time operation, incoming sensor readings are compared with the learned baseline to detect deviations. The detected variations are analyzed using dynamic threshold limits to differentiate between normal behavior and fault conditions, allowing the system to respond proportionately.

When a minor anomaly is detected, the system generates a user notification through an IoT based alert mechanism to indicate potential inefficiencies or early stage faults. In the case of severe or persistent abnormalities, the Raspberry Pi issues a control command to isolate the appliance from the power supply using a relay module, preventing further damage or energy wastage.

Proposed System Architecture



Simultaneously, power and energy consumption are calculated from voltage and current measurements and logged over time, enabling users to analyze usage patterns and identify inefficient operating conditions.

This algorithm is computationally lightweight, making it suitable for real time execution on low-power edge devices. Approximately 60% of the collected data was used to establish baseline operating parameters, while the remaining data was used to validate anomaly detection performance.

ALGORITHM 1: INTELLIGENT APPLIANCE MONITORING

Step 1: Begin System Operation
Step 2: Initialize Sensors (Voltage, Current, Temperature)
Step 3: Acquire real time data (V,I,T) from sensors
Step 4: Check if baseline model is created If NO: Step 4.1: Collect data for training phase Step 4.2: Compute mean and variance Step 4.3: Store as baseline profile If YES: Proceed to Step 5
Step 5: Compare real time data with baseline values.
Step 6: Calculate deviation from baseline.
Step 7: Classify system condition: • Normal (Within Threshold) • Minor Anomaly • Severe Fault
Step 8: Take action based on classification: • If Normal – No action • If Minor – Send user alert • If Severe – Activate relay and cut power supply.
Step 9: Compute power and energy consumption.
Step 10: Update log database.
Step 11: Repeat Continously.
Step 12: End

Table 1: System Response Under Different Operating Conditions

Operating Conditions	Current Deviation	Temperature Rise	System Response
Normal Operation	±5%	< 2°C	No action
Minor Anomaly	5-15%	2–5°C	User alert
Severe Fault	>15%	>5°C	Relay cutoff

IV. RESULTS & DISCUSSIONS

The proposed intelligent appliance monitoring system was evaluated through real-time experimental testing under both normal and abnormal operating conditions. The objective of the evaluation was to assess the system's ability to learn normal operating behavior, detect anomalies, and respond appropriately through alerts and automatic power isolation.

During normal operation, the appliance exhibited stable current consumption and temperature profiles. The observed values were collected over a sufficient time period to establish stable operating conditions. Once the baseline was learned, real time sensor readings consistently remained within acceptable limits, confirming accurate recognition of normal system behavior without false alerts.

To evaluate anomaly detection performance, different abnormal conditions were intentionally created to evaluate system performance.

Under these scenarios, a gradual increase in temperature and current was observed, reflecting abnormal behavior. The system successfully identified these deviations when sensor values exceeded the learned baseline range. Minor anomalies triggered warning notifications to the user, while sustained or severe deviations resulted in automatic disconnection of the power supply.

This step-wise response mechanism effectively prevented damage and reduced unnecessary energy consumption. Energy consumption analysis revealed a noticeable increase in power usage during abnormal operating conditions.

By correlating energy consumption patterns with detected anomalies, the system was able to classify excessive energy usage as a soft fault condition. This capability demonstrates the effectiveness of the proposed approach in addressing not only safety related faults but also energy wastage in household appliances.

A comparative evaluation with fixed threshold monitoring highlighted the advantages of the adaptive baseline approach. Fixed thresholds were observed to either delay fault detection or generate false alarms under varying operating conditions. In contrast, the proposed system dynamically adapted to normal appliance behavior, resulting in more reliable anomaly detection and improved fault response.

Overall, the experimental results confirm that the proposed methodology provides an effective, low cost solution for intelligent fault detection, fault prevention, and energy monitoring in conventional household appliances. The results validate the feasibility of deploying adaptive, edge based monitoring systems for improving safety and energy efficiency in residential environments.

V. CONCLUSION

The proposed intelligent appliance monitoring system effectively integrates Internet of Things (IoT) technology with data-driven techniques to improve the safety, reliability, and energy efficiency of conventional household appliances. By utilizing a dual-layer architecture with ESP32 for real-time data acquisition and Raspberry Pi for centralized processing, the system ensures continuous monitoring of key electrical and thermal parameters.

The developed approach establishes an adaptive baseline representing normal operating conditions and detects deviations using a machine learning-based anomaly detection method. This enables accurate identification of abnormal behavior and classification of appliance conditions into normal, warning, and critical states. Unlike traditional threshold-based systems, the proposed method adapts to changing operating patterns and reduces the chances of false alarms.

Experimental results demonstrate that the system can successfully detect faults such as overheating, overcurrent, and voltage fluctuations under different operating conditions. The implementation of a staged response mechanism, including user alerts and automatic power isolation, enhances system reliability and prevents potential damage to appliances.

In addition, real-time energy monitoring allows users to analyze power consumption and identify inefficient usage patterns, contributing to reduced energy wastage. Comparative analysis confirms that the proposed adaptive approach performs better than fixed-threshold methods in terms of accuracy and responsiveness.

Overall, the system provides a practical and cost-effective solution for intelligent monitoring of household appliances. Future work can focus on integrating advanced learning techniques, expanding multi appliance support, and incorporating renewable energy sources for improved performance and scalability.

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