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Affordable IoT-Based Controllers for Future-Ready Smart Homes

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Abstract: The Internet of Things (IoT) has become widely used in modern technology and is now a key part of smart device applications. There are several ways to connect these devices, such as Bluetooth, ZigBee, Wi-Fi, and wired options like RS485/Modbus. Among these, WiFi is the most popular because it allows users to connect their devices to the internet and control them remotely from anywhere. While many affordable and DIY smart home setups have been developed over the years, most rely on unique, non-standard communication systems. This makes it difficult to connect everything to a single, unified control system. To solve this, we designed a low-cost control board that uses Wi-Fi and works with standard smart home servers and commonly available smart devices. The system uses microcontrollers from the Espressif family, which can be integrated into any home IoT setup. This approach makes it easier to turn regular homes into smart homes and helps support better energy management for future smart power grids, allowing people to save on energy costs.
Keywords: Future smart homes, home automation server, Internet of Things (IoT) network, monitor and con trol, smart controller board, smart grids, wireless fidelity (Wi-Fi) communication.

I. INTRODUCTION

The Internet of Things (IoT) refers to devices that can be connected and controlled through the internet. The main goal of IoT is to bring different devices together into a single system that can be managed remotely. By allowing devices to communicate and share information, users can build smart homes where everything is linked and easy to control. In a typical IoT setup, each device can operate independently and be managed using a phone, tablet, or computer. However, managing many separate devices can be confusing. That's why the idea of a Local Home Automation Server (LHAS) is useful it creates one network that connects all the devices and keeps the user informed using a shared communication protocol. Recently, many companies have started offering branded IoT products, mainly aimed at newly built homes.While these commercial systems allow users to monitor and control their devices, updating older homes can be difficult and expensive. Most of these commercial systems are also quite costly.In this project, we designed and built control boards using affordable ESP microcontrollers from Espressif Systems. These boards can be powered by 5V, 12V DC, or 230V AC, depending on what's needed. The main goal was to create a low-cost IoT system that works in both old and new buildings and can connect to standard smart home servers. The devices communicate using the MQTT protocol, which is common in IoT systems. Unlike some commercial devices, this solution is flexible and works seamlessly with various smart home setups.

The key contributions of this project include: A new system was developed to create a smart IoT network suitable for modern homes. An open-source automation server (LHAS) was set up, using Wi-Fi and MQTT to connect and control smart devices. This server also supports advanced features like fuzzy logic and deep learning. A Raspberry Pi was configured to run this server, and ESP-based modules were created to connect home appliances, turning them into smart devices capable of measuring electricity use. The system supports demand-side energy management by saving sensor data, helping users better control energy usage and understand their power consumption habits—useful for future smart grid planning.

II.SIMILAR WORKS

Many researchers have explored different methods to develop smart home systems. For instance, one early study used dual-tone signals to control devices remotely, while another used GSM communication and microcontrollers like Atmega and PIC to operate devices through text messages—offering benefits like easy customization and no internet dependency. Raspberry Pi has often been used in smart homes for controlling devices and managing sensors. More recent systems rely on ESP microcontrollers, especially the ESP32, which includes built-in Wi-Fi. These controllers support advanced applications, such as triggering appliances using a smartphone app or even streaming video through modules like the ESP32-CAM. Some studies also implemented the Home Assistant (Hassio) platform on Raspberry Pi for managing the smart home network.Several projects have focused on tracking and controlling energy usage. One study designed a system that monitors how much electricity is used and can even detect electricity theft. Other systems give users control over energy consumption through IoT devices and make smart recommendations based on their energy habits.IoT has also been used in home security. Some researchers created smart surveillance systems with intrusion detection and real-time video monitoring. Others developed systems that automatically trigger devices and alert homeowners when unusual activity is detected. Different studies have examined the communication methods used in smart home networks. These include WiFi, Bluetooth Low Energy (BLE), ZigBee, RS485/Modbus, and ESP-NOW. Research shows that the ESP32, with its combination of Wi-Fi, BLE, and ESP-NOW support, is ideal for low-energy sensor networks in future smart homes. Voice-controlled smart homes have also been developed. For example, one project used the ESP32 with Google Assistant to control appliances and monitor environmental conditions. Data from sensors was saved in cloud databases for later analysis. Advanced systems have been proposed to learn from user behavior and suggest energy-efficient appliances. Other solutions include fuzzy logic and machine learning to reduce energy waste, and systems that schedule home energy use based on demand and time-of-day pricing. While many earlier projects focused on specific controllers or communication types, this study proposes an approach that brings together various intelligent modules and commercial devices into one open-source network. Using a Local Home Automation Server (LHAS), the system ensures compatibility and enables efficient demand-side energy management—supporting smarter power usage in future energy grids.

III.PROPOSED SYSTEM

This smart home system uses ESP-based boards for both control and monitoring. The modules used include the ESP8266 ESP-01, ESP8266 NodeMCU (ESP-12E), and the ESP32-Wroom-32D. These microcontrollers allow devices to connect over Wi-Fi and are ideal for affordable smart home projects.

3.1 System Architecture and Functionality

The proposed smart home system uses several microcontroller modules, including the ESP8266 (ESP-01, ESP-12E Node MCU) and the ESP32-Wroom-32D. These modules allow devices to connect through Wi-Fi for easy communication. The system is controlled and monitored through the Local Home Automation Server (LHAS), which uses the open-source platform Hassio. Hassio can communicate with devices using various protocols, with Wi-Fi and MQTT being the main communication methods.

- ESP32-based devices communicate via Wi-Fi, and MQTT is used when more complex software is required or when non-ESP-based devices are involved.
- The system integrates both commercial smart devices and ESP-based modules, providing a comprehensive solution for managing appliances and energy consumption in homes.

3.2 Hardware Components

The system is built using the following key hardware components:

Hardware components	Purpose
ESP-01 Wi-Fi Module (ESP8266)	Small, inexpensive, and popular for IoT applications. Supports Wi-Fi communication but lacks analogto-digital conversion (ADC) pins.
ESP-12E NodeMCU	More advanced than the ESP-01, with additional GPIO pins and an ADC pin. Allows for better control and sensor integration.
ESP32-Wroom-32D	Offers more GPIO and ADC pins, better processing power, and more memory. Suitable for more complex smart home tasks, such as energy monitoring and light control.

These modules allow for seamless communication between the devices and the LHAS through wireless connections.

3.3 Security

The system employs MQTT as the communication protocol, which ensures secure, efficient, and lightweight message transmission. To maintain security and reliability:

• Mosquitto, an open-source MQTT broker, is used to manage communication between the devices. • Data is transferred using topics, ensuring that publishers and subscribers only receive the relevant information.

• Encryption methods can be integrated with MQTT for added security in real-world applications.

3.4 Operational Workflow

The operational workflow of the system follows these key steps:

1. Device Integration: All smart devices (whether ESP-based or commercial) are connected to the LHAS.
2. Communication: Devices communicate with the server through MQTT, sending and receiving data.
3. Control and Monitoring: Users can control and monitor the devices through a web interface or mobile apps (Android/iOS).
4. Data Storage: All data collected (e.g., energy consumption, device status) is stored in the database of the LHAS for later analysis.

3.5 Additional Features

• Energy Monitoring: Smart plugs equipped with energy measurement sensors (e.g., Pzem-004T) provide real-time data on voltage, current, power, and energy consumption.
• Environmental Sensors: Modules such as temperature and humidity sensors (DHT11) enable home automation based on environmental factors.
• Lighting Control: Using light intensity sensors, the system can automate lighting based on ambient conditions.

3.6 Block Diagram

Here's a simplified block diagram of the system:

1. Smart Devices (Relays, Sensors, LED Modules): Connect to the ESP-based microcontrollers.
2. ESP Modules (ESP-01, ESP-12E, ESP32): Act as interfaces for smart devices to communicate with the LHAS.
3. LHAS (Hassio): Central server for controlling and monitoring devices, installed on a Raspberry Pi.
4. MQTT Broker (Mosquitto): Manages message communication between the smart devices and the LHAS.
5. User Interface: Users interact with the system through a web browser or mobile apps (Android/iOS) for monitoring and control.

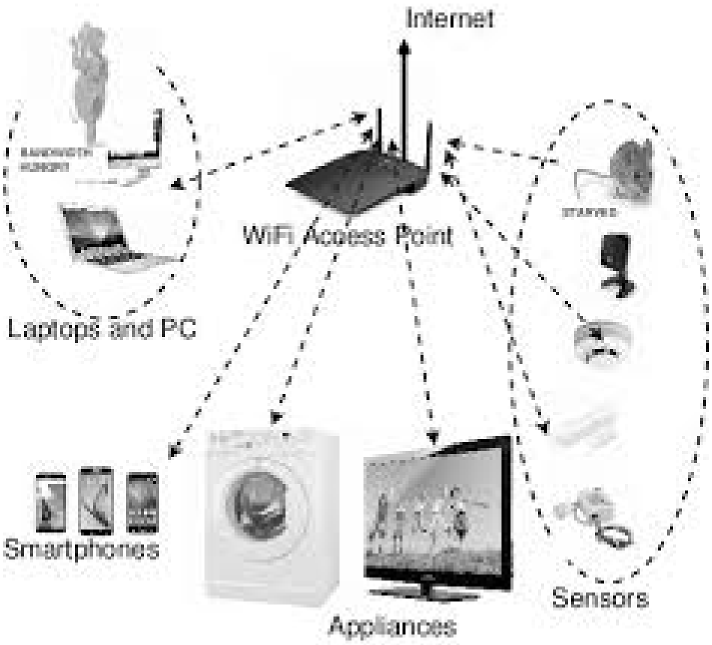

FIG:1 PROPOSED SYSTEM

IV.ADVANTAGES AND DISADVANTAGES

4.1 ADVANTAGES

• Cost-Effective: Utilizes affordable ESP-based modules, reducing implementation costs.
• Scalability: Easily expandable by adding new devices without significant changes.
• Energy Monitoring: Tracks energy consumption and helps optimize usage.
• Flexibility and Customization: Users can modify and configure the system as needed.
• Open-Source and Community Support: Benefits from open-source software and a supportive community.

4.2 DISADVANTAGES

• Complex Setup: Requires technical knowledge for setup and configuration.
• Limited Device Compatibility: Not all commercial devices may be compatible with MQTT.
• Dependence on Wi-Fi: Relies on a stable Wi-Fi connection for functionality.
• Security Concerns: Potential vulnerability to unauthorized access without proper security measures.
• Limited Cloud Integration: Lacks native cloud support for remote monitoring and control.

V. RESULTS

The LHAS software and ESP-based modules were successfully implemented and tested in a real home setting. The user interface was designed to be clear and informative, with all home components connected to a local area network. While the system doesn't require an internet connection, it can be remotely controlled and monitored through the internet.All data related to control, measurement, and calculations were saved in a database, which allows for future analysis. The system was tested for five months in a house, monitoring energy, temperature, humidity, and light intensity, with ON/OFF control functions. The system performed well during the testing period, with all sensors and the LHAS operating correctly. Data was recorded in the database, and the control signals and MQTT commands were executed with minimal delay. This study proposed an intelligent energy management system using affordable equipment and software. While recent studies have focused on certain aspects like communication technologies and protocols in home automation, this system integrates all aspects.It uses low-cost modules to make household appliances smart. A mobile app for Android and iOS was developed for secure connection to the server, both inside and outside the home.All energy consumption data is stored in a database, enabling the analysis of user behavior and supporting demand-side energy management in smart grids. The system's primary goal was to create intelligent modules for demand-side energy management.A comparison of the system's components with commercial alternatives revealed that the cost of the modules in this study is about one-third of the commercial modules' cost.

FIG :2 RESULTS

VI.APPLICATION

The system hardware includes the LHAS mini-computer, various environmental sensors, and smart plugs, all using ESP-based boards. The LHAS is set up on a Raspberry Pi 4B using Hassio, which handles automation tasks and communication between microcontrollers and the database for energy management.ESP32 boards were used to create modules that measure temperature, humidity, and light intensity. These modules also include control features like Fuzzy Logic and use MQTT for data transmission. Smart plugs contain current sensors (up to 100A) and relays (up to 10A), which are enough for normal home appliances .Setting up the system is straightforward. The LHAS runs on a mini-computer, and sensor modules are placed around the home. Smart plugs and relay modules connect to appliances to provide control and monitoring functions. The ESP boards require firmware updates to work with LHAS. Tools like ESP-Home Flasher are used to upload the required configurations. The ESP32 modules are set up for MQTT communication, functioning as both data senders and receivers. Temperature and humidity are measured using the ESP-01 with a DHT11 sensor. Smart plugs, based on NodeMCU and PZEM-004T sensors, monitor energy use and help analyze appliance behavior. NeoPixel LEDs use built-in WS2811 drivers and WS2812 components, making them individually addressable. This allows each LED to show different colors and patterns, offering advanced lighting control.

VII .FUTURE ENHANCEMENT

In future iterations, the Local Home Automation System (LHAS) can be enhanced by integrating machine learning algorithms to predict energy consumption patterns and optimize appliance usage. This predictive control can help reduce electricity bills and improve overall energy efficiency by automatically adjusting appliances based on user habits and weather conditions.

Additionally, support for voice control through integration with smart assistants like Amazon Alexa or Google Assistant can offer users a hands-free experience. Expanding the system to include more wireless communication protocols, such as Zigbee and LoRa, will also improve device compatibility and extend communication range for larger properties.

Security enhancements will be a crucial focus in upcoming versions. Implementing end-to-end encryption for all device communications and adding multi-factor authentication for remote access will significantly strengthen system security.Cloud integration can also be introduced to store backup data and provide remote diagnostics and firmware updates. Furthermore, adding a mobile app with real-time alerts and control capabilities will enhance user convenience. Environmental sensing can be extended to include gas leak detection, motion sensing for intrusion alerts, and air quality monitoring, making the system more comprehensive and improving the safety and comfort of smart homes.

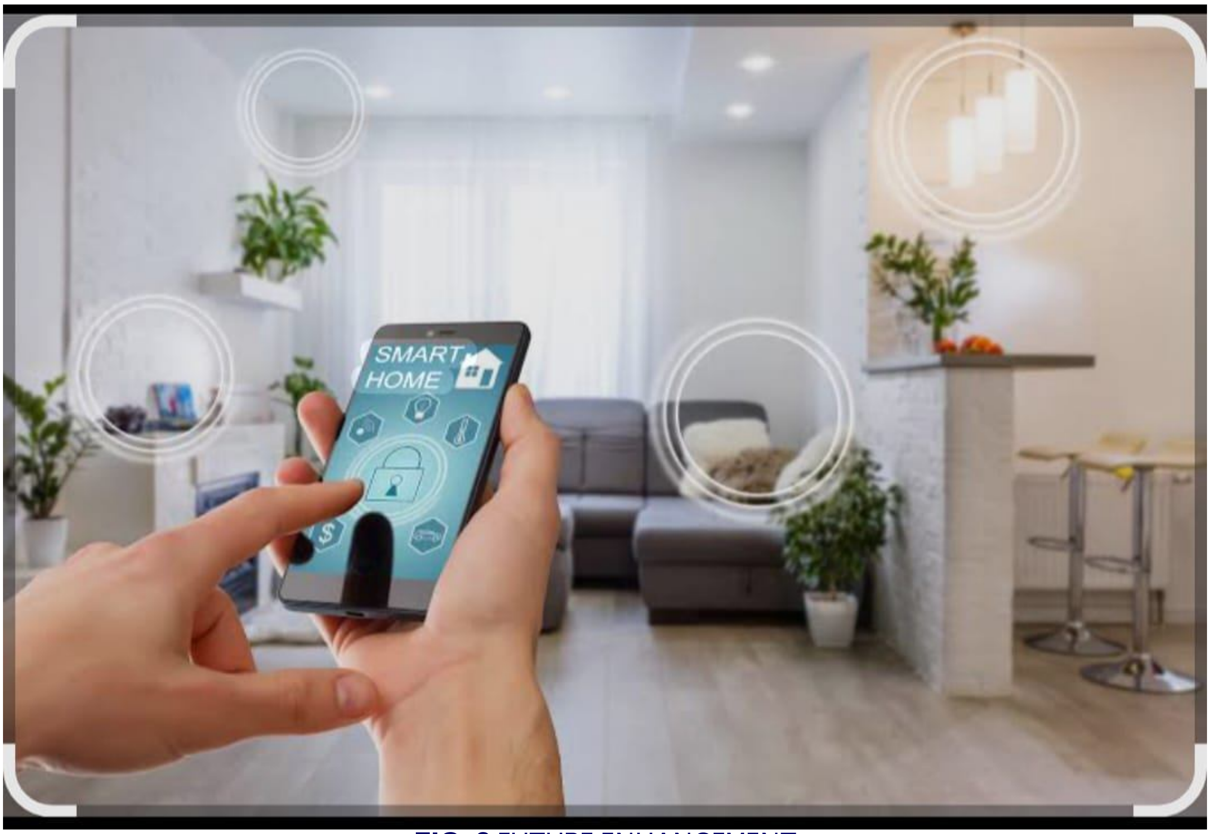

FIG :3 FUTURE ENHANCEMENT

VIII.CONCLUSION

This study highlights the importance of smart grids and demand-side energy management for future homes. It demonstrates how low-cost, open-source modules and a Local Home Automation Server (LHAS) can turn an ordinary house into a smart home. Devices like the NodeMCU and PZEM-based smart plug help monitor energy usage, which is vital for smart grid integration. The system collects data that can be used for deep learning to analyze consumer behavior and load profiles. Future enhancements could involve using advanced AI models like convolutional neural networks and LSTM with tools like Jetson Nano for better prediction and energy optimization.

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