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Design and Implementation of Controller Boards to Monitor and Control Home Appliances for Future Smart Homes

Abdulkadir Gozuoglu, Okan Ozgonenel, *Senior Member, IEEE*, and Cenk Gezegin

***Abstract*—Internet of Things (IoT) applications have become popular and are used in innovative device applications. Although radio frequency communication methods, including Bluetooth, zonal intercommunication global standards such as ZigBee, and wireless fidelity (Wi-Fi) and wired communication such as RS485/Modbus, can be used in IoT networks, Wi-Fi is preferred by users due to its ability to connect to the internet and allow users to control devices from anywhere in the world. In addition, numerous do-it-yourself and low-cost solutions have been presented for intelligent home applications in recent decades. However, many solutions use proprietary communication protocols that are not standards-based, so integrating a standardized local home automation server is difficult. We proposed a design based on low-cost Wi-Fi-based IoT-capable control boards that communicate with an IoT network of standard home automation servers and commercial intelligent home devices. The primary focus of the proposed system is to implement control boards for IoT applications by using Espressif systems series microcontrollers that can run in any IoT network used for home automation. Converting traditional houses into smart homes will support demand-side energy management applications in future smart grids and allow customers to use low-cost energy.**

***Index Terms*—Future smart homes, home automation server, Internet of Things (IoT) network, monitor and control, smart controller board, smart grids, wireless fidelity (Wi-Fi) communication.**

I. Introduction

INTERNET of Things (IoT) can be defined as devices that can be managed or controlled over the Internet [1]. The main objective of IoT devices and networks is to combine separate devices and control them via the Internet [2]. Bringing all devices within a network, allowing equipment to communicate with each other, and sending helpful information to the user creates smart homes [1], [3].

In IoT applications, devices are independent and can be managed through smartphones, tablets, or personal computers. However, having separate devices may confuse a user and make use difficult. The main objective of an IoT system is to create a single network and provide a local home automation server (LHAS) that connects the devices using an appropriate communication protocol and provides information to the user.

Recently, several trademarks have appeared to market IoT devices [4]. Most IoT devices are intended for installation in new builds. All the devices are connected to the smart home automation system, which allows users to view status and control capabilities; upgrading old houses with smart devices is usually very hard and expensive. Commercial IoT devices usually appear as high-cost.

In this study, Espressif systems (ESP)-based control boards were designed and implemented. Depending on the need, the boards can be supplied with 5/12 V dc or 230 V ac. The project's primary goal is to develop a low-cost IoT network system that can be applied to new and old buildings and communicate with all standard home automation servers. The ESP series microcontroller is used as a low-cost solution. The message queuing telemetry transport (MQTT) protocol was used to communicate between devices. Commercial IoT switches partially communicate with IoT networks but must be fully flexible.

The significant contributions of this study are summarized as follows.

1) A new architecture was designed and implemented to form an intelligent IoT network for future smart homes.
2) The use of an LHAS was proposed. An open-source automation server has been adopted; this allows the required settings to be configured. The server uses wireless fidelity (Wi-Fi) and MQTT as communication methods and is configured to integrate with smart home appliances. It is capable of applying Fuzzy Logic controllers and deep learning methods.
3) A Raspberry Pi mini-computer has been configured to run the automation server. ESP-based innovative modules have been designed and implemented. Home appliances are attached to the modules to form smart devices and provide ac energy measurements.

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4) The demand-side energy management system monitors and saves all sensor data. The management system offers users an improved method of control. The data can be used to learn the energy consumption behavior of users and create load profiles that are important for future smart grids.

The rest of this article is organized as follows. Section II discusses related works. Section III introduces the automation server and intelligent modules that form the IoT network and provides an overview of the communication protocol. Section IV gives an overall description of the solution and experimental applications. Section V reports the evaluation results, and Section VI concludes this article.

II. Related Works

Several smart home automation applications have been studied and performed. Koyuncu [5] introduced a smart home using dual-tone multifrequency for transmitter and receiver. Erdem and Uner [6] investigated a system based on a global system for mobile (GSM) communication and used the Atmega and peripheral interface controller microcontrollers for devices. These studies had the advantage of using easily customizable microcontrollers, and no internet connection was needed [7]; the GSM system used texts to send commands. Many studies use the Raspberry Pi as a microcontroller to control devices and integrate sensors within smart homes [8], [9]. Ahammed et al. [10] proposed an IoT network for electrical load classification.

Recent studies have used ESP microcontrollers, which contain Wi-Fi. Kabir et al. [2] proposed an ESP32-based study that used an Android application to control relays that trigger home appliances. Akhmetzhanov et al. [11] designed a remote access application that used an ESP32 module with a built-in camera module (ESP32-CAM) and used a Raspberry Pi to run the Home Assistant (Hassio) platform to create a home automation system. The application recorded real-time video and collected sensor data to monitor and control a house. Stolojescu-Crisan et al. [12] developed an IoT-based smart home automation system that integrated information from different home automation applications developed over the last decade. Harishma et al. [13] proposed an IoT-based energy consumption monitor system that allows users to control their energy consumption and detect power theft.

IoT devices can be used for applications other than energy usage. Alani and Awad [14] designed an intelligent system to provide remote control and monitoring of an intrusion detection system. Sultana and Wahid [15] investigated home security systems that could trigger loads and devices automatically and provide real-time video recording. Khanchuea and Siripokarpirom [16] implemented a multiprotocol gateway for intelligent home applications based on a multihop wireless network. The application analyzes the behavior of different communication protocols, including Wi-Fi, Bluetooth low energy (BLE), ZigBee, RS485/Modbus, Espressif-based communication protocol (Esp-Now), and MQTT. The study concludes that the ESP32 Wi-Fi/BLE chip, combined with the ESP-NOW protocol, represents a good choice for low-power sensor networks for future intelligent homes. Liao et al. [17] constructed a smart home that used the ESP32 for the applications and demonstrated how the blink application could be controlled using voice commands via Google Assistant. The application used several sensors to monitor the environment, and data was stored in an online database.

Luo et al. [18] proposed a system that learns users' energy consumption and usage behavior of appliances. The system makes recommendations to the users about suitable appliances based on different user profiles.

Ducange et al. [19] introduced a study on improper usage of home appliances. The system used fuzzy logic and machine learning to monitor each home appliance and perform analyses to lower residential energy consumption. Luo et al. [20] designed a multistage home energy management system to schedule and estimate the energy needed in the house. Sanjari et al. [21] proposed an intelligent energy management system to analyze energy costs and times of usage of residential loads—the system aimed to manage the optimal operation of hybrid energy flow. Ahmad et al. [22] developed a short-term load forecasting model to predict electrical energy demand for smart grids. Zielonka et al. [23] designed a microcontroller-based intelligent management system and IoT network for optimal air flow in intelligent homes. Yousefi et al. [24] compared several techniques for modeling smart homes' non-periodic loads and energy demands.

Various applications have been used to create intelligent homes with demand-side energy management systems for future smart grids.

Previous studies have been based on a specific controller and communication environment. This study considers that the intelligent modules and commercial products can be integrated into a standard system using an open-source IoT network and LHAS. This approach ensures that demand-side energy management will contribute positively to future smart grids.

III. Concept of Designing IoT Networks and Smart Modules

This application's control and monitoring boards have been designed using the ESP8266-based ESP-01 Wi-Fi module development kits, ESP8266-based ESP-12E NodeMCU Wi-Fi module, and ESP32-Wroom-32D module.

The LHAS is based on the open-source Hassio and has been created to control and monitor the entire intelligent system in the house; the general working principle is shown in Fig. 1. The LHAS can communicate with smart devices using numerous protocols; however, the ESP32-based devices perform communication via Wi-Fi. MQTT is preferred for communication in cases where the software is too complex to be written in the ESP-Home application or if the smart device is not ESP-based. ESP-Home provides a framework for creating configuration files to integrate the ESP boards.

Commercial intelligent modules are generally a barrier to users due to their high cost and installation difficulty. ESP-based innovative modules are designed to convert home appliances into smart devices.

The ESP-based modules are capable of firmware updates, particularly the configuration files created for each ESP module

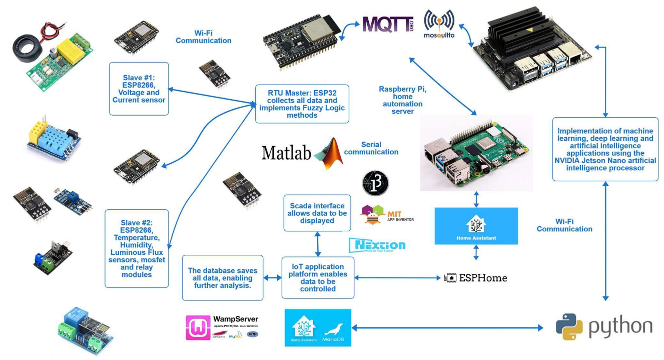

Fig. 1. General working principle of the proposed system.

in this application. The ESP modules communicate with the LHAS via wireless communication.

Commercial smart devices can be integrated with the LHAS using MQTT, and an MQTT broker was used in this study to support communication with commercial devices in the home.

The intelligent system supports smart grids by analyzing users' demand-side consumption behavior. The measurements in this study are saved in the database installed in the LHAS. The data can provide information on the consumption behavior of users.

A. Local Home Automation Server

Smart home applications can be created by applying a smart plug to each appliance. The overall control performance can be increased by integrating all the devices with the LHAS.

In this study, Hassio was used as the LHAS. Hasio is designed to have a user-friendly and customizable user interface. Hassio is open source and free to use to control and monitor all appliances in smart homes using a Web browser or Android/iOS applications.

The Hassio distribution includes an operating system and can be installed on many computers. Raspberry Pi is the most popular hardware environment in smart home applications. The mini-computer is a relatively low-cost, low-power, and silent single-board computer. The Raspberry Pi works as a local server and database. My-structured query language database was configured in the LHAS.

B. Esp-Series Microcontroller and Circuit Design

The ESP-01 Wi-Fi module is based on an ESP8266 microcontroller capable of connecting devices via Wi-Fi. The small dimension (14.3 mm × 24.8 mm) and the low cost of the board make it popular in IoT applications. The microcontroller is integrated with transmission control protocol/internet protocol (TCP/IP), 802.11 b/g/n, and Wi-Fi Direct (P2P). It has 32 kB of flash memory and two general-purpose input and output (GPIO) pins. The board does not support analog-to-digital converter (ADC) pins. It supports the inter-integrated controller, universal asynchronous receiver transmitter, and serial peripheral interface communication protocols [25].

The ESP-12E NodeMCU Wi-Fi module is also based on the ESP8266 microcontroller. The NodeMCU module has 17 GPIO pins and 1 ADC pin with a 10-bit resolution. The NodeMCU also includes reset and boot buttons, an onboard light emitting diode (LED), and a micro universal serial bus (USB) connector for uploading and debugging purposes [26].

The ESP32 development kit is based on the ESP32-Wroom-32D microcontroller. The ESP32 Module has 32 GPIO and 16 ADC pins with 10-bit resolution. It has 520 kB static random-access memory and 4 MB flash memory. The ESP32 development kit also includes a reset boot button, an onboard LED, and a micro-USB connector for uploading and debugging purposes [27].

1) ESP-01-Based Relay Module: The relay module is a widely used device to control appliances (ON/OFF control). The relay module includes a relay and an ESP-01 board. Other ESP boards can be used as the module only requires one digital output from the microcontroller.

2) ESP-01-Based Temperature and Humidity Module: Temperature and humidity are essential measurements in smart homes. The DHT11 is used as a sensor; it is low-cost and easy to use, with an accuracy of ±2 °C for temperature and 5% for relative humidity, which is adequate for most in-home measurements.

The sensor uses one digital input pin from the microcontroller, so the ESP-01 is adequate for this application. The module measures temperature and humidity with a preset interval (5 s). If a module is placed in several places around a house, the measurements can be used for various automation scenarios using control methods such as Fuzzy Logic.

3) ESP 32-Based Light Intensity Module: Smart home automation can include applications based on ambient light levels, and light intensity measurements are required. Light intensity measurement using an ESP32 module with a light sensor has been implemented.

4) ESP-01-Based NeoPixel-LED Driver Module: NeoPixel LEDs are addressable red, green, and blue (RGB). The application uses WS2811 drivers and WS2812 LEDs. The LEDs have separate integrated chips, enabling them to have a separate predefined color, creating various effects.

One data pin controls the LED strip so that the controller board can be based on ESP-01.

The controller board can operate several LEDs or LED strips. The controller and local server can perform specific colors or various light effects.

5) NodeMCU and PZEM Sensor-Based AC Energy Metering Module: Smart plugs can incorporate both relay modules and power and energy measurement. The NodeMCU microcontroller and Pzem-004t v3.0 sensor have been used. The Pzem 004t v3.0 is a sensor to measure alternating current (ac) voltage, instantaneous power, and energy. The sensor communicates over a TTL interface using a Modbus-RTU-like communication protocol. The Pzem 004t sensor can operate in 80–260 V and 100 A (max: 23 kW) conditions, with 16-bit resolution. AC voltage, current, active power, power factor, and energy consumption measurements can be obtained [28].

The energy consumption behavior of the house was monitored, with the overall energy consumption taken from the main supply box. NodeMCU saved all measured data in the LHAS database.

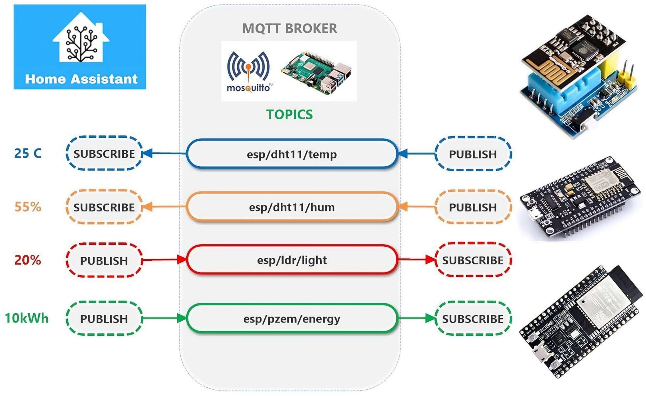

Fig. 2. MQTT broker communication.

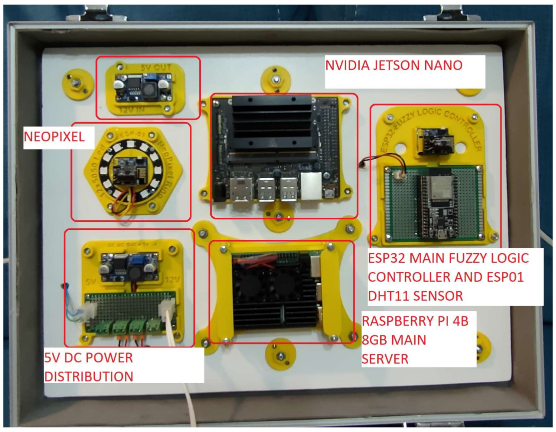

Fig. 3. LHAS and IoT controller boards.

C. MQTT Communication

MQTT data communication is transferred between publishers and subscribers using topics, and a broker manages the transfer process. Mosquito is widely used as a broker and was used in this study, being installed alongside Hassio.

MQTT has several advantages. As shown in Fig. 2, the main functionality of the broker is to filter data streams between subscribers and publishers according to the topic information. There is no direct connection between publishers and subscribers. Communication can be two-way. MQTT brokers do not save the messages [29].

IV. Applications

The hardware developed to monitor a house is shown in Figs. 3 and 4. The hardware consists of the LHAS mini-computer, the monitoring sensors for environmental information, and smart plugs. All measuring and control modules are based on ESP boards.

Hassio is installed on a Raspberry Pi 4B mini-computer as LHAS and manages the automation and scenario applications.

It also implements the communication between the microcontrollers and database to form an energy management system. The temperature, humidity, light intensity, and NeoPixel LED controller modules were implemented using ESP32 modules.

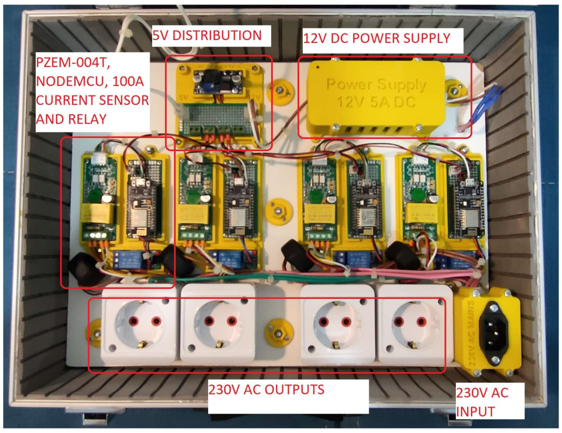

Fig. 4. AC energy meters and smart plugs.

The light intensity module also implemented control methods (Fuzzy Logic) and used the MQTT communication protocol to transfer data and commands. This ESP32 board included a relatively high amount of flash memory for the applications.

The smart plugs include a current transformer capable of 100 A; however, the relay modules can only handle 10 A, which is sufficient for a typical home load (<2 kW).

A. Converting Home Appliances Into Smart Devices

The installation of modules to control and monitor appliances is straightforward. The LHAS is installed on a mini-computer (e.g., Raspberry Pi), and sensing modules (temperature, humidity, light intensity, and energy) are positioned in the house as required. The smart plugs and relay modules are connected to the desired load or appliance and control and monitor the appliance.

B. Firmware Update

The default factory settings of the ESP boards are not applicable for LHAS applications and must be updated to support the LHAS server requirements. ESP-Home Flasher was used for this purpose [30]. Commercial smart plugs can also be integrated into the LHAS.

The ESP32 module was integrated with the MQTT broker, as shown in Fig. 5(a). Two-way communication was tested and implemented, with the ESP32 board being set to perform both Publisher and Subscriber tasks. In this example, the intelligent module periodically published light-intensity information to the broker and requested temperature, humidity, power, and energy information from the broker by subscribing to specific topics.

C. Smart Controller Boards and IoT-Network

The temperature and humidity measurement module is shown in Fig. 5(a) and is based on the ESP-01 and DHT11.

The smart plug module is shown in Fig. 5(b) and is based on the NodeMCU development kit. Any appliance can be connected to the relay module and the PZEM-004T-based smart plug allows measurements to analyze consumption behavior and determine load profiles.

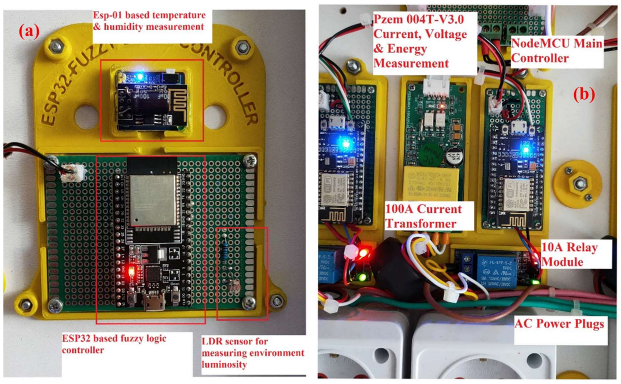

Fig. 5. (a) Esp-01-based temperature and humidity sensing module and ESP-32-based controller board. (b) NodeMCU and Pzem sensor-based smart plug.

Fig. 6. ESP-01-based NeoPixel driver.

The NeoPixel LED driver, shown in Fig. 6, has a working principle that differs from regular RGB LEDs. RGB LEDs use pulsewidth modulation (PWM) signals from the microcontroller to control the intensity of each LED color as a separate signal connection with a common ground. The NeoPixel LEDs are addressable RGB LEDs and use the WS2811 driver and WS2812 LEDs. As all the LEDs are individually addressable, each LED can light with a separate color and be made to perform various lighting effects.

D. Data Visualization

The IoT network and Hassio local automation server are used to achieve communication and integration between devices and provide information to the user. Sample screen views of the user interface are shown in Fig. 7.

E. Intelligent Control and MQTT

Ambient luminosity was measured on the ESP32 module using a light-dependent resistor. The fuzzy logic controller used the luminosity and other data to control the intensity of the LEDs. Values were sent to Hassio via the MQTT broker using a specific topic, and the automation defined in Hassio performed automatic control of the light in the house; in this example, the brightness of the NeoPixel LEDs.

Fig. 7. Sample screen views from the LHAS user interfaces. The screens include (from left top to right) general control, energy measurement, smart plugs, voltage measurements, home intelligent devices, and total energy consumption tabs.

F. LHAS and ESP-Based Module Communication

Wi-Fi is the primary communication protocol between clients and the central server. The ESP-based modules and LHAS integration were achieved using the Hassio server's ESP-Home application.

V. Results and Discussion

The LHAS software and ESP-based modules were implemented and tested. The user interface was designed for clarity and to be informative. All the home components are connected to the local area network, although connection to the internet is not required. The internet connection may be used to control and monitor the system remotely.

All control, measurement, and calculated data are saved in the database, which can be used as historical data for further analysis.

The system has been implemented in a real house to monitor energy, temperature, humidity, and light intensity and provide ON-OFF control. Fig. 8 shows the energy module and a record of energy usage.

The system has been tested in a house for five months. All the sensors and LHAS performed correctly. All measurements were saved to the database: the control signals and MQTT commands were performed with minimum delay.

This study has proposed an intelligent demand-side energy management system using relatively low-cost equipment and software. Recent studies have focused on specific parts of the system, such as the communication technologies and protocols in home automation systems [2], [4], [5], [6], [7], [8], [9], [10],

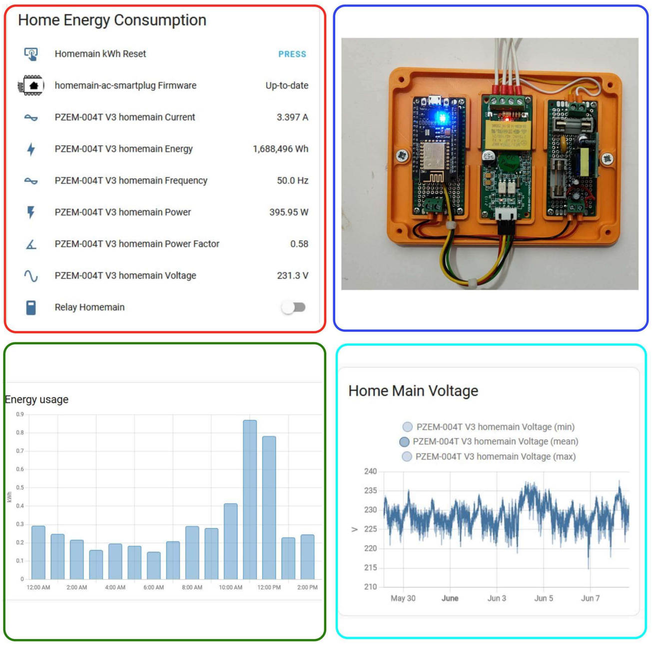

Fig. 8. Implementation of the proposed application into a real house and monitoring real-time measurement.

TABLE I
COST COMPARISON FOR SMART MODULES

Commercial Smart Modules	~Cost ($)	The Modules in This Study	~Cost ($)
One-channel smart relay module	$21.67	Esp-01-based relay module	$2.78
Smart switch with temperature and humidity sensor	$27.50	Esp-01-based temperature and humidity module	$4.17
The smart home ambient luminosity sensor	$19.44	Nodemcu-based light intensity module	$5.00
Smart ws2811 neopixel driver	$19.44	Esp-01-based neopixel LED driver module	$3.33
Smart energy measuring module	$27.78	Nodemcu and pzem sensor-based AC energy metering module	$13.89
The smart home main controller	$333.3	Raspberry-based central controller for LHAS	$138.89
Total	**$449.17**	**Total**	**$168.06**

[11], [12]. Many studies on home automation systems have used ESP32-based microcontrollers and Raspberry Pi processors. However, these studies generally investigated monitoring and controlling the devices inside or outside the home.

Communication technologies have been developed, including Wi-Fi, BLE, ZigBee, RS484/Modbus, and phone applications [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24].

This study uses Hassio as a source of LHAS. Up-to-date and low-cost modules are used to implement modules that can make household appliances smart. An Android/IOS mobile application has been implemented to connect securely to the server from inside or outside the home. All measurements have been saved to the database to allow the energy consumption behavior of consumers to be determined and provide essential information for demand-side energy management in Smart Grids.

The study's primary purpose has been to design and implement intelligent modules for use in demand-side energy management systems. An analysis has been performed to compare commercial innovative modules with the modules designed and implemented in this study. The comparison is given in Table I for some of the components in the system.

The cost of the commercial modules was obtained as an average value from online stores. The average cost of the modules in this study is almost one-third of the cost value of the commercial modules.

VI. Conclusion

Smart grids and demand-side control are essential for future energy management; demand-side control systems will need to be implemented in intelligent houses. Implementation can be achieved with low-cost innovative systems. This study is based on low-cost, open-source smart modules, and LHAS. The database provided data for further analysis and was used for graphical display in the user interface.

The LHAS and intelligent modules show that an ordinary home can be converted into a smart home with low-cost devices and open-source software. The energy measurements to monitor consumption in the home, which are essential for demand-side energy management applications for future smart grids, can be implemented using the NodeMCU and Pzem sensor-based smart plug shown in Fig. 5(b).

The overall energy consumption in the house can be analyzed. All measurements are used as input data in deep learning, which can give information to smart grids about consumption behavior and the load profile of each consumer in the electrical network. Future smart grids will be more effective with demand-side monitoring and electrical network energy management in the high, medium, and low-voltage stages (HV, MV, and LV). Future research will be oriented toward extending the system with deep learning applications.

This study performed IoT network data flow, MQTT communication, and fuzzy logic control for home appliances. Tests were performed on the fuzzy logic control. The aim was to extend the use of fuzzy logic controllers to increase the resolution and sensitivity of controlling home appliances.

In contrast, convolutional neural networks and long short-term memory based deep learning models can be applied to the system with the help of the Jetson Nano developer kit. The neural network is trained on the measured data. As a result of the learning procedure, consumers' consumption behavior and load profiles can be obtained. The up-to-date load profiles will help future smart girds implement optimal energy management and load flow analysis.

Appendix

This study developed five modules. Further modules can be developed as required using similar design methods. Fig. 9 shows the current system and how it may be extended.

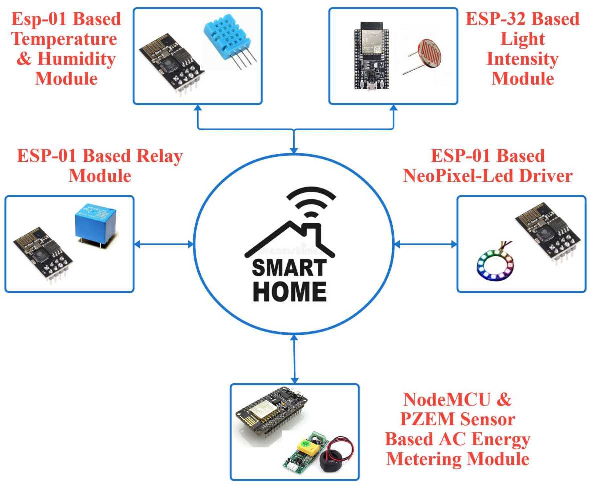

Fig. 9. Block chart of the proposed technique.

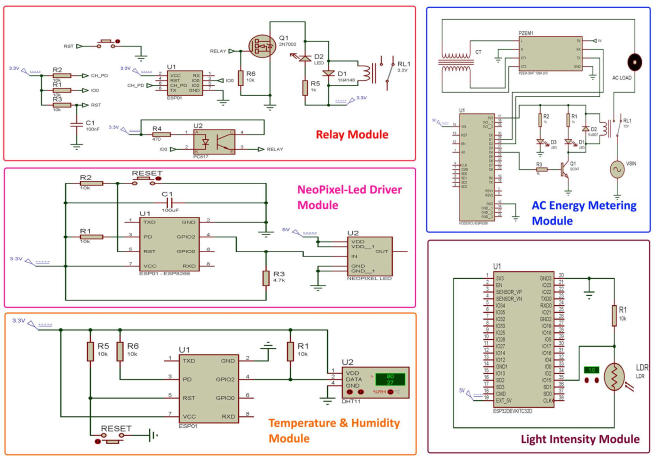

Fig. 10. Schematic diagram of modules.

Fig. 10 shows a schematic diagram of the relay module, ac energy metering module, NeoPixel LED driver module, temperature and humidity module, and light intensity module.

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