ASHESI UNIVERSITY

ENERGY MONITORING FOR SMART HOMES USING INTERNET OF THINGS

CAPSTONE PROJECT

B.Sc. Electrical and Electronic Engineering

Dzifa Mercy Hodey

2020

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CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Electrical and Electronic Engineering.

Dzifa Mercy Hodey

2020

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: ………………………………………………………

Candidate's Name: Dzifa Mercy Hodey

Date: 11th May 2020

I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University College.

Supervisor's Signature:

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Supervisor's Name:

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Date: …………………………………………………………………………………………

Acknowledgements

I would like to express my sincere appreciation to my supervisor, Mr Richard Awingot Akparibo, who gave me the golden opportunity to undertake this wonderful project. I am very grateful for your encouragement and academic advice, which helped bring the project to completion. I am also thankful to all Engineering Department faculty members for their help and support. Very special gratitude goes to God, and to my family for their immense support while working on this project. Finally, I would like to thank all colleagues who helped me learn and understand concepts for successful implementation of the project.

Abstract

The increasing demand for electricity in Ghana has led to concerns about energy conservation, to reduce the rising energy costs as well as the carbon emissions produced from energy generation. Popular energy conservation methods used in Ghana include turning off devices when not in use and using Light Emitting Diode (LED) lamps in place of incandescent bulbs which consume more power. However, these methods do not have very significant results and are not very efficient. Additionally, the use of energy management systems or smart home systems is not very common in Ghana, although proven to be effective. Most approaches to smart energy management for households encompass sensor-based or application-based control of devices and monitoring of energy consumption. However, in this project, the development of a smart home operated using both sensor-based and application-based control is explored while monitoring energy consumption. This is achieved using Internet of Things.

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Chapter 1: Introduction

1.1 Background

Electrical energy is a convenient form of energy which can be monitored and controlled easily. Its ability to be transferred easily adds to its preference over other forms of energy. The demand for energy is constantly increasing, hence energy management is very important [1]. Also, there is a need to develop energy management solutions that make use of modern technologies and innovations. Smart building control is an innovation that is presently being explored as a method of energy management [2]. Smart buildings have been found to reduce energy consumption and costs [3]. Furthermore, the implementation of energy monitoring and control in smart homes is very efficient in reducing energy consumption [4]. However, the existing systems in Ghana do not incorporate Internet of Things. This research project seeks to explore the development of a cost-efficient smart building with an energy monitoring system controlled using Internet of Things (IoT) for average middle-income Ghanaians.

1.2 Problem Definition

With an annual population growth rate of 2.2% in Ghana, there is an increasing demand for utilities, specifically electricity [5]. Also, the demand for electricity in Ghana is growing at an annual rate of 10 to 15% [6]. This widens the gap between energy demand and supply. Hence, energy management is very essential in the development of the country since it influences energy costs and the amount of carbon emissions which pollute the environment. Various approaches have been implemented to ensure adequate energy management. However, the development of smart buildings based on IoT is an approach that is not usually explored in Ghana. Also, there is a need for a very responsive and efficient system for the monitoring and control of devices and appliances in homes.

1.3 Objectives of the Project Work

This research project seeks to investigate the use and control of an IoT-based smart home as a method of energy management. The specific objectives are as follows:

1. To develop a cost-effective, functional and responsive smart home prototype.
2. To efficiently monitor energy consumption and control devices accordingly.
3. To provide overall integration of lighting, security, fire detection and air conditioning systems in a smart home.
4. To analyse the speed, accuracy, responsiveness and overall performance of the IoT system.
5. To conserve energy through smart operation.

1.4 Expected Outcomes of the Project Work

It is expected that after the completion of this project, the following outcomes would be achieved:

1. Well-simulated and functional prototype is developed.
2. A smart building with efficient communication techniques and protocols is implemented.
3. The speed, accuracy and responsiveness of IoT system is determined.
4. Energy is conserved through smart operation.

1.5 Motivation of the Project Topic

Electrical energy is one of the most utilized forms of energy in the world, and in Ghana, to be specific. As population growth continues, the demand for electricity increases.

Increasing energy demand drives the need for more power generation, and this incurs more cost on the government of Ghana. Additionally, more power generation causes more greenhouse gases to be released into the atmosphere, further degrading the environment. Hence, the motivation for this research project includes the need for effective energy management, the current advancement in technology and the rising need for environmental sustainability.

1.6 Research Methodology Used

The research methodology used in this project include:

1. Systematic Literature Review
2. Computer modelling and simulation
3. Smart home design and prototyping

1.7 Facilities Used for the Research

The facilities used for the research include:

1. Library and internet facilities at Ashesi University
2. Electronics Laboratory at Ashesi University
3. Mechanical Workshop at Ashesi University

1.8 Scope of Work

This project is limited to designing and implementing a smart home system based on Internet of Things using protocols such as Message Queuing Telemetry (MQTT) and Hypertext Transfer Protocol (HTTP). An energy management system is developed to monitor energy consumption and control devices accordingly. This system is implemented using smart sensors for automatic control, alongside a mobile application to manually control lighting, air conditioning and other home appliances. The performance of this system is analysed.

Chapter 2: Literature Review

2.1 Introduction to Smart Homes

As traditional sources of energy such as fuel have been found to have negative impacts on the environment, saving energy is becoming a more common topic of discussion. High gas emissions of carbon dioxide from the burning of fuel, for example, have been identified as a major factor of global warming. Also, majority of the consumed energy is from buildings [7]. As a result, smart home systems were innovated to reduce energy wastage.

A smart home is a residential building where lighting, Heating, Ventilation and Air Conditioning (HVAC) and other electronic appliances can communicate with each other and be remotely controlled. This system involves the automation and control of electronic appliances in the home [8]. Smart homes also include real-time data collection and status updates. They are comprised of a network of sensors which are used to control both mechanical and electrical actuators using communication framework [9]. These systems can be used in applications such as analysing data collected to provide information about past and future energy usage [9], [10]. They are also very useful in reducing energy consumption as well as human efforts, and to make life easier [11]. Figure 2.1 [12] shows the structure of smart or intelligent buildings.

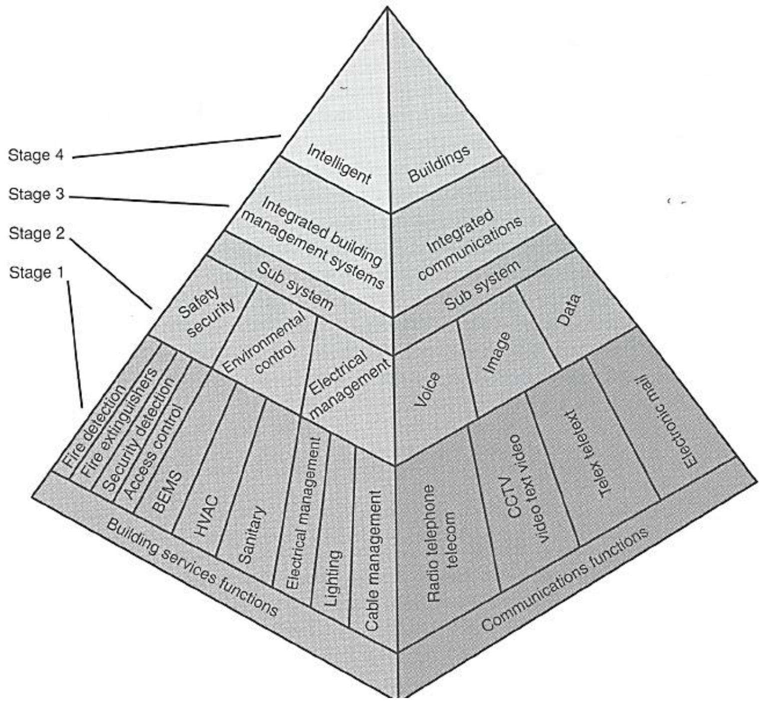


Figure 2.1: Stages of integration for smart buildings

2.2 Smart Home Technologies

The automation of smart homes can be performed using various technologies such as Bluetooth, Internet of Things (IoT), Supervisory Control and Data Acquisition (SCADA), Global System for Mobile communication (GSM) [11]. These technologies have their respective advantages and disadvantages; however, the most commonly used technologies are IoT and SCADA in this fourth industrial revolution (Industry 4.0) [13].

Table 2.1 [11], [14] shows a comparison made between Bluetooth, GSM, IoT and SCADA communication technologies for a smart home system. While the Bluetooth and GSM illustrations do not include sensor operation, IoT with Wi-Fi and SCADA analysis included sensors.

Table 2.1: Comparative summary of GSM, Bluetooth, IoT and SCADA technologies

Technology	**Feature**	**Disadvantage**
GSM	Access home appliances and control home security by sending and receiving commands in form of SMSs.	Delays in sending commands in case of weak mobile network
Bluetooth	For Bluetooth technology android-based GUI is developed to help owner communicate with smart home.	Bluetooth have a range limitation of 100 meter hence cannot access system outside range.
IoT	Sensors and IoT enabled devices used to satisfy the smart home conditions.	In case of sensor failure entire system will collapse because of great dependency on sensors.
SCADA	Ability to connect several sensors and store massive amounts of data.	System is complex and expensive.

2.2.1 IoT-enabled Smart Homes with Wireless Connectivity

IoT is a system of inter-connected computing devices, communication technologies and machines with the ability to transfer data over a network remotely, without any human intervention [8], [11]. IoT systems in smart homes are connected using servers over wireless internet for communication with sensors and actuators. These systems merge information from different embedded devices, that is, sensors and actuators, for intelligence and control of the smart building [15]. The signals from the sensors and actuators are sent to a microprocessor which sends the information to a cloud system. The cloud system is connected to a remote system which is used for control and the database which gathers real-time data from the system [8]. IoT systems do not have any distance limitations, since communication between smart devices is usually done over a wireless network [11]. The collection of large amounts of real-time smart building data is a challenge with IoT systems, hence the need for a Big Data Analytics framework to manage the data [16]. Figure 2.2 [17] shows the architecture of IoT systems used in smart homes.

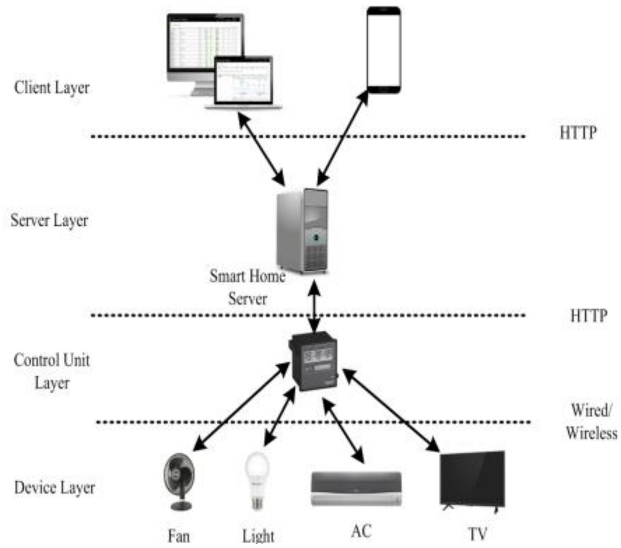


Figure 2.2: System architecture of IoT-based smart home

2.2.2 SCADA-enabled Smart Homes

Supervisory Control and Data Acquisition (SCADA) is a technology that is used to remotely monitor and control systems [18], [19]. It also allows direct interaction with smart devices and human-machine interface software and records events into a log file. SCADA systems are implemented using devices such as Electronic Load Controller (ELC), Programmable Logic Controller (PLC), Energy meters and communication channels such as serial port RS232 and IP Protocol [18], [19]. Figure 2.2 shows a SCADA network.

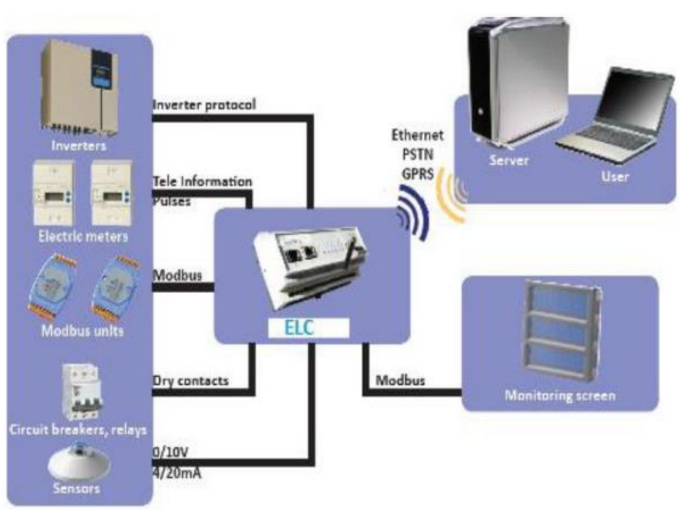


Figure 2.3: SCADA network with ELC

2.2.3 Smart Home System based on Bluetooth

Bluetooth is a low-cost flexible technology which when used in smart homes works using android applications on smart phones. In some applications, home automation with Bluetooth is developed using a Microcontroller Development Kit for ARM processors. This system works based on an operating system called Wince 6.0 [20]. In another application, an HC-06 Bluetooth module was used alongside an Arduino Mega Microcontroller, with ethernet and GSM communication. Graphical user interface was developed using MIT App Inventor [21]. Room temperatures, water temperatures, gas leakage and lighting were monitored and controlled using the sensors, and programming was done on the microcontroller [11], [20]. Another proposed system involves lights and motors which were controlled manually using a mobile application software connected through Bluetooth [21]. Figure 2.4 [21] shows the block diagram of one Bluetooth application in smart homes.

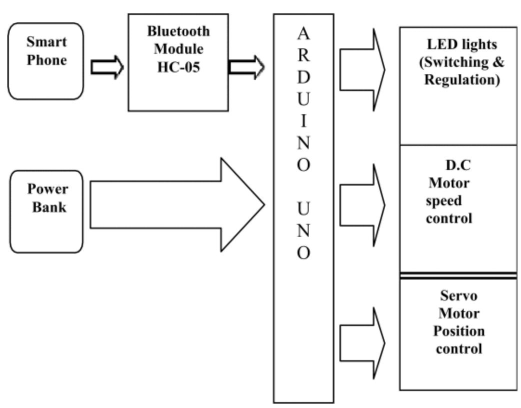


Figure 2.4: Block diagram of Bluetooth-based smart home

2.2.4 GSM-based Smart Home System

GSM is a wireless mobile communication system which operates over a network. This system depends on a mobile network signal to function and sends commands in the form of SMS. A GSM based smart home consists of a microcontroller, GSM phone with a GSM module, relay module, sensors and application software for smartphones. With these systems, weak mobile network leads to delays in sending commands [11].

2.3 Review of Related Works

Basol *et al*. [20] designed and implemented a smart home system based on Bluetooth and GSM. This system was made up of an Arduino microcontroller, an ethernet module, a Bluetooth module, sensors, actuators and a mobile application. This system was designed to remotely control lighting, heating, security and gas range in a house. The house was powered by solar energy. Each room has a separate controller, hence is controlled separately. GSM was used for internet connection between the application software and ethernet module and microcontroller. In case of no internet connection or GSM network failure, Bluetooth can be used for the system control, which is efficient.

Alhasnawi *et al*. [18] presented a smart home system which used SCADA, Raspberry Pi3 System on a Chip (SoC) and Wemos-D1 microcontroller. Raspberry Pi acted as the base station unit which represented the network or server for the system. The Wemos-D1 microcontroller was programmed using Arduino IDE software and connected to Wi-Fi using an ESP8266 module. Wemos-D1 was used for communication and control of the system. Remote control operation was performed using a computer supported by an Interactive Graphical SCADA System (IGSS).

Samuel [19] designed a smart home controlled by advanced SCADA. This system was composed of a Building Management System for control of the home. An energy meter with a current transformer (CT) was installed to measure the power and voltage drawn from the various loads in the house. An ethernet logic controller (ELC) was used to read sensor and energy meter data which is sent to the gateway computer or server. Maestro software was used to store, process and analyse the data collected and displays it on a screen. Varying load demand and respective system response was also monitored.

Davies and Anireh [8] proposed a smart home system built on IoT which manually controlled the loads in a house using a mobile application. The IoT system was made up of three sub-systems namely the Remote System, Simulated System and Cloud System. The Remote System is the mobile application software which sends and receives messages to and from the user. The simulated system consists of the microcontroller which receives commands and sends visual notifications to the user and triggers actions from instructions given by the user. The cloud system performs all the remote business logic linked with the database. The gap identified is the absence of aggregation or filtering of data collected as a method of big data management.

Bashir and Gill [16] designed a smart home system based on an IoT Big Data Analytics (IBDA) Framework. The development of an IoT-controlled smart home leads to the collection of enormous amounts of data. Hence, the IBDA framework is used for the storage and analysis of real time data generated from IoT sensors, specifically, oxygen, smoke and luminosity sensors deployed inside the smart building. This system is responsible for automatically managing the oxygen level, luminosity and smoke/hazardous gases in various parts of the smart building. The IBDA framework is made up of a Transmission Control Port where an Apache Flume Agent is set up to receive the data generated and stores it in a Hadoop Distributed File System (HDFS). Pyspark is then used to analyse the data generated.

Kim *et al.* [22] presented a Smart Home Web of Objects (SWO) IoT model with an analytics platform. This system is made up of a gateway which connects smart devices to the internet. There is also a management plane which stores home device information and their data as objects. This system is characterised by a home analysis service, SWO analytics platform (SWOAP), which combines device information, user information, stream data, and physical space information. This implementation uses real data from smart metering devices for analysis of appliance usage patterns and prediction.

Prasetyo *et al.* [4] presented an application of an IoT-based smart home which was used for monitoring and control of energy consumption for households in Indonesia. This was set up using current sensors which monitor how much energy is being consumed by each load, and the results are displayed on a mobile application. The system also has the ability to control the loads in the house through the mobile application, which is a representation of two-way communication. With this system, Raspberry Pi was used as the server, while STM32F103 microcontroller coupled with an internet module was used in controlling the sensors and actuators. When the energy consumption measured exceeds a certain value, the system enters into power-saving mode. However, the aspect of system security and big data management was not explored in this research.

Chapter 3: Design Methodology

3.1 Introduction

The smart home system is made up of blocks such as security, fire detection, lighting and HVAC, energy monitoring and control. This is implemented using sensors to collect data of temperature, occupancy, fire, proximity and brightness, which are used to control actuators such as lights, fan, alarms and other home appliances. Energy monitoring is performed using the current sensor which measures the consumption of the loads in the home. In coherence with the Fourth Industrial Revolution, Industry 4.0 [23], Internet of Things (IoT) was selected as the technology to be used for the smart home system. Also, IoT based on Wi-Fi is cheaper, more efficient and less complex, as compared to SCADA based systems which use Programmable Logic Controllers. The structure of the IoT system comprises of sensors and actuators, microcontroller, routers, a database and mobile application, all based on a star topology.

3.2 System Requirements and Architecture

Table 3.1 shows the system requirements and their respective justifications for the smart home.

Table 3.1: System requirements for the smart home

No.	System Requirements	Justification
1	Main power supply from power grid, with battery as a backup power source.	Energy supply from the grid is required because of its reliability and efficiency as compared to a battery source.
2	An efficient microcontroller with architecture to support sensors and actuators should be used.	The microcontroller acts as the brain of the smart home system and its efficiency impacts results.
3	Energy consumption of devices should be measured.	This helps the user monitor energy consumption and identify patterns.
4	Sensor, actuator and consumption data should be aggregated every thirty minutes and sent to a database.	The large data generated by sensors and actuators need to be pre-processed before being sent to the database to limit the occurrence of big data.
5	Non-essential high-power devices should be shut off when a set limit of energy consumption is exceeded.	This helps to reduce energy consumption and costs of the user.
6	Loads in the home can be controlled manually using a mobile application.	Easy access for the user to control the devices in the home as desired.
7	User should be able to view home information using a mobile application.	This provides an interface for the user to monitor devices in the home.
8	User authentication and authorisation in the mobile application for security	To prevent unauthorised access which can threaten the life of user.

Table 3.2 illustrates the criteria that was used in selecting the communication technology to meet the design requirements. All criteria had equal weights. After comparison,

Wi-Fi (IEEE 802.11ah) was selected due to its higher data rate, low-cost and long-range communication characteristics. This was selected over Bluetooth, GSM, Zigbee.

Table 3.2: Pugh matrix for selection of communication technology

Criteria	Wi-Fi	Weight (out of 5)	GSM	Bluetooth	Zigbee
Range	0	5	-1	-3	+2
Data Rate	0	5	-1	-1	-1
Cost	0	5	-2	+1	0
Availability	0	5	-2	+1	-1
TOTAL	**0**		**-30**	**-10**	**-16**

Table 3.3 illustrates the criteria that was used in selecting the microcontroller to meet the design requirements. From comparative analysis, Raspberry Pi was chosen over Node MCU, Arduino Uno and Udoo Neo as the microcontroller to be used. This is attributed to its performance in terms of memory, architecture, speed and direct connection to Wi-Fi. Although the cost of the Raspberry Pi is higher than that of Arduino Uno and Node MCU, more consideration was given to the speed and general efficiency of the smart home system.

Table 3.3: Pugh matrix for selection of microcontroller

Criteria	Raspberry Pi (baseline)	Weight (out of 5)	Node MCU (ESP8266)	Arduino Uno	UdooNeo
Memory	0	4	-2	-4	-1
Architecture(GPIO)	0	4	-4	-2	+2
Cost	0	3	+5	+4	-2
Speed	0	4	-2	-4	-1
Wi-Fi	0	5	0	-5	-1
Ethernet	0	3	-3	-3	0
TOTAL	**0**		**-26**	**-62**	**-11**

Figure 3.1 displays the standardised architecture of IoT systems published by the IoT World Forum [24]. This structure is applied in this implementation of an IoT-based smart home. The first layer is the Physical Devices and Controllers, also known as the Edge, where sensors and home devices are made smart using a microcontroller. The second layer, Connectivity, represents communication between devices on the edge and the cloud. Gateways such as routers and switches are used in this layer. In the edge computing layer, data generated from the sensors and actuators are pre-processed as a method of big data management, and the microcontroller sends that data to the database in the Data Accumulation layer. The Data Accumulation layer involves storage of pre-processed data from layer 3. Data Abstraction entails checking if data sets are complete, and regulation of access to stored data. The Application layer is characterised by the value given to stored data, represented through monitoring, control and data analytics in software applications. The Collaboration and Processes layer involves the interactions of the user with the system and takes the form of notifications and alerts from the mobile application which inform the user's actions.

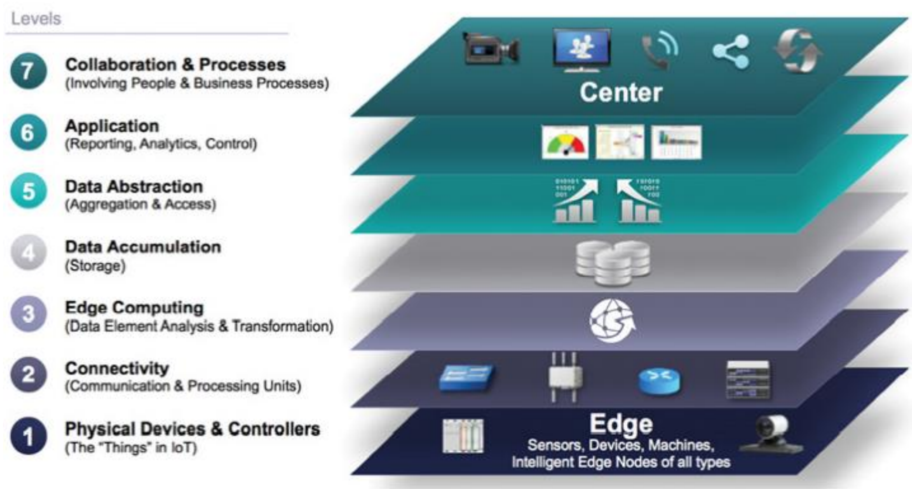


Figure 3.1: Architecture of IoT system

Figure 3.2 shows a context diagram of the relationships between the different blocks of the smart home system. From the illustration, components of the IoT system architecture can be identified. The sensors, actuators and microcontrollers are the "things" in the network, while the router is the gateway used in connecting to the cloud (internet). The mobile application also connects to the cloud where the database is stored.

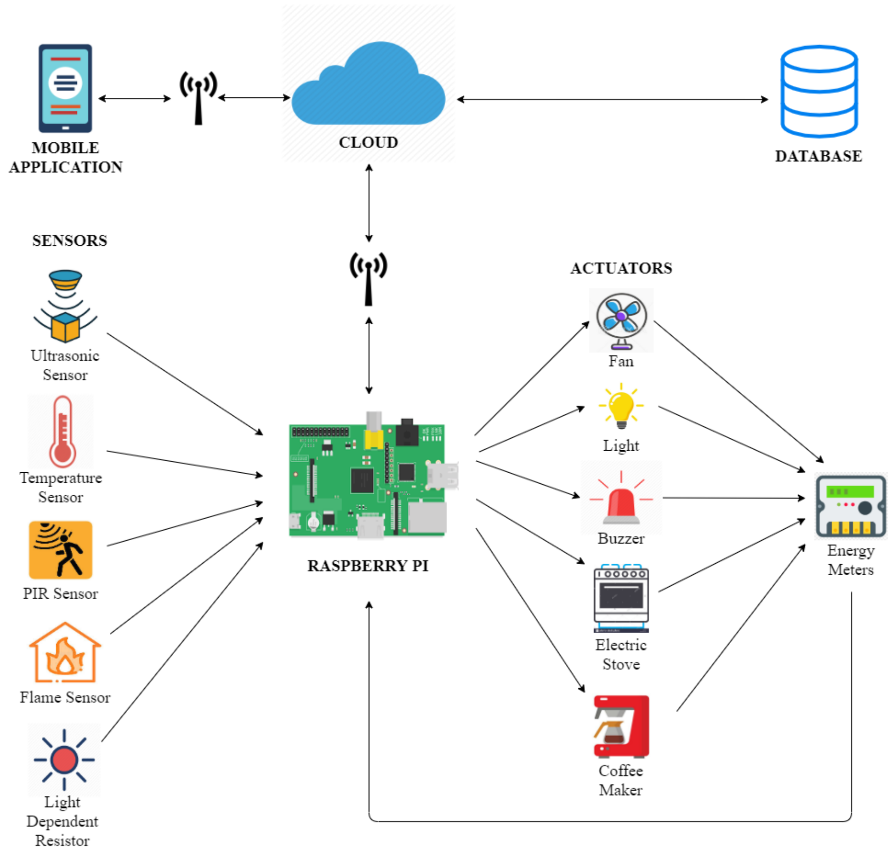


Figure 3.2: Context diagram for smart home system

3.3 Materials

The materials used in the implementation of the IoT-based smart home are power supply, boost converter, PIR sensor, temperature sensor, flame sensor, current sensor, ultrasonic sensor, fan, relay, LEDs, light dependent resistor (LDR), buzzers, LCD display, Raspberry Pi, breadboard, jumper wires.

3.4 Hardware Design

The hardware implementation of this research project is characterised by power supply, Raspberry Pi system on a chip connected to the power supply, a boost converter, analog to digital converter (ADC) , sensors such as occupancy sensor, temperature sensor, flame sensor, current sensor and actuators such as lights, fans and buzzers.

Figure 3.3 shows the block diagram of the hardware design.

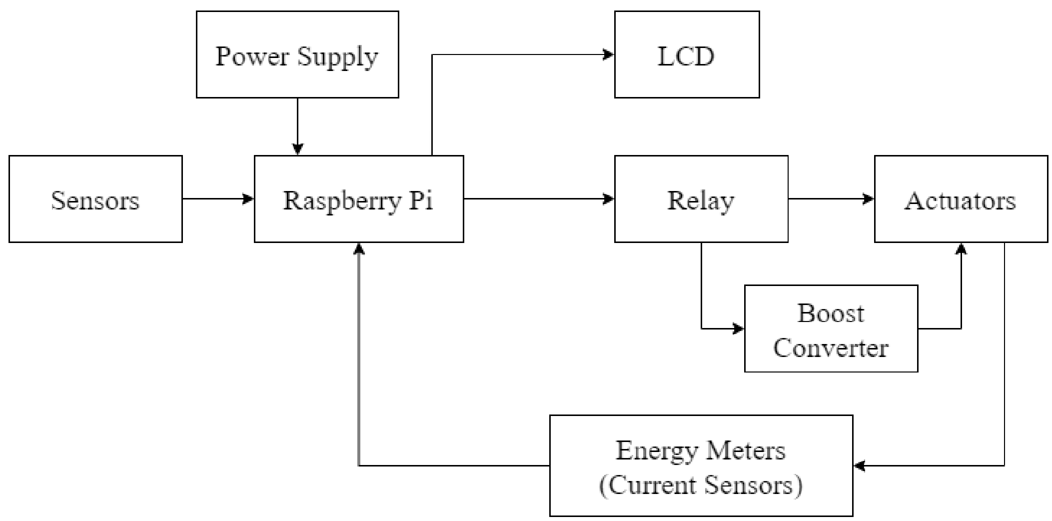


Figure 3.3: Block diagram of hardware design

3.4.1 Raspberry Pi 3 Model B

Raspberry Pi is a system on a chip (SoC) which has the ability to communicate with various electronic devices using wired connections, Wi-Fi, ethernet or Bluetooth [25]. Raspberry Pi acts as the brain of the entire system. The Raspberry Pi 3 Model B is made up of a Quad Core 1.2 GHz Broadcom BCM2837 64bit CPU and 1GB RAM. It also has wireless LAN, Bluetooth Low Energy (BLE) on board and 100 Base ethernet for communication. It holds 40 GPIO pins and 4 USB ports. In this research, the Raspberry Pi was used as the microcontroller to read data from the sensors and control the actuators. It was also used to connect to the internet to access the database. Data from sensors and actuators are pre-processed before being sent to the cloud system and then stored in the database.

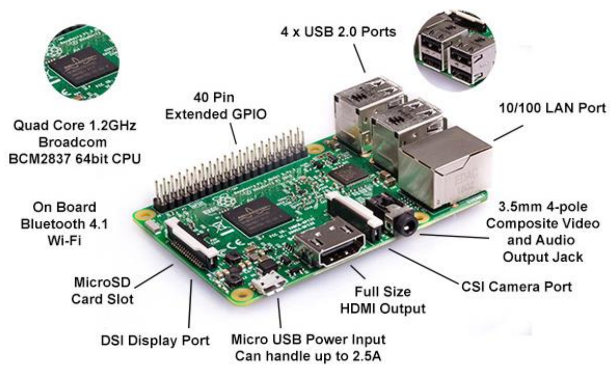


Figure 3.4: Raspberry Pi 3 Model B

3.4.2 HC-SR501 PIR Sensor

The HC-SR501 Pyroelectric Infrared Sensor is used to detect the presence of people. The HC-SR501 sensor is based on pyroelectric infrared technology. It features high sensitivity, high reliability, and low-voltage operation. The specifications of this sensor are 5V to 20V operating voltage range, current consumption of 65 mA, sensing range less than 120° and within 7 meters [26]. The HC-SR501 PIR sensor will be used to detect motion in the various rooms and the number of times motion is detected is sent to the database. The sensor is operated in the non-repeatable mode.

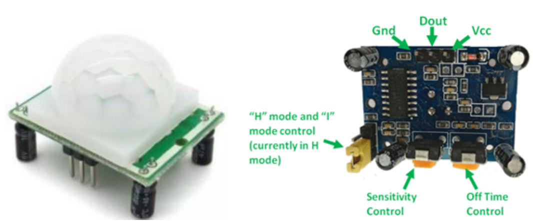


Figure 3.5: HC-SR501 PIR sensor

3.4.3 LM35 Temperature Module

The LM35 module is a low-cost temperature sensor which is calibrated directly in Degrees Celsius [27]. The LM35 temperature module has an operating voltage range from 4V to 30V. The sensor draws only 60 µA from power supply and is rated to operate over a −55°C to 150°C temperature range. The LM35 module was used to collect temperature data for HVAC applications in the smart home.

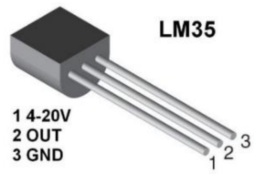


Figure 3.6: LM35 temperature module

3.4.4 Flame Sensor Module

A flame sensor module consists of a flame sensor (IR receiver), resistor, capacitor, potentiometer, and comparator LM393 in an integrated circuit [28]. It can detect infrared light with a wavelength ranging from 700nm to 1000nm and converts it into current. Sensitivity is adjusted through the onboard variable resistor with a detection angle of 60 degrees. The sensor has a working voltage between 3.3V and 5.2V DC, with analog and digital outputs to indicate the presence of a signal. This sensor is used in the smart home system to detect fire.

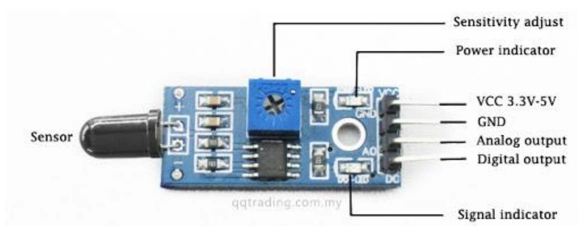


Figure 3.7: Flame sensor module

3.4.5 ACS712 Current Sensor / Energy Meter

The ACS712 module is used to measure both AC and DC in a circuit. It has an input voltage of 5V and provides analog output voltage proportional to the current measured [29]. It has the ability to provide isolation from the load. The ACS712 module is easy to integrate with a microcontroller unit. The current sensor acts as the energy meter for calculation of energy consumption in the smart home.

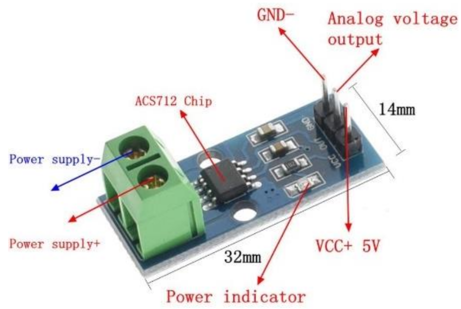


Figure 3.8: ACS712 current sensor

3.4.6 HC-SR04 Ultrasonic sensor

An ultrasonic sensor is an electronic device that measures the distance of a target object by emitting ultrasonic sound waves and converting the reflected sound into an electrical signal. This sensor has a supply voltage of 5V (DC) and a supply current of 15mA. It also has a distance coverage of 2cm to 400cm, accuracy of 0.3cm and maximum beam angle of 15 degrees. In this application, the ultrasonic sensor is used at front door as a proximity sensor, to detect the presence of guests for security.

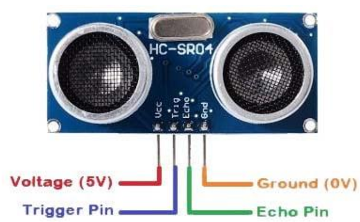


Figure 3.9: HC-SR04 ultrasonic sensor

3.4.7 Active Buzzer

An active buzzer produces sound at a predefined resonant frequency (2300 ±300 Hz) when DC power is applied to it. The features of an active buzzer include its operating voltage of 4V to 8V, maximum rated current of 32mA, minimum sound output is 85 dB at 10cm. The active buzzer is used in this application as a doorbell and in the case of a fire outbreak.

Figure 3.10: Active buzzer

3.4.8 5V Relay Module

The 5V Relay Module is a relay interface board which can be controlled directly by a wide range of microcontrollers. It uses a low-level triggered control signal (3.3-5V DC) to control the relay. The relay is an automatic switch which can control high-voltage circuits. It can provide both AC and DC to the respective loads. The relay will be used to trigger the fan, lights and buzzers based on sensor input to the microcontroller.

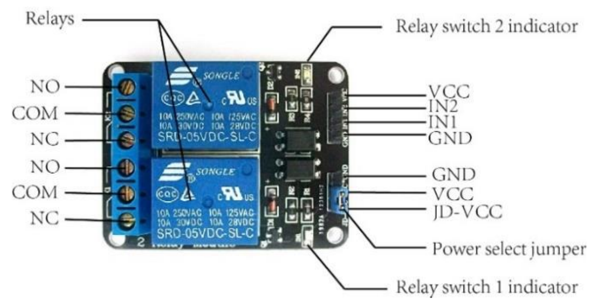


Figure 3.11: Two-channel 5V relay module

3.4.9 5V Mini Cooling Fan

This miniature fan is usually used for air cooling inside the smart home. Its rated voltage is 5VDC with current of 0.1A. This fan has an invariable speed of 3000RPM. It is controlled using a relay which takes input from the temperature sensor.

Figure 3.12: 5V DC mini cooling fan

3.4.10 LED Indicator Lights

A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it. They are usually produced in red, green, blue, yellow and white colours. Each indicator light has a rated voltage of 24V and consumes a maximum current of 20mA. Since the Raspberry Pi can only output 5V, a boost converter is used to provide 24V to the lights. In this research project, these indicator lights are used for room illumination.

Figure 3.13: Light emitting diode

3.4.11 Light Dependent Resistor (LDR)

The LDR, also known as a photoresistor, is a light sensitive sensor whose resistance decreases when light falls on it and increases in the dark. It is small and easy to interface with microcontrollers. The LDR is used together with a capacitor to detect the level of brightness at the exterior of the house.

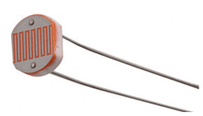


Figure 3.14: Light dependent resistor

3.4.12 Liquid Crystal Display (LCD)

A 16x2 I^2C LCD display is used in this project. It is characterised by 2 rows with 16 characters on each row. The LCD is a cost effective and energy efficient method of display for electronic systems. The rated voltage for the LCD is 5V DC. The LCD is used to display energy consumption of the smart home in real time.

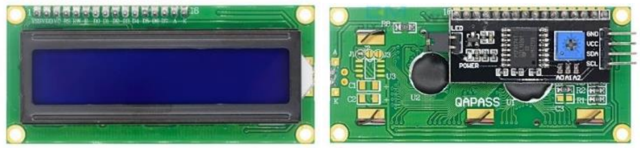


Figure 3.15: Liquid crystal display

3.4.13 ADC MCP3008

MCP3008 is an 8-channel 10-bit chip used to convert analog input to digital. This is used to take data from the temperature and current sensors since the Raspberry Pi cannot process analog inputs.

Figure 3.16: MCP3008

3.4.14 XL6009 Boost Converter

XL6009 is a DC step up module which has a rated input voltage from 3V to 32V and an output voltage of 5V to 35V. It has a maximum input current of 4A. It is used in the smart home to power the LED indicator lights.

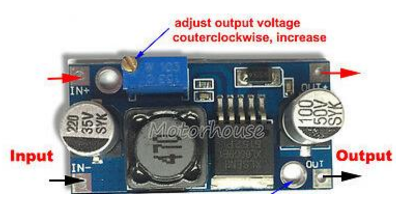


Figure 3.17: XL6009 boost converter

3.4.15 Power Supply

An adapter charger with Micro USB is used as power supply since the Raspberry Pi has a micro USB port. The charger has the ability to convert the 240V AC from the mains to 5V DC for input to the Raspberry Pi.

Figure 3.18: Adapter charger with micro USB

3.5 Methods

The hardware and software components of the smart building are integrated to work effectively. The Raspberry Pi, being the microcontroller, has all the sensors, actuators, energy meter and LCD display connected to it. The system control is divided into automatic and manual. For the automatic control of the smart home, the exterior of the building is made up of an LDR which monitors the brightness of the surroundings and turns on an LED when darkness is detected. At the entrance of the house, an ultrasonic sensor is used to detect people approaching the premises and sounds a buzzer to alert the house owner. Inside the building, there are motion (PIR) sensors which detect movement in the rooms and turn on LEDs accordingly. A temperature sensor measures the room temperature and turns on a fan using the relay if the temperature is above 23°C. A flame sensor is used for fire detection and alerts the homeowner using a buzzer in the case of a fire outbreak. LEDs are used to represent other loads such as an electric stove and a coffee maker. A current sensor is used to measure the energy consumption of the various devices in real time, and corresponding data is displayed on the LCD display. The calculated cost of energy consumption is also displayed on the LCD. The analysis of sensor and manual control data for actuator control is performed on the edge of the IoT system. Sensor and actuator data are generated per second and then aggregated and sent to the database every thirty minutes. For sensors which produce data values such as temperature, distance and brightness, averages are computed and sent to the database. On the other hand, the sum of data values is computed for sensors with digital data such as PIR and flame sensors.

The automatic control is the default mode of operation. However, the manual control is characterised by commands sent from the mobile application which disable the controls based on sensor data. Also, the mobile application allows the user to view summaries of energy consumption data and set a monthly consumption limit. In the case where the limit is reached, the user receives a notification, and power to designated non-essential high-power devices is shut off irrespective of whether system is in automatic or manual control mode. The user also has the ability to report issues or request for maintenance using the mobile application.

3.5.1 Circuit Diagram

The circuit diagram for the smart home system was designed using Autodesk Eagle software. Figure 3.19 shows the various connections between the components listed in Section 3.4.

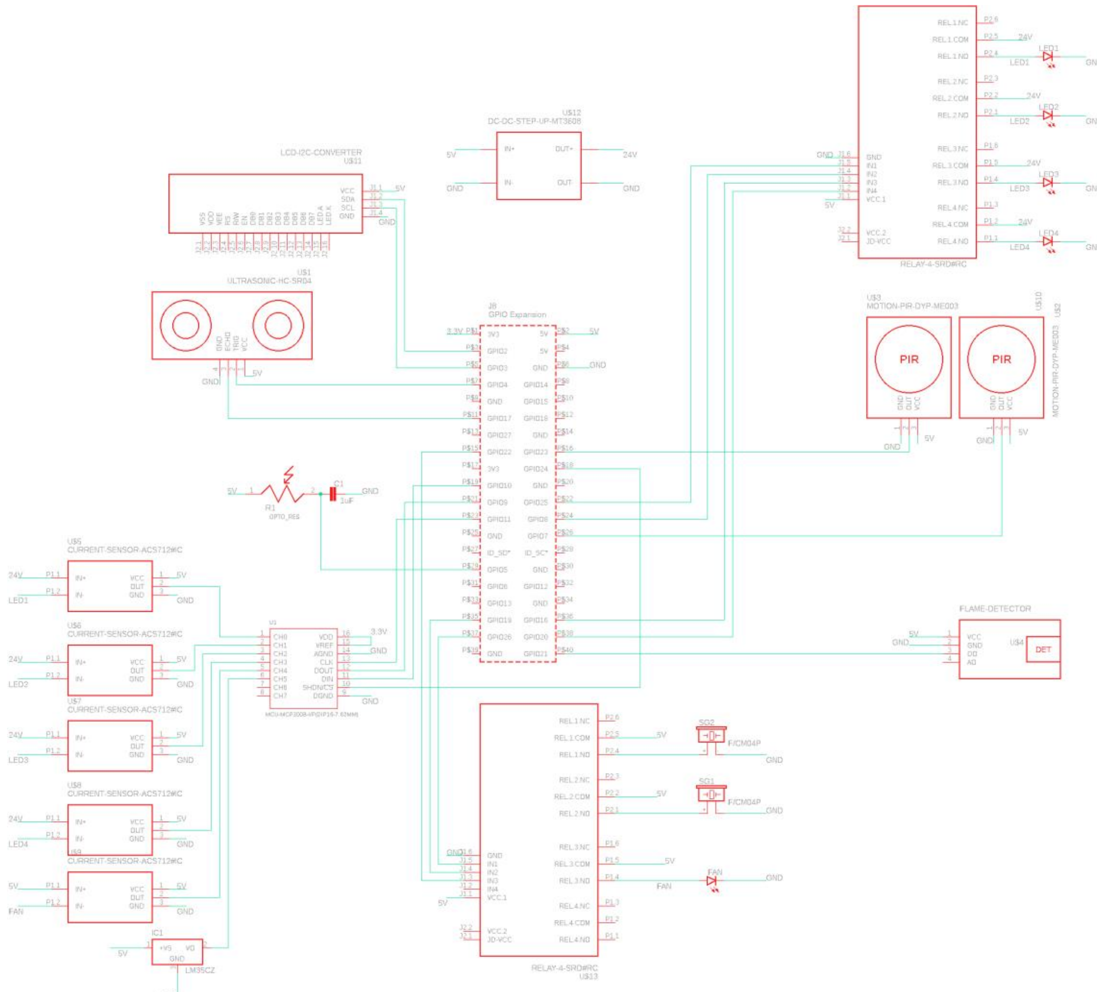


Figure 3.19: Circuit schematic

3.5.2 Software Design

The software aspect of this project includes the programming of the Raspberry Pi SoC for circuit functionality and a server for backend operations. Programming of the circuit was done using Multithreading methods in Python to allow the different functions to run concurrently. The backend was developed using Flask-SQLAlchemy Application Program Interface (API), a RESTful API which makes use of HTTP requests based on Python programming language. HTTP is a reliable application protocol characterised by point-to-point exchange [30]. A relational database was set up using MySQL Workbench, a database management tool, on a remote MySQL server for storage of data collected from sensors, actuators and energy meters, and reports from the user. The Flask API is connected to the remote database for adding and retrieving data using HTTP POST and GET requests, respectively. A mobile application software was developed using Ionic Angular framework to facilitate remote monitoring and control. The Raspberry Pi and mobile application connect to the Flask server also using HTTP requests to send and receive data.

The automatic control, which is the default mode of operation, is derived from sensor data, while the manual control is based on instructions from the mobile application. Monitoring and control using the mobile application is achieved through HTTP requests to the API. With regards to user creation and authentication, the user is added to the database by the system administrator, hence the mobile application only supports login authentication. The user can also report identified issues from the mobile application. This is carried out using a lightweight protocol known as Message Queuing Telemetry Protocol (MQTT). MQTT is an application protocol characterised by publish-subscribe utility [30]. The message containing the report is published through the MQTT WebSocket Client broker with Quality of Service (QOS) level 2 (exactly once delivery) which guarantees safe and reliable data transmission. The published message is sent to the system administrator who is subscribed to the topic and then sent to the database. The interconnections between the Raspberry Pi (circuit), database through the API and MQTT client, and the mobile application were facilitated through a Wireless Local Area Network (WLAN, IEEE 802.11ah).

Figure 3.20 shows the structure and relationship diagram of the MySQL database.

Figure 3.20: Enhanced entity-relationship model for database

For the “users” table, the size of each dataset is 246 Bytes. For the “consumption” table, each dataset has size 76 Bytes, while the size of each dataset in the “actuator_data” table is 70 Bytes. Each row in the “sensor_data” table has size 36 Bytes. Therefore, the total size of stored data for each row in the database is 428 Bytes. This was calculated based on the size of the various MySQL data types used in the database [31].

Figure 3.21 shows the flowchart for the automatic control of the smart system. The Raspberry Pi checks if automatic control mode is enabled and allows sensors to input generated data. The Raspberry Pi checks if data is within the set ranges for actuator action and responds accordingly.

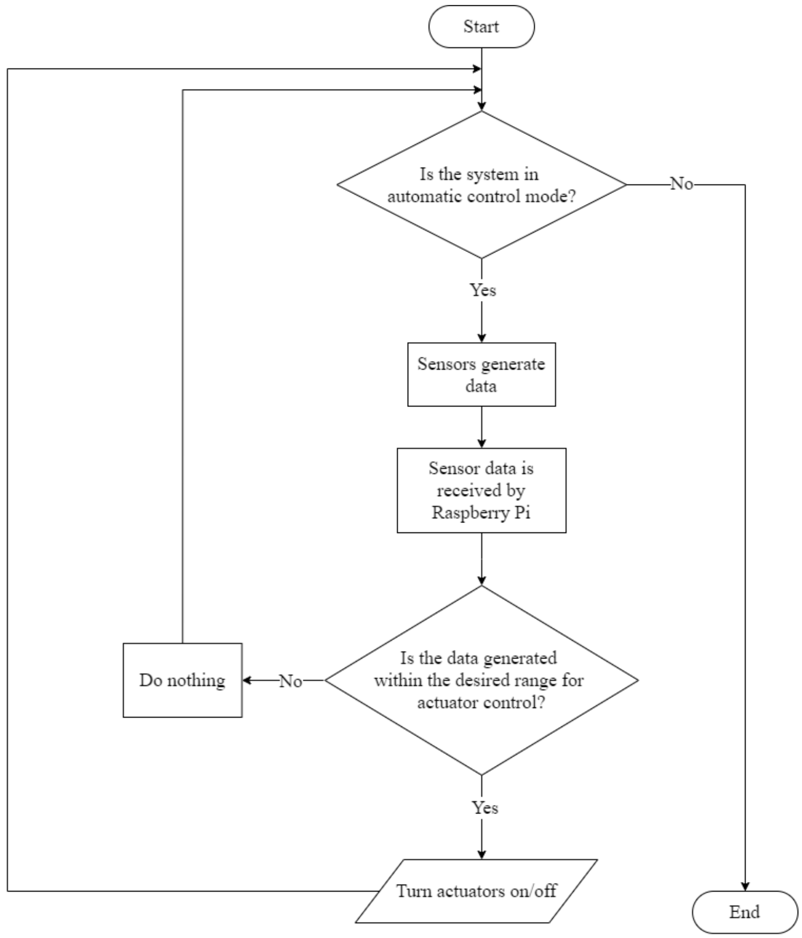


Figure 3.21: Flowchart for automatic control

Figure 3.22 shows the logic used for monitoring and manual control of devices in the smart home using the mobile application.

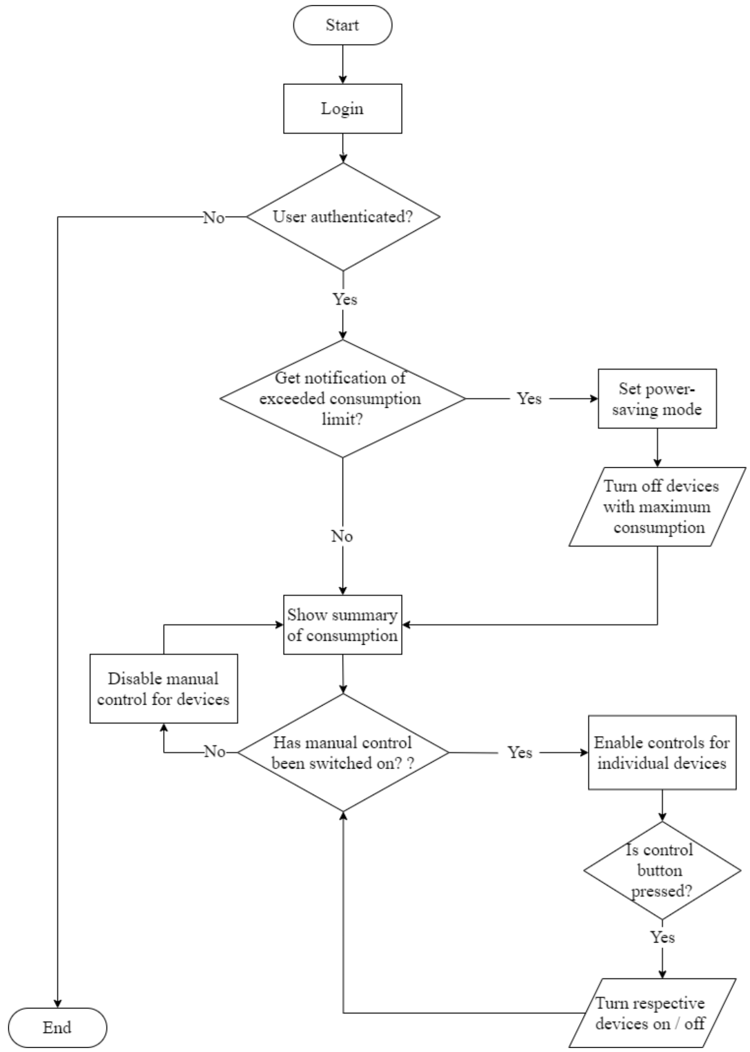


Figure 3.22: Flowchart for mobile application

Finally, system security was ensured by setting a new user and password for the Raspberry Pi as well as the database. Full permissions were granted to the new user and the default user was deleted. The security of Secure Shell (SSH) operation was enhanced using key-based authentication to restrict unauthorised remote access to the microcontroller. With regards to the mobile application, only the authorised API is allowed to control the application. In addition, only authorised users are allowed to access the application. Each session terminates after the application is closed and the user is required to log in upon reopening.

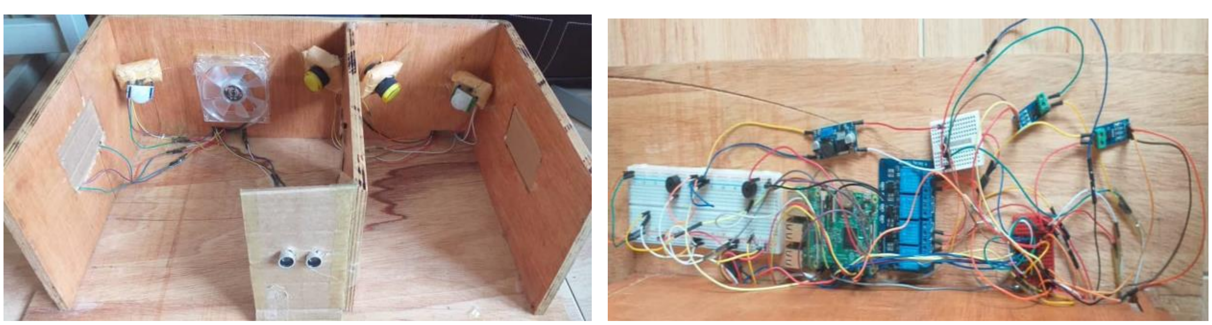
Chapter 4: Results and Discussions

4.1 Introduction

This chapter presents the results from implementations of the circuit, backend server, database and mobile application. These results are grouped based on their roles in either hardware or software design. The result of the hardware design comprises of circuit implementation, while software design results consist of backend server, database and mobile application.

4.2 Results of Hardware Implementation

The hardware implementation of this project mainly constitutes the circuit. The circuit is made up of sensors, actuators and the Raspberry Pi. All devices are connected to the Raspberry Pi which takes both analog and digital input from sensors, processes it and provides output in the form of voltage to actuators. Upon implementation, it was observed that while in automatic control mode, each sensor generated data and each actuator was able to reflect the necessary changes based on sensor input. For manual control mode, each actuator responded to user input. The hardware components were housed in a wooden structure for real-life semblance. Figure 4.1 shows the hardware set up for the smart home. Figure 4.1(a) is the part of the home the user interacts with and (b) is the circuit connection.



(a) (b)

Figure 4.1: Hardware setup

4.3 Results of Software Implementation

The software design is composed of programming of the circuit, setting up the database, backend server and building the mobile application. Programming of the circuit was based on Multithreading for running the various sensor and actuator functions simultaneously, and HTTP POST and GET methods for sending and receiving data from the database and mobile application. Furthermore, the control mode used during the operation of the smart home was identified using data from the mobile application and this data was sent to the Raspberry Pi to either enable or disable sensor functionality.

The SQL database was created on a MySQL server using queries in MySQL Workbench. In the database, five tables namely “users”, “sensor_data”, “actuator_data”, “consumption” and “reports” were constructed. The “users” table contains information about users, while “sensor_data” table holds aggregated forms of data collected by each sensor. “Actuator_data” table contains data about the status of the various actuators, and “consumption” table holds data of the energy consumption of the various devices in the home. “Reports” table is made up of data concerning issues reported by the user. Figure 4.2 shows the structure of the database in phpMyAdmin, a database management tool.

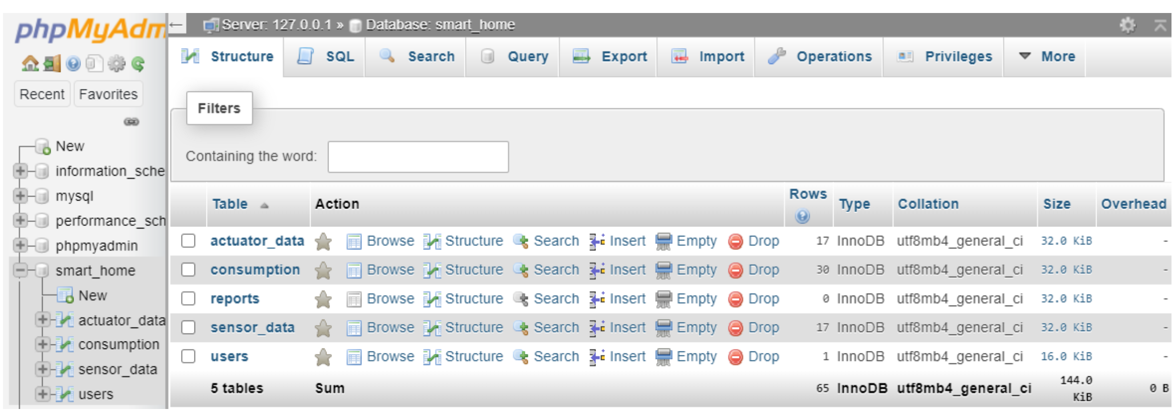
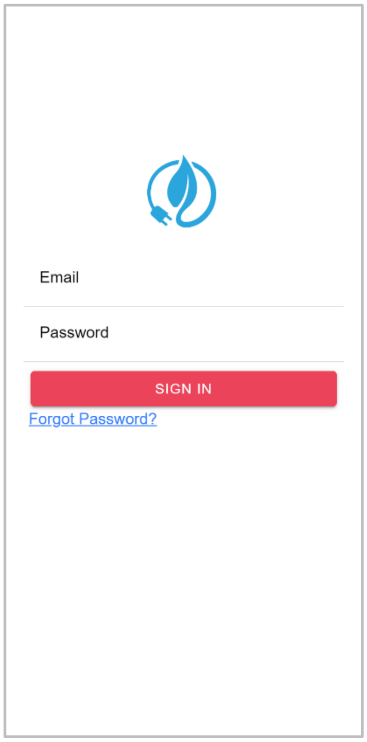


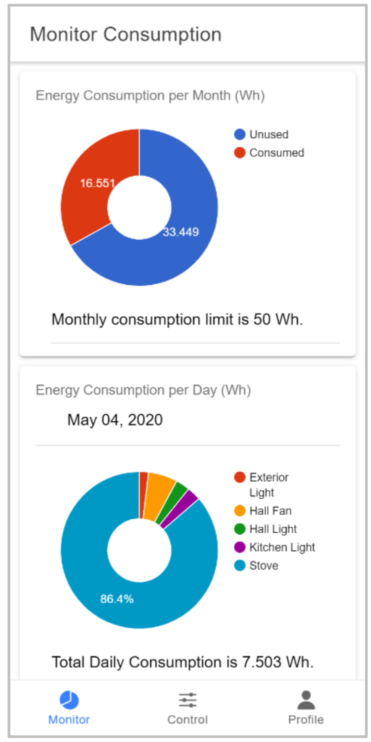
Figure 4.2: MySQL database

The backend server was set up using Flask-SQLAlchemy which was configured to have access to the database. POST and GET methods were declared with their corresponding functions for adding to and retrieving from the database respectively. The Flask-SQLAlchemy API facilitated login authentication as well as adding and retrieving sensor, actuator and consumption data. The API was used to pass information about the control mode from the mobile application to the Raspberry Pi for circuit control. The source code for the circuit, API and MQTT client can be found in Appendix A.

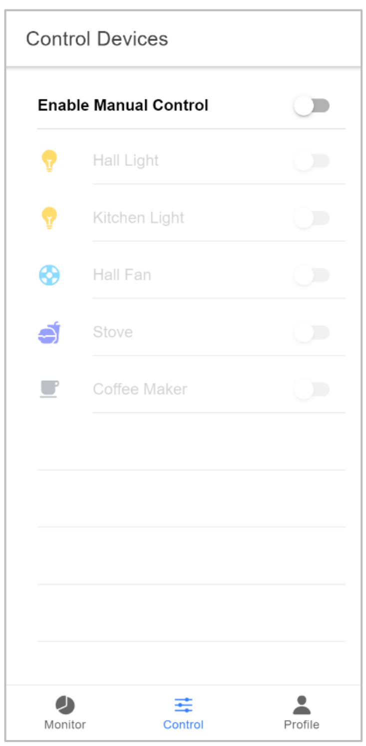
The mobile application was built using Ionic Angular framework. The mobile application has three main screens for monitoring consumption, controlling devices and viewing profile information. The monitoring screen allows the user to view charts of consumption data of the various devices for varied time periods. The screen for control is used to manually control the devices in the home. These functions were carried out successfully using HTTP requests. The profile information screen is used to view the history of consumption data, set consumption limits and report issues to the system administrator. The report from the user is published to a topic and then sent to the database using the MQTT WebSocket Client. Figure 4.3 shows the various screens for the front end of the mobile application. Figure 4.3(a) shows the login page and (b) shows the screen for monitoring consumption. The screen shown in Figure 4.3(b) contains a pie chart showing the power consumed per month and the remainder of unused power based on the consumption limit. The second pie chart displays the consumption of the various devices per day. Figure 4.3(c) display the screen for controlling devices, and it can be observed that the controls for the devices have been disabled because manual control is off. Figure 4.3(d) shows the profile page for setting the consumption limit, viewing history and reporting issues.



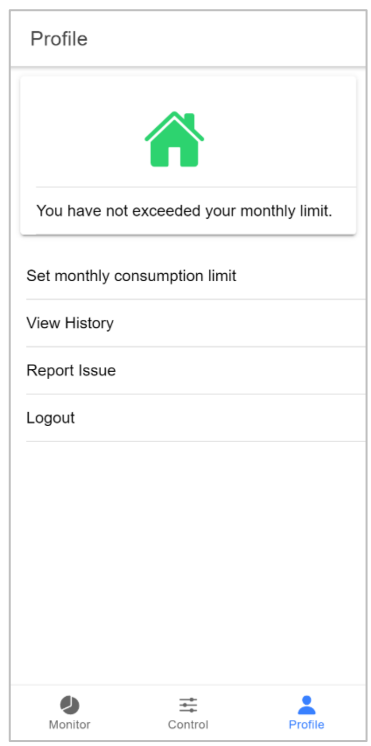
(a)



(b)



(c)



(d)

Figure 4.3: Results from mobile application

4.4 Results from Statistical Analysis

After implementation, statistical analysis was performed on the system to determine its speed, accuracy and responsiveness. Comparative analysis was performed on the response times for automatic and manual control. The latencies for application protocols MQTT and HTTP were compared. The test for accuracy involved observing the various responses to input.

4.4.1 Test for Responsiveness

The smart home system was tested for the response time for both automatic and manual control. A two-sample t-test was performed in MATLAB to determine if the average response time for automatic control is the same for manual control. Data for the first sample was obtained from the time taken for sensors to generate data and control actuators accordingly, while that of sample two was obtained from the time taken for commands from the mobile application to control actuators. The assumptions made are listed below:

1. The two samples are normally distributed and do not contain any outliers.
2. The two samples have unequal variance.
3. The observations are random and independent of each other.

The null hypothesis (H_0) assumes that the average time taken for response to manual control has no statistical difference from time taken for response to sensor input. The alternative hypothesis (H_A) is that the true mean difference is not zero. With a confidence level of 5% and sample size of 20, a two-sample t-test was performed. The data collected is displayed in Appendix B. Figure 4.4 displays the results of the t-test.

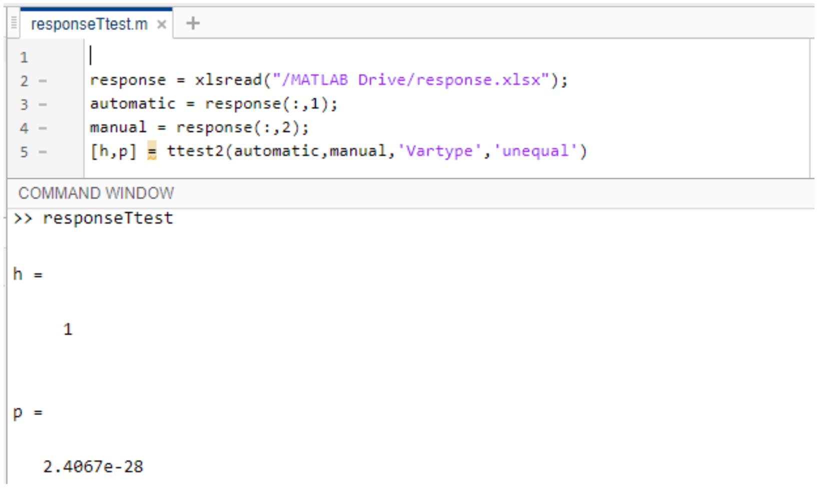


Figure 4.4: Results of t-test for responsiveness

From the results, h represents the test result of the null hypothesis. Its value as 1 rejects the null hypothesis which assumes that the means of the samples are the same. This means that the average time taken for devices to respond to sensor input is not the same as the time taken for devices to respond to control input from the mobile application. The p-value obtained which is less than 0.05 implies that the two data sets are statistically different. Also, from observation of the data, it was noted that manual control had a higher response time. This can be attributed to the time taken in passing data from the mobile application to the Raspberry Pi during manual control.

4.4.2 Test for Latency of Application Protocols

The latencies of the two application protocols, MQTT and HTTP, used in the implementation of the smart home were recorded. The time delay of the two protocols in posting data with payload of 31 bytes from the mobile application to the database was compared using a two-sample t-test. The t-test comprised of data samples of latency of MQTT with QOS level 2 and that of HTTP was performed with the following assumptions:

1. The two samples are normally distributed and do not contain any outliers.
2. The two samples have unequal variance.

3. The observations are random and independent of each other.

The null hypothesis (H_0) assumes that the average time taken for MQTT protocol to post data to the database from user input is the same as the time taken for HTTP to post the same data to the database. The alternative hypothesis (H_A) is that the true mean difference is not zero. The data used for this test is displayed in Appendix C. Figure 4.5 displays the results of the t-test performed with a sample size of 20 and confidence interval of 5%.

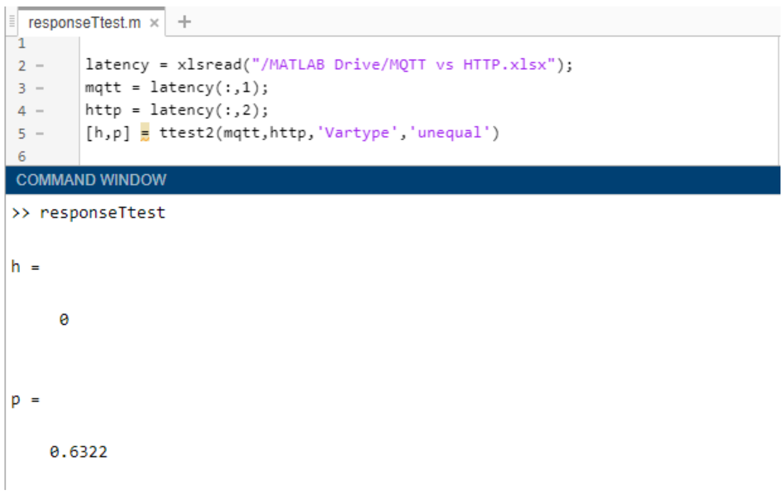


Figure 4.5: Results of t-test for latency

From figure 4.5, it can be observed that the h value is equal to zero, which implies that the null hypothesis is accepted. Hence, in this system, MQTT has the same latency as HTTP. The p-value greater than 0.05 confirms that the two samples have statistically equal means. The investigation of MQTT and HTTP protocols show that for smaller payloads with fewer clients, the latency of the two protocols are almost equal [32]. However, due to its light-weight nature, MQTT is found to be significantly faster than HTTP for higher payloads and network traffic. Hence, it is preferred for IoT networks.

4.4.3 Test for Accuracy

The test for accuracy was performed by carrying out test runs for both automatic and manual control and examining whether the output was accurate. For automatic control, the ability of actuators to respond to sensor input accurately was checked. With respect to manual control, the control actions were tested, and the actuators were observed for correct responses. From the analysis, each sensor and actuator responded accurately as expected. Also, when a test was conducted for an exceeded consumption limit, an alert was successfully sent to the user through the mobile application.

Chapter 5: Conclusion, Limitations and Future Work

5.1 Conclusion

This smart home system was designed to allow sensor operation as well as manual control of lighting, security, fire detection and air conditioning systems using wireless communication of IoT devices. The system supports both sensor-based and manual control modes and allows the user to set monthly energy consumption limits for the home. The user is notified when the consumption limit is exceeded, and designated high-power devices are shut off. The user has the ability to monitor the energy consumption of the various devices using a mobile application, and this can inform future usage of devices. The smart home system was able to process information responsively and accurately with high security to achieve the goal of efficient energy management. Finally, the more suitable protocol, MQTT, was identified for fast and reliable transmission of data across the application and database.

5.2 Limitations

As the project progressed, the level of knowledge required for IoT implementation increased, hence it was imperative to learn new concepts and methods such as the development of an API for remote access to the database, mobile application development and the use of MQTT. The time taken to learn the new concepts and technologies caused the project to slow down, limiting the extent to which research could be done. This limitation prevented the possibility of extending the research to investigate the comparative performance of Raspberry Pi and another microcontroller.

5.3 Future Works

Further analysis can be carried out to compare the performance of Raspberry Pi microcontroller against another microcontroller. Moreover, a machine learning model can be developed to identify patterns in consumption and device usage to enhance user experience. For larger applications, the SQL database can be migrated to a NoSQL database which supports the addition of more data types and parameters to an already existing system, making it more scalable and flexible. MQTT protocol can also be used for reduced latency.

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Appendix

Appendix A: Source Code

Code for circuit operation for the Raspberry Pi: https://github.com/DzifaHodey/energy-monitoring-with-iot/blob/master/smarthome-raspberry-pi.py

Flask API: https://github.com/DzifaHodey/energy-monitoring-with-iot/tree/master/restful-api

MQTT client: https://github.com/DzifaHodey/energy-monitoring-with-iot/blob/master/mqtt-client.py

Appendix B: Table of response time sample data

No.	Response Time for Automatic Control (s)	Response Time for Manual Control (s)
1	0.33	0.79
2	0.27	0.81
3	0.29	0.69
4	0.37	0.72
5	0.38	0.76
6	0.28	0.76
7	0.31	0.73
8	0.27	0.77
9	0.27	0.83
10	0.28	0.73
11	0.26	0.8
12	0.39	0.84
13	0.4	0.69
14	0.37	0.71
15	0.32	0.74
16	0.29	0.82
17	0.32	0.79
18	0.31	0.74
19	0.29	0.77
20	0.39	0.78

Appendix C: Table of latency sample data for application protocols

No.	Latency for MQTT (s)	Latency for HTTP (s)
1	0.052	0.102
2	0.064	0.076
3	0.059	0.084
4	0.073	0.075
5	0.1	0.101
6	0.165	0.06
7	0.037	0.102
8	0.05	0.056
9	0.333	0.052
10	0.088	0.07
11	0.095	0.064
12	0.099	0.062
13	0.093	0.056
14	0.0558	0.075
15	0.082	0.104
16	0.042	0.065
17	0.092	0.088
18	0.059	0.048
19	0.056	0.072
20	0.089	0.213