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Implementation of Smart Distribution Board for Domestic Energy Management and Regulatory System

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ABSTRACT

Technology has become vast as it finds its way into many sectors of life such as smart energy management in cities and energy optimization at home. Automating home appliances in view of the available energy resources posed challenges arising from the available control techniques such as the use of Bluetooth, Wi-Fi, or manual operation having stand-alone configurations. Also, already existing energy management systems do not make provisions for high energy-demanding appliances, thereby limiting their application which possibly leads to energy wastage. This paper reviews existing energy management systems for homes and develops a system for easy installation in residential settings to mitigate the aforementioned challenges. This design deploys the use of smart controllers to provide varieties of control choices using Wi-Fi, Bluetooth connectivity, and manual control devices; the developed smart system provides energy allocation for both the low and high-energy demand appliances at home; and the system incorporates visitors' notification system to alert the owners of an event at home in their absence. The prototype demonstration reveals that the system allows for easy scalability and employability in bigger homes, where more devices and power distribution are required. Further works will consider image recognitions and documentaries for the intending visitor.

Index Terms—Energy management, Internet of Things, smart distribution systems

I. INTRODUCTION

Food, clothing, and shelter are the basic elements for living and over the years, the designs of shelters have been upgraded marginally, with the breakthrough being the introduction of electricity [1]. Now, automation has been introduced to household power installations, that is Domotics. Domotics is the encounter of information technology, electrotechnics, and electronics that makes a home smart [2]. In a simple sense, home automation most commonly connects simple binary or "ON and OFF" devices such as lights and power outlets, but real control comes in when one starts interacting with devices from a remote location through a control device [3]. This can be achieved using Bluetooth, Wireless Fidelity (Wi-Fi) connectivity, infrared remote controls, and Internet of Things (IoT), where all devices are integrated into a network, they are interfaced and controlled, thus energy management becomes inevitable for efficient control of these devices in the home.

This work is inspired by a study of the application of the IoT to satisfy the purpose of energy allotment in domestic dwellings. It solves the problems of control of only low-power appliances, control schemes limitation, and complexity of systems. The problem of heavy devices not being accounted for results from the requirements inherent in satisfying their electrical demands. Many systems are limited to only one piloting system; only one means of control is employed in most cases.

The envisaged target of this work is to investigate home energy management systems, seeking a modified system capable of undertaking multiple control tasks as well as low and high energy demand allocations for available appliances. This system offers users an easy and effective means of controlling their home appliances from any location. Users have alternative means of control while in the house. This system provides remote controllers and switches to access certain devices. Apart from merely controlling the ON and OFF state of appliances, an extension is

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provided to allow users to have multiple devices access the network locally and globally.

This work efficiently designs a home energy allotment system that solves the problems of stand-alone connectivity, energy wastage, and control limitations, guided by the following specific objectives: to sufficiently design a smart power distribution board comprising the control unit, and an AC power source for the loads; to configure controllers for an intelligent switching, comprising a power distribution unit and a control distribution unit; to interface the control unit to the distribution unit; to establish of a secure online connection to the Internet for web control; and to set up mechanical controls and remote-control systems.

Multiple connectivities are provided in this work. Also, in cases of lack of proximity to the smart device or unavailability of the device, there is a need for manual access or control. Sometimes, the strength of the telecommunications network in the country weakens and varies, thus the need for manual energy control incorporation into the smart energy allotment device. Therefore, what makes this work stand out is its user-friendliness, simplicity yet robust properties, cost-effectiveness, and global master control over home appliances through the Internet. In addition, this work provides recommendations on expanding its scope thus making it suitable for a larger scale of applications like duplex house settings, offices, and others.

To achieve the objectives, the proposed smart distribution board will provide controls and energy to efficiently interface the electrical devices in a simple single-bedroom apartment. This houses the microprocessor, microcontroller, relays, contactors, and other materials relevant to the control circuit. The final design is a panel that houses the control circuit.

II. LITERATURE REVIEW

The Internet is a network of computers comprising private, public, academic, business, and government networks of local to global scope, linked by a broad array of electronic, wireless, and optical networking technologies [4]. These interconnected devices collect data regularly, analyze it, and use it to initiate actions [5]. The IoT has evolved over the years to a network of devices of all types and sizes: vehicles, smartphones, home appliances, industrial systems, and many others, all connected, all communicating and sharing information [6]. Connectivity refers to the enabling devices or technologies of the IoT. They include wireless sensor networks, 2G/3G/4G, Wi-Fi, Global Positioning System, Radio Frequency Identification, Bluetooth, infrared technology, and others. These provide the medium through which the data interchange between devices takes place [7].

The actual idea of connected devices had been around longer, at least since the 1970s. Then, the idea was often called "embedded Internet." The term IoT was coined by Kevin Ashton in 1999 during his work at Procter & Gamble. Even though Kevin Ashton grabbed the interest of some P&G executives, the term IoT did not get widespread attention for the next 10 years [7]. The Internet of Things has over the years emerged from the convergence of wireless technologies, microelectromechanical systems, microservices, and the Internet. The convergence has helped tear down the silos between operational technology and information technology, enabling unstructured machine-generated data to be analyzed for insights to drive improvements [7]. The first IoT device was a Coke machine designed by students of Carnegie Mellon University, Pittsburgh, Pennsylvania, in the early 1980s, where the content of a Coke machine in the university was tracked remotely [8]. Internet of Things evolved from machine-to-machine communication, where a device is connected remotely to a cloud or database and it is managed through this.

According to [9], the number of connected online devices have over the years risen from 300,000 in 1990 to about 16.4 billion in 2022 and is predicted to reach 75.44 billion in 2025. Since early 2014, the mobile has overtaken the personal computer (desktop/laptop) as the leading device used to navigate the Net. Along with the mobile, several portable devices that connect to the Internet have also started proliferating at a very quick rate. These devices can sense the environment around them and, accordingly, act intelligently, thus are referred to as connected devices, smart objects, or the web of Things [7, 10]. The applications of IoT include smart homes, smart cars, industrial automation, healthcare, smart cities, and smart agriculture [11]. It allows easy access to information from any location and at any point in time provided there is necessary administrative access to the information, improves the overall efficiency of performance and output, optimized protection of systems, and real-time monitoring of systems among others. Some downsides include costly initial capital, susceptibility to hacking, and cumbersomeness in data management for larger provisioning [3]. When designing a home automation system, it should be ensured that it is scalable, allowing easy integration of new devices. It should provide a user-friendly interface on the host side, to ensure easy monitoring and control, and the overall system should be fast and cost-effective [12].

Bluetooth as a means of connectivity was designed as a cable replacement technology and has become a smart technology for reliable wireless communication systems [13, 14]. It is a standardized protocol for sending and receiving data through a 2.4-GHz wireless network. It is a secured protocol, and it is perfect for short-range, low-power, low-cost, wireless transmission between electronic devices [14]. Today, home automation is one of the major applications of Bluetooth technology, linking devices within a range of 100 m at a speed of up to 3 Mbps depending on the Bluetooth Device Class [15]. Simple automation configuration could be achieved using a Bluetooth module and an Arduino microcontroller as done by [12].

Infrared is also a wireless connectivity means [16]. An infrared transmitter contains a light-emitting diode that emits infrared light. The receiver contains either a photodiode or a phototransistor, passing more or less current due to the amount of infrared radiation light falling on it [17]. Wireless Fidelity is another wireless connectivity. It is very fast, several times faster than the fastest cable modern connection, using radio waves [18]. A simple Wi-Fi-based home automation could be achieved like that of infrared and Bluetooth [19].

The properties of the discussed connectivity media differ in many ways. Wi-Fi covers more distance than Bluetooth and infrared and is not affected by line of sight [15]. It is faster but more expensive than the others. Bluetooth and Wi-Fi support multiple devices in a single connection, but this is a limitation in infrared which is affected by line-of-sight problems [15].

For IoT to stand, it needs a platform and tools. These platforms help to fill the gap between the device sensors and the data network by connecting the data to the sensor system and gathering data developed by the many sensors, providing the energy necessary to power up and control the sensors, store and transmit the data meant for the implementation of the sensor. The tool is usually a microcontroller or microprocessor with desired hardware and software characteristics for the job at hand [20].

The common platforms used for the IoT are Node-Red, Eclipse IoT, Arduino, Rasbian, and PlatformIO among others [11, 21, 22]. Common tools used for the IoT are the Raspberry Pi computer and the Arduino microcontroller [23]. Arduino and Raspberry Pi are open-source electronics platforms based on easy-to-use hardware and software. Using them requires Arduino Integrated Development Environment (IDE) and Rasbian Operating System [24, 25]. The platforms used in this work are Anvil Works and Rasbian. Anvil is used for building and hosting web apps based on Python, supporting visual programming, and Python is used on the front-end and back-end to make it all work [26].

A Smart Home system was designed using the Raspberry Pi computer and other smart sensors [27]. The proposed IoT-based smart system includes such devices as a smart fridge and it incorporates a web-based control alongside a speech recognition system. An Android-based app is used for remotely controlling the system. As long as there is Internet coverage, the system can be controlled from anywhere in the world [27]. This design properly utilizes the power of IoT by offering a means of control over the Internet.

A GSM-based home automation system was designed by [28], and in their design, they established a remote connection to control the various devices using an ESP module, ESP camera, and a few sensors. Their system is very cost-efficient and simple and handles efficiently the visitor's security system.

Z. L. Oo et al. [29] worked on a system using Arduino Uno, HC-06 Bluetooth module, and some sensors and deployed a mobile app to efficiently control the system through Bluetooth connectivity. An IoT-based smart home automation system with Raspberry Pi integrating motion sensors and cameras into a web-based application was developed, using Raspberry Pi controls, motion sensors, and video cameras for sensing and surveillance [30].

The major drawback in these works is a restriction in control, giving the user only one option of controlling the system. There is no provision for manual control using switches. Also, there is no provision for the integration of many devices. This work efficiently solves these drawbacks identified in the related works cited here. The design template provided by this paper sufficiently adds multiple wireless connectivities and also makes provisions for manual controls, while scaling the output capability to meet the requirements of heavy appliances.

III. METHODOLOGY

The design template provided by this research work is a panel box housing all the components necessary for setting up the smart energy allotment system. This box replaces the normal distribution boards in houses with provisions for mains output through contactors that carry heavy loads as presented in Fig. 1. Provisions for small loads are also given through relays. There is a Bluetooth card already embedded in the Raspberry Pi computer used for this work. This setup enables serial communication between Bluetooth remote and the system. For direct control of the system, pushbuttons are added through connection to an Arduino microcontroller, which interfaces with the Raspberry Pi through a USB wired connectivity. The security system is a proximity sensor and a camera, capturing images when the proximity sensor senses objects and sending images to an email address.

The Raspberry Pi 4B is used in this work. It comes with an in-built Bluetooth card. The Bluetooth device used to control home appliances is an Android Phone and Bluetooth application is designed for it. The Bluetooth device operates within the confines of the house such that when the user steps outside, connectivity is lost due to distance, thus at this point, an online connection is used. The system flowchart and its Pseudo code are presented in Fig. 2.

Arduino Nano is used as a slave to the Raspberry Pi, the master controller, allowing the Pi computer to get data and send data to the Arduino Microcontroller. The Arduino is programmed to act as a slave to the Raspberry Pi computer using a python Library called "PyFirmata." To do this, the Standard Firmata sketch is uploaded to the Arduino through the IDE.

A cooling system was designed with a 12 V dc fan, positioned very close to the Processor and the Wireless NIC (Network Interface Card), powered by a rectifier circuit from the mains input through the Double Pole circuit breaker. A 220 V ac triggered contactor is used in this work. It is both manually and automatically operated. The coil circuit of the contactor is connected to the normally opened output of the relay as shown in Fig. 5. The contactors provided are rated 15 A

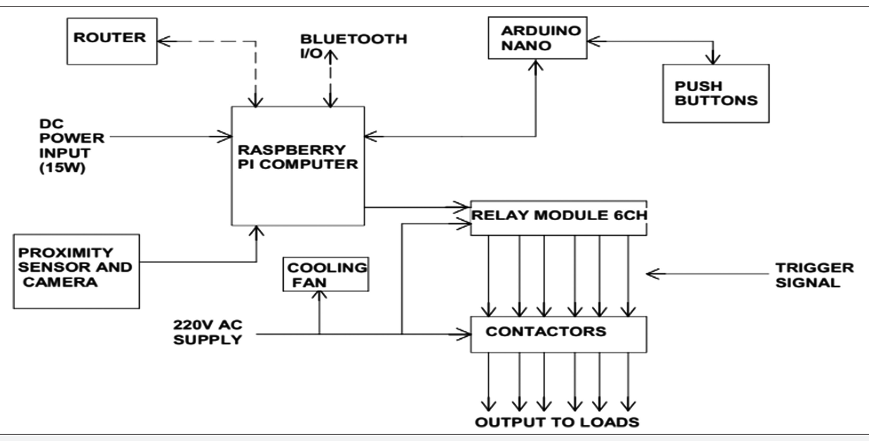
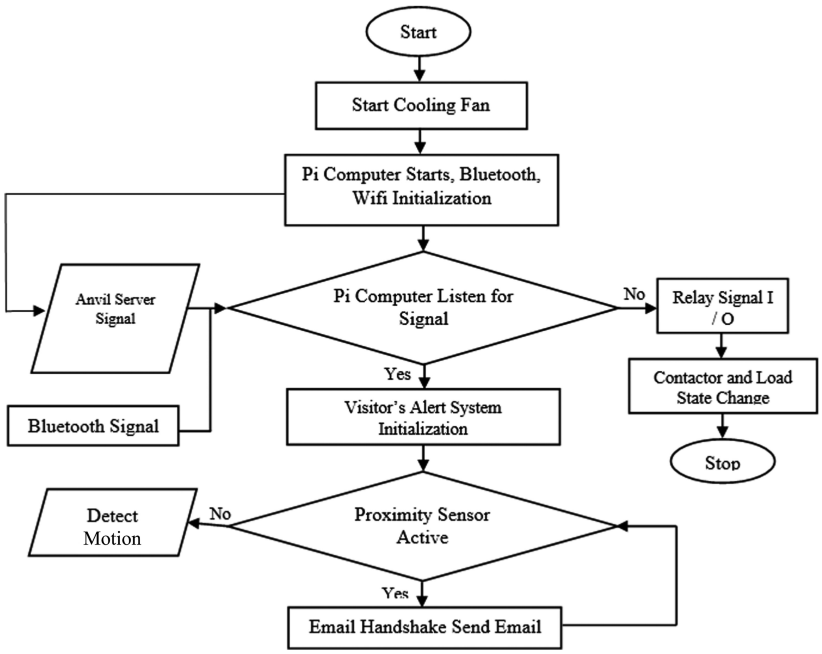


Fig. 1. Block diagram of model.



Pseudocode

Start Cooling Fan
Run Pi Computer Starts, Bluetooth, Wifi Initialization
Input Anvil Server Signal
Input Bluetooth Signal
If Pi Computer Listen for Signal
Then, initialize the visitor's alert system
Else, Relay Signal I / O
Contactor and Load State Change
If Proximity Sensor Active
Then, Email Handshake Send Email
Else, Detect Motion

Fig. 2. Flow chart of the system.

and 20 A for the maximum load current. The relay is a low-level trigger eight-channel relay module and is connected GPIO pins of the Raspberry Pi, with the trigger pins connected to a 5 V output pin. Two channels of the relay module are utilized for lighter loads such as lighting points since the relay module is rated 3 A max output.

The Pushbuttons in this work replace the generic gang switches used in electrical installations, since they do not have a fixed state, they are normally open and only close when pushed. When pressed, the computer senses this signal and in turn, switches on or off the associated load. A separate relay module powered from a separate power rectified from the mains supply is used to power the buttons allowing the pushbuttons to be situated at long distances within the apartment.

The control over the Internet is done with anvil, using the anvil uplink library. This is set up by downloading the anvil repository from the server using the code "*pip install anvil-uplink*." The server code is written in the Anvil platform. A Python script is written in raspberry to enable the GPIO controls. A special key is issued on the server side which is included in the Python script for the GPIO controls in the Raspberry Pi machine. The designed web app and Bluetooth app interface are shown in Fig. 3.

The method used to configure the Python script to run at start-up is the "SYSTEMD" method. It uses SYSTEMD files, creating a process that runs the Python script at start-up. The Raspberry Pi serves as a Bluetooth server, with ports set to listen for available connections and signals from the client side which is the Android device.

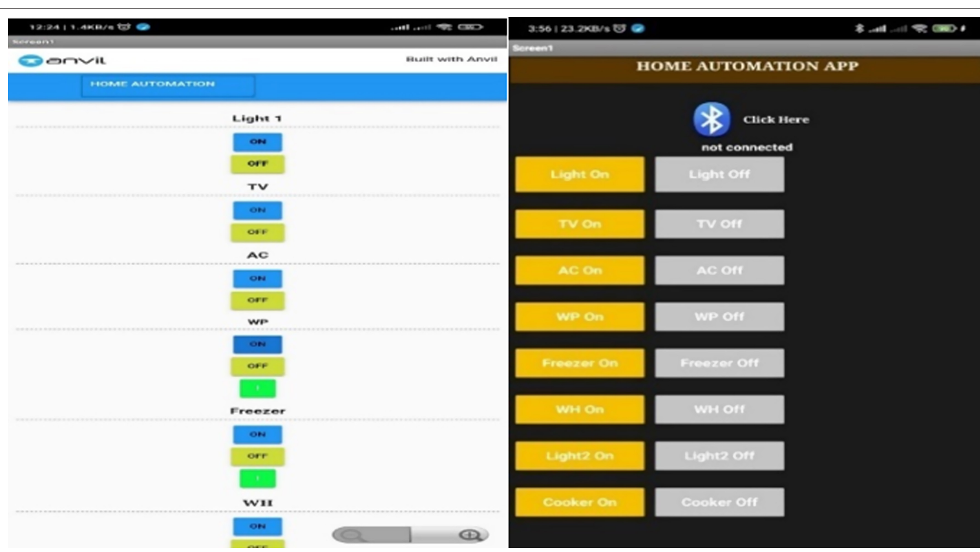


Fig. 3. Web and Bluetooth application interface.

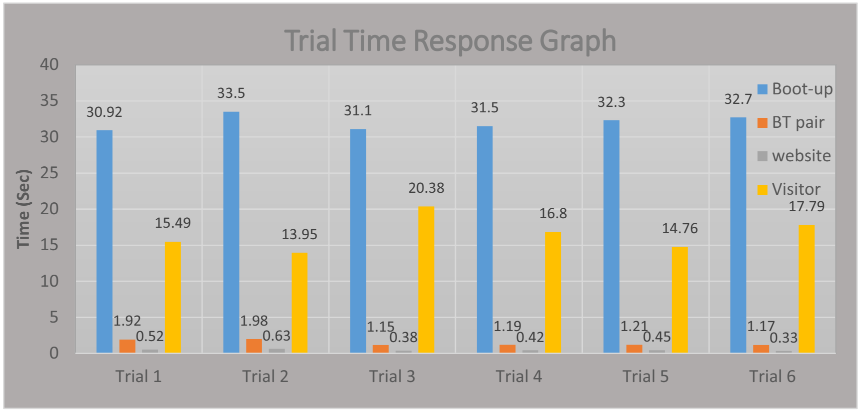


Fig. 4. Chart showing time response.

An Android Bluetooth application and web application to the Anvil server are shown in Fig. 3. Serial communication is enabled on the Pi for Bluetooth communication by installing a Bluetooth protocol called bluez: "*sudo pip3 install pybluez*" and setting the device be discoverable.

The visitors' notification system in this research work is a simple one that sends snapshots to an email address. It consists of a proximity sensor and a Pi camera. The camera is connected to one of the provided camera ports. The switch provided in this setup allows the user to turn ON or OFF the system.

The complete circuit diagram is shown in Fig. 5, and it was earlier established that the main control unit is the Raspberry Pi computer. It has Bluetooth and Wi-Fi modules embedded in it. It interfaces with the Arduino Nano through a USB connection. The proximity sensor is connected to the Raspberry Pi through one of the GPIO pins as shown earlier. The contactor takes its supply from an AC source.

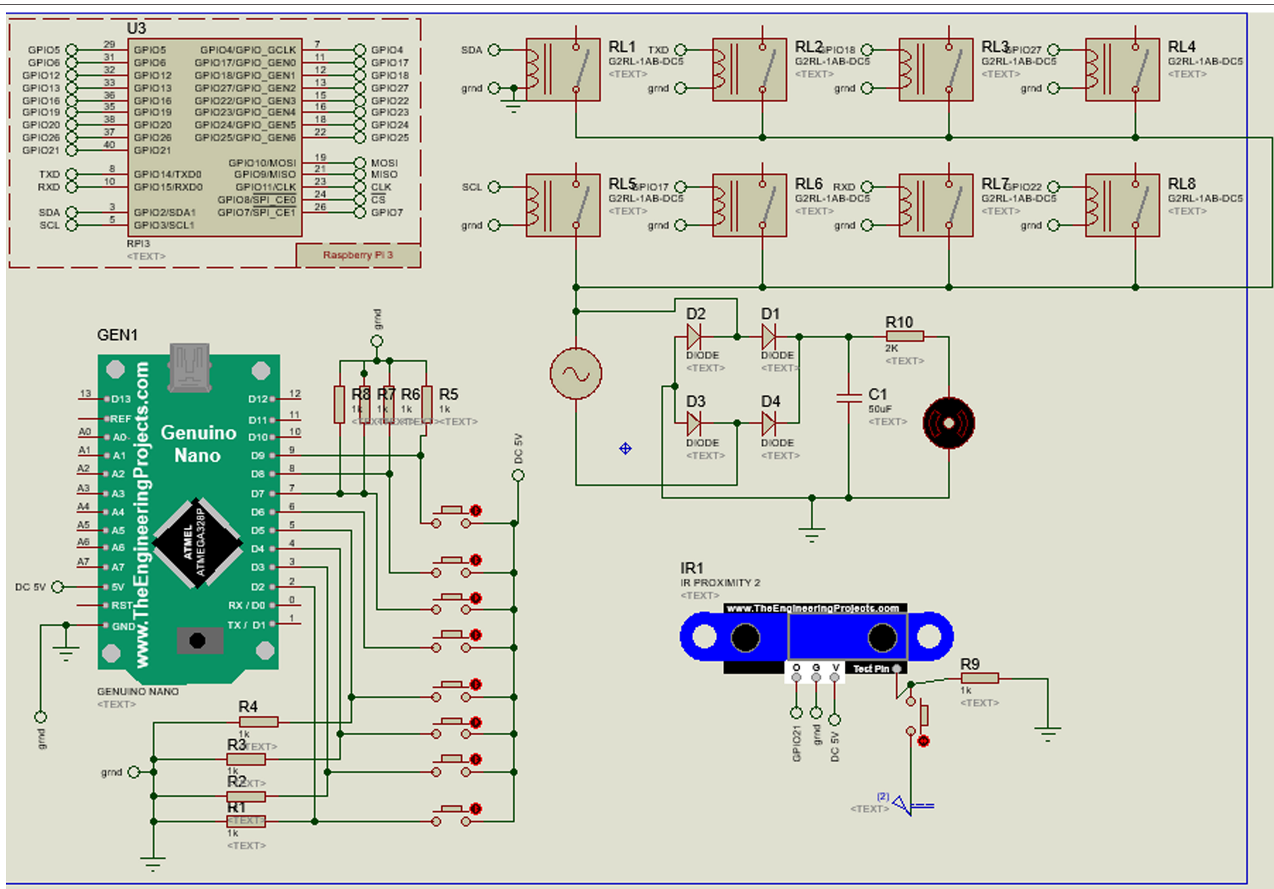


Fig. 5. Circuit diagram for overall system.

Fig. 6. The prototype of the smart distribution board with visitor check.

A part of the supply is used to power the DC fan through a rectifier circuit. Fig. 6 shows the implemented prototype of the smart distribution board with visitor check features.

IV. RESULTS AND DISCUSSION

The push button and visitors' notification system are demonstrated using the small adaptable boxes attached to the smart distribution board and various loads are demonstrated using incandescent light bulbs. This box replaces the distribution board in a residential building. The following are taken into consideration:

i. The switches can be placed anywhere in the building, as long as they are connected to the power source which is the relay module.
ii. The Visitors' system is placed at the entrance of the building. The camera can be replaced with a USB-powered camera or a wireless camera
iii. The control unit of the system which is the Raspberry Pi computer is provided with a separate power supply, via a USB cable from a power source. This ensures that in cases of outages or overloading or fluctuations in the supply, it does not affect the control part of the system.
iv. The computer is put on first before the main power supply is put on. This prevents transients from occurring from the control system when booting up as the codes are being mounted in the command terminal and initialized.

A. Speed of Operation and Latency Results for Start-Up Time, Bluetooth Handshake, Web Control, Visitors Notification

The Raspberry Pi is a complete computer with peripherals. When the system is booted up, some time is taken by the computer to fully go into operation, also, the time taken for Bluetooth control signals, Internet signals, and snapshots images to be received and processed successfully are tested and recorded as shown in Table I.

In Fig. 4, the data from Table 1 are plotted. The time taken for the system to receive signals from the Bluetooth, Wi-Fi, and manual controls.

1) Load Management

The separation of control relays and contactors AC power supply effectively manages load distribution in the system. Heavy appliances take their supply directly from the contactor outputs, and this supply in no way affects the control unit in terms of energy demand. This form of energy management ensures that there is seamless power distribution and control of both heavy and light-load electrical appliances. This is evident in the power consumed by the contactor and relay coils during trigger operations and maximum load operations. The power consumed for the coil of the contactor is:

TABLE I. TABLE SHOWING TEST ON BOOT-UP TIME

Trial S/N	Time (s) Boot-Up	Time (s) Bluetooth	Time (s) Web Control	Time (s) Visitors' Alert
1	30.92	1.92	0.52	15.49
2	33.5	1.98	0.63	13.95
3	31.1	1.15	0.38	20.38
4	31.5	1.19	0.42	16.8
5	32.3	1.21	0.45	14.76
6	32.7	1.17	0.33	17.79

Current at instance of trigger = 22 m,

minimum current required to keep the circuit closed (Current after 5 s) = 5 mA

$$P = IV \cos\varnothing \tag{1}$$

Power required to trigger the contactor gives us 4.114 Watts

Power required to keep contacts closed gives us 0.935 Watts

The power consumed by the contactor is completely independent of the power and circuit of the Pi computer and Arduino, thus giving complete control over heavy loads.

V. CONCLUSION

It was earlier established, the major setbacks in many already existing energy management systems are the inability to incorporate the control of heavy loads or appliances into the system, lack of alternative control methods through which the system can be controlled in the absence of proximity to one control medium and the property of controlling so many loads. These problems have been looked into and resolved by the template presented in this work. The applications of this work transcend beyond just home automation. It can be successfully used in remote controlling of certain devices and systems, in industrial applications, agriculture, and others. With little modifications, the system can fully suffice the electrical requirements of duplex residential settings. This research work contributes to existing knowledge in the following ways: provision of a range of control choices, these are Bluetooth control, web control, and manual control with pushbutton switches; the research work comfortably carries heavy loads and machinery, up to power requirements of about 3 kW per load. A simple notification system is set up in the research work which notifies users of any movements taking place in their respective domiciles. The research work as tested requires the following upgrades and recommended thus: a separate power supply system should be designed for the control circuit, an inverter system is recommended with 5 V dc, and 3 A ratings; strong security is required for the web control, a login and password encryption should be set up at the client-side.

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