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Design and Validation of a Multifunctional Android-Based Smart Home Control and Monitoring System

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ABSTRACT Users often need to control and monitor the environmental variables of their homes, even when they are not at home. In this paper, we present a multifunctional, low-cost, and flexible system for smart home control and environmental monitoring. This system employs an embedded micro web server based on an Arduino Yún microcontroller with Internet connectivity that allows remote device control. The proposed system can be controlled via the Internet through an Android-based mobile app. To guarantee access regardless of Internet availability, the proposed system can also be controlled via standalone manual operation using a touch display. The proposed system transmits sensor data to a cloud platform and can receive commands from the server, allowing many devices to be automatically controlled. To demonstrate the feasibility and effectiveness of this system, devices such as light switches, power plugs, and various sensors, including temperature, gas, 2.5-μm particulate matter (PM2.5) and motion sensors, were integrated into a prototype of the proposed home control system. Finally, we implemented the prototype in a model home to validate the flexibility, scalability, usability and reliability of the system.

INDEX TERMS Microcontroller, smart home, Arduino, the Internet of Things (IoT).

I. INTRODUCTION

Smart home systems currently play an important role in ensuring a high quality of life [1]. A smart home system consists of subsystems based on Internet of Things (IoT) technology that are suitable for various purposes, such as surveillance, intruder control and fire detection [2]–[4]. Consider a scenario in which the user can view the status of his or her home environment and control his or her home appliances, for example, turn on the television and set it to his or her favorite channel, turn on the air conditioner, or switch the lights on or off, from anywhere in the house. The core requirements for such a scenario are to provide an easy, convenient and efficient way to monitor home security and improve comfort [5]–[7].

Sensor technologies have improved rapidly in recent years. With corresponding developments in IoT technology, sensors are simplifying tasks such as monitoring and interacting with the environment. Simultaneously, the rapid development of embedded systems, including both hardware and software, has made these systems easier to implement and more flexible, leading to lower costs. For example, a commercial microcontroller evaluation board (EVB), such as an Arduino board, can be used to simplify and accelerate system development while satisfying the requirements mentioned above. Both mobile technology and applications have

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TABLE 1. Literature survey of smart home control and monitoring systems.

Reference	Communication	Sensor usage	Control and monitoring methodology	Cloud platform	Main contribution
Bassoli et al. [11]	Wi-Fi; TCP/IP	Armchair/bed sensor; Magnetic contact; Toilet sensor; Passive infrared (PIR) sensor	Motion detection	IBM Bluemix Watson IoT platform	IoT prototyping
Monteriù et al. [11]	Wi-Fi; TCP/IP	Electrocardiogram (ECG) signal; Heart rate (HR); Breathing waveform; Breathing rate (BR); Oxygen saturation; Blood pressure (BP); Body weight; Body temperature; Glycemia	Physiological monitoring	Open Services Gateway Initiative (OSGi) framework	A classification method for judging sensor data accuracy
Lin et al. [12]	Not reported	Particle meter; Carbon monoxide (CO); Nitrogen oxide (NOx); Volatile organic compounds (VOCs)	Air quality detection	User-defined storage	Use of machine learning algorithms and SH features
Alirezaie et al. [13]	Wi-Fi	No specific sensors	Building ontology-based relationships for sensor networks	Ontology web	Use of a semantic web to generate a semantic representation of sensor relationships
Barsocchi et al. [14]	Wi-Fi; Bluetooth; Konnex;	Wi-Fi; Bluetooth; Konnex	Image processing and pattern recognition (CNN, AI) integrated with complex event processing	Mongo DB	Development of an access control engine using policy enforcement points (PEPs), policy decision points (PDPs), and policy administration points (PAPs) to identify unauthorized access events
Hsu et al. [15]	Wi-Fi	Wearable inertial sensing module; CO sensor; Temperature sensor	Intelligence-based gesture recognition algorithm using a probabilistic neural network (PNN); indoor positioning algorithm using a support vector machine (SVM); Fire detection; Alarm algorithm based on a PNN	Self-developed information processing module	Automated household appliance control; Smart energy management; Home safety

advanced rapidly in recent years, and apps for mobile devices, including tablets and smartphones, have become indispensable for people today. Many people cannot work or conduct their daily tasks without mobile devices. Hence, we designed our proposed system to run on mobile devices. Furthermore, the mechanism of the proposed system integrates a cloud platform and a database in the form of a web service to enable flexible and extensive scalability to heterogeneous systems in the future [8], [9]. Based on a survey of the literature, information from a number of helpful and useful papers is summarized in Table 1. Our literature survey suggests that a common and easy communication methodology is Wi-Fi access [10]–[15]. In addition, relatively low-cost sensors provide valuable advantages, and commercial cloud platforms are stable and robust. All sensors used in the proposed device were selected based on the user requirements and related suggestions from our survey of the previous literature [10]–[15].

To ensure the practical usability of the proposed device, we also surveyed some currently marketed products that can meet some of the needs discussed above, including smart thermostats developed by Nest Labs [16]. However, these thermostats need to be combined with additional independent products to achieve multisensor capabilities. As another example, the ASUS SmartHome Gateway (HG100) [17] is a centralized product that allows the stacking of independent sensor-based products. However, it is quite costly. The IoT products developed by Tatung Company are also independent sensor-based products [18] that can be used with universal development kits. Their disadvantages include a high entry cost. Additionally, many single-use sensors cannot be integrated with heterogeneous products. Thus, users must buy homogeneous products and combine their functions to satisfy multifunctional requirements.

To achieve a multifunctional smart home control and monitoring system, the proposed system includes sensors that can monitor environmental temperature and humidity and detect environmental changes. In addition, users can use mobile devices to power the system on and off and to view data. To achieve these functions, the cloud platform and database system must be integrated into mobile services such that access is available anytime and anywhere [19]. Because such continuous applications face critical technical issues at all points of the system development cycle, the proposed system must be implemented using the waterfall methodology based on software engineering (SE) approaches.

Currently, Internet access is almost ubiquitously available; however, a manual mode of operation and an independent display for data visualization must also be implemented to guarantee that a system can continuously operate in environments in which no Internet connection is available. With these requirements in mind, we need to construct a mixed Internet-based and standalone home automation system; notably, such systems are currently rare and expensive on the market [6], [20], [21].

Although the proposed system may be difficult to design and implement due to the complexity of the required technology, the benefits of our system include the ability to connect to the Internet and cloud platforms, a user-friendly graphical user interface (GUI) for controlling home appliances using mobile devices, a visual display that allows users to operate the system in an environment without an Internet connection, support for multiple sensors to detect the state of the environment, and the ability to notify users of intruders. Despite the difficulty of implementing and optimizing the algorithms designed for the proposed system, to achieve our goals, our research integrates several methodologies, including system integration, IoT technology, mobile computing and cloud computing.

II. MATERIALS AND METHODS

A block diagram of the conceptual architecture of our multisensor smart home system describing the sensor locations and usage is shown in Figure 1. The proposed system uses a Wi-Fi adaptor to connect to an access point (AP) and send sensor data to the ThingSpeak web service in the interoperable layer. The system consists of a smart home app based on the Android OS, a tiny web service running on an Arduino Yún with a dual-CPU architecture as the kernel processor, sensor modules and a standalone thin-film transistor (TFT) display for manual operation. The proposed smart home system utilizes Wi-Fi and Internet connectivity to enable features such as the generation of security and fire alarm alerts in the app when environmental abnormalities are detected [22]. Contingency measures can then be taken by the user in a timely manner.

The system currently employs six types of sensors running on an Arduino Yún to achieve comfort and convenience within the context of the Lifestyles of Health and Sustainability (LOHAS) paradigm, which is particularly focused on ensuring human health. These six sensors were selected to detect harmful pollutants or factors that can cause discomfort; they include a passive infrared (PIR) LED (digital communication), a DHT22 AM2302 temperature and humidity sensor (digital communication), a GP2Y1010AU0F sensor for 2.5-μm particulate matter (PM2.5) (analog communication),

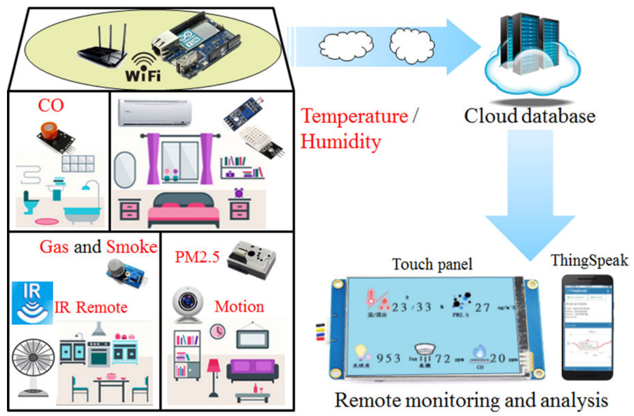


FIGURE 1. Conceptual overview of the smart home system architecture. The system employs six popular types of sensors to detect harmful pollutants or factors that can cause discomfort, including a CO sensor for detecting carbon monoxide, a PM2.5 sensor for detecting environmental nanoparticles, and a temperature and humidity sensor for detecting high-temperature and high-humidity conditions. The design also includes a convenient function whereby family members can turn home appliances on and off. An example is controlling the air conditioner to adjust temperature and humidity. In addition, to address security considerations, the system architecture includes an advanced mechanism for detecting intruders by means of a PIR motion sensor to protect family members and instantly notify users of current conditions via the ThingSpeak website (https://thingspeak.com/), which is a commercial product that transmits one message/second and 33 million messages/year and supports C/C++/MATLAB.

an MQ7 (CO) sensor (analog communication), an MQ2 (gas) sensor (analog communication), a BH1750 light intensity (lux) sensor (I^2C communication) and a photoresistor (analog communication) (Figure 2). All collected data are uploaded to ThingSpeak via a Wi-Fi adaptor, allowing the home environment to be monitored using the developed app. The system is designed to control more than switching functionality. For example, conditions related to security and surveillance (intruder and fire detection), energy management, and the home environment can all be fully monitored. Another feature of this system is intruder detection based on the PIR motion sensor. These functions can all be controlled from the smart home app, which is based on the Android OS [23].

A. ARDUINO-BASED MICROCONTROLLER

The Arduino is an easy-to-use, low-cost tool for controlling and sensing physical parameters via hardware and software. Its advantages include open-source resources that are more extensive than those of any previous microcontroller, a freeware development kit supported by billions of devices, a layered architecture, and plug-and-play modules that support thousands of compatible boards and sensors. Arduinos are usually used for developing interactive objects that take inputs from a variety of switches or sensors for controlling a variety of lights, motors, and other physical outputs. Arduino projects can be standalone or can communicate with software running on other computers. Although many other microcontrollers and platforms are available for physical computing, their development kits require engagement with the complicated details of embedded programming and often involve

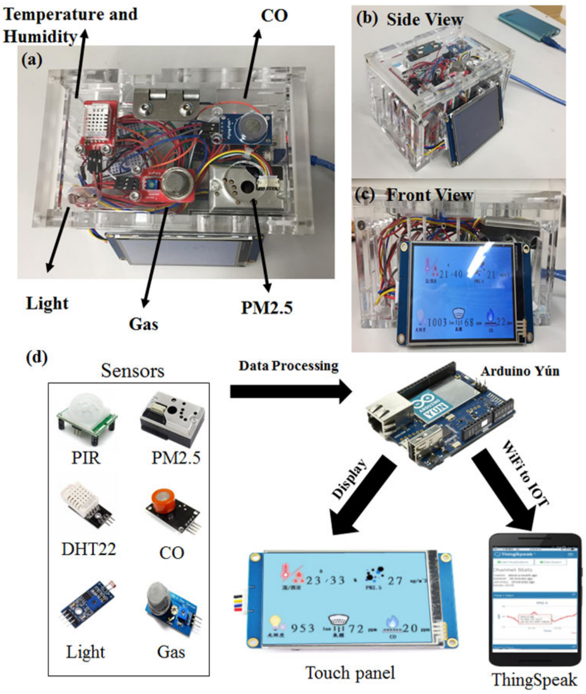


FIGURE 2. (a-c) The proposed smart home system as viewed from the top (a), left (b) and front (c); (d) a block diagram of the smart home system showing the components of the multisensor system module, including the six sensors for environmental detection, the TFT display with a touch screen (4.3" universal asynchronous receiver/transmitter (UART) communication) for user interactions and the Wi-Fi adaptor for transmitting sensor data to enable synchronous visualization via the ThingSpeak website.

extra components or hardware. In comparison, Arduino simplifies development efforts through its support for open-source resources. It supports various coding styles, including C/C++-based, GUI-based and block-based coding. Teachers, students and interested amateurs can learn and develop on Arduino more easily than on other systems. The Arduino Yún is an AVR-based EVB that includes digital input/output pins, 6 analog inputs, a 16-MHz ceramic resonator, a USB connection, a power jack, an ICSP header and a reset button. It includes everything needed to support the microcontroller. To begin, one can simply connect it to a computer with a USB cable or provide power through an AC-to-DC adapter or battery.

B. ANDROID-BASED SMARTPHONE APPLICATION AND FEATURES

The software suite for the proposed home automation system is divided into two parts: the server-side software and the embedded system software. The server-side software implements a micro web server running on the Arduino Yún that acts as a communications bridge based on a REST/RESTful architecture between the ThingSpeak platform and the embedded system, providing an easy way to read/write sensor data from/to a website or database management system [24]. Its mechanism hides the communication layers and enables the use of computer languages

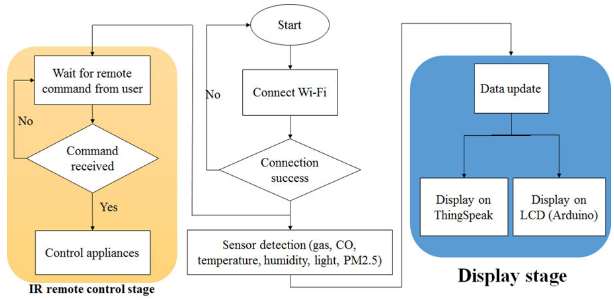


FIGURE 3. Home gateway flowchart for establishing a Wi-Fi connection, showing the process flow for implementing the smart home system. Users can access the IR remote control stage to control their home appliances. The proposed system architecture has dual channels for visual display: web-based viewing and a touch-panel display.

such as Ruby, HTML and PHP to simplify implementation in Arduino. Figure 3 shows a flowchart of the process of establishing an Internet connection from the Arduino. Users can access the infrared (IR) remote control stage to control their home appliances. The proposed system architecture has dual channels for visual display: web-based viewing and a touch-panel display.

Android is a general-purpose OS with a software stack architecture intended for mobile devices. It includes numerous middleware layers and bridges for integrating heterogeneous hardware and software and provides many application programming interfaces (APIs) for controlling mobile device components. This architecture allows both application developers and third-party software providers to easily develop complex and powerful applications with multiple SDKs [25], [26].

Android has become the most popular OS for tablets, smartphones, mini PCs, etc., surpassing iOS. Hence, the proposed system was implemented for Android-based devices. Android is a customizable platform that looks and feels quite different on different handsets. Various development tools support Android, allowing developers to create apps that look attractive and take advantage of the hardware capabilities available on each mobile device. Android is based on the Linux operating system and uses Java-like languages for building applications. The main goal of using Android is to allow control signals to be easily sent from smartphones through Wi-Fi or 3G/4G to provide users with the following functionalities: 1) a remote connection to the home gateway, 2) device control, 3) device monitoring and 4) schedule management. Figure 4 shows the GUI for controlling and managing the home environment using the integrated TFT display. The multisensor system proposed here includes a TFT display for convenient viewing even in a standalone environment without an Internet connection. The user can touch appropriate icons on the display to request the display of specific data. On the sensor data display, temperature and other values remain constant, while a lux graph shows the result of switching a light on and off. Figure 5 shows the GUI used to control and manage the home environment through a smartphone. Similarly, on this display, a lux graph shows

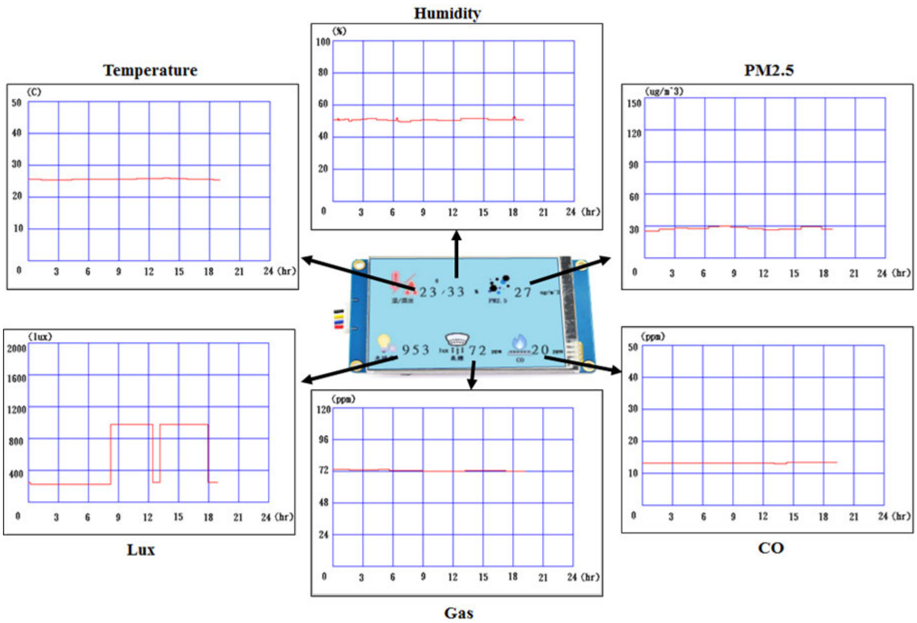


FIGURE 4. GUI for the home control system and its real-time TFT display. The multisensor system proposed here includes a TFT display for convenient viewing even in a standalone environment without an Internet connection. A user can touch appropriate icons on the display to request specific data. On the sensor data display, temperature and other values remain constant, while a lux graph shows the result of switching lights on and off.

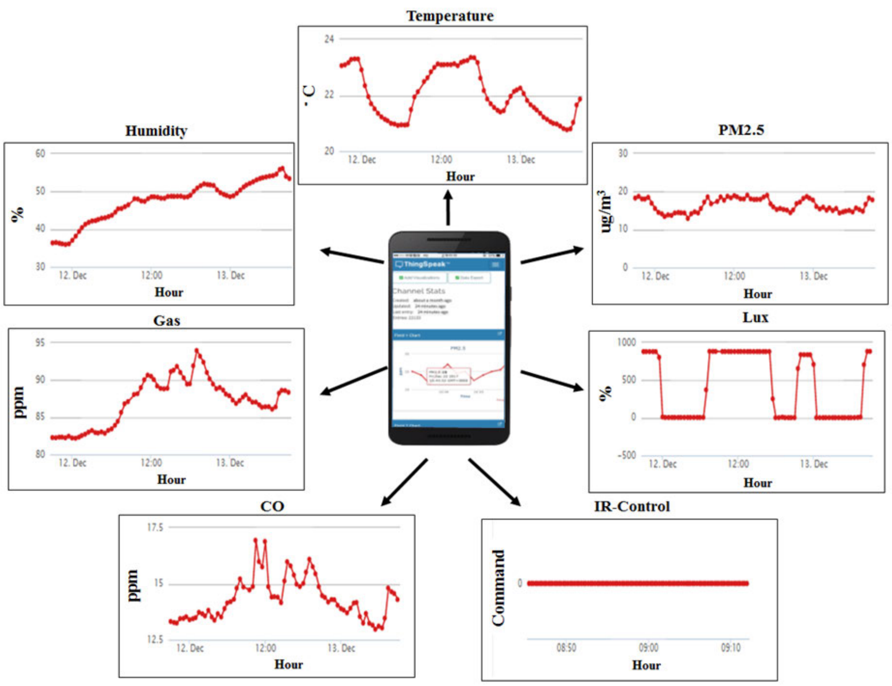


FIGURE 5. Screenshots of the smart home app GUI. To view the visualized charts and data, a user runs the proposed app on an Internet-connected Android-based mobile device. The raw data from the proposed multisensor system are analyzed and visualized in chart form via the ThingSpeak website. A lux graph shows the result of switching lights on and off, while the sensor data vary over time. The advanced features of the ThingSpeak website allow the use of MATLAB- or C-based code for preprocessing and postprocessing raw data.

the result of switching lights on and off, while the displayed sensor data vary over time. A user can run the proposed app on an Android-based mobile device that is always connected to the Internet to view the visualized charts and data. The raw data from the proposed multisensor system are analyzed and can be visualized in chart form through the ThingSpeak

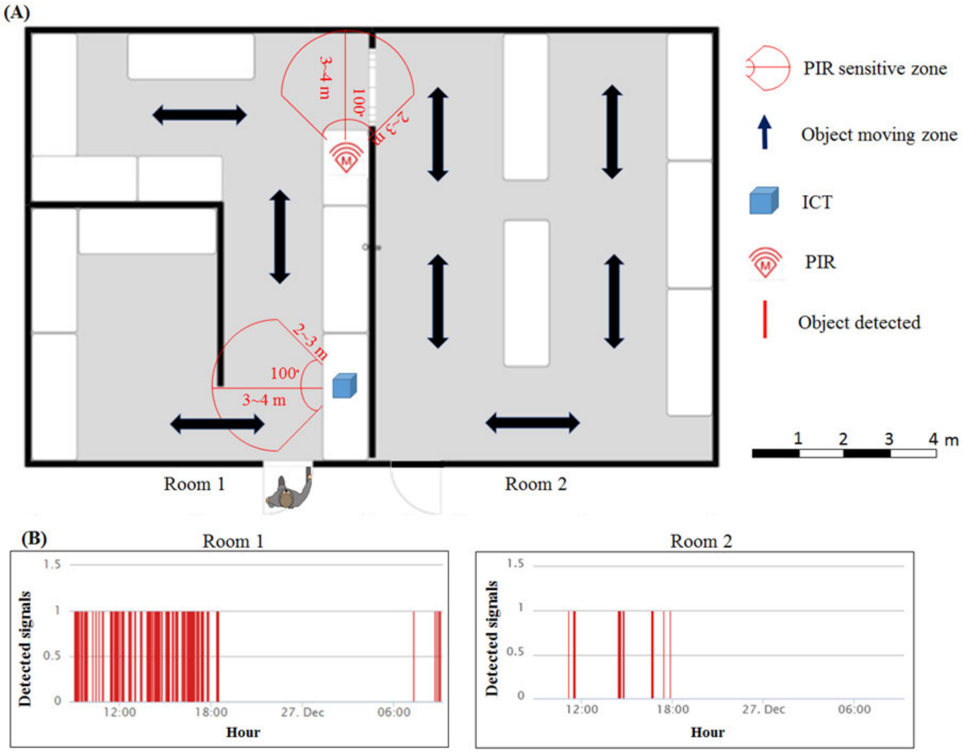


FIGURE 6. The intelligent motion detector in the smart home system identifies movement reliably and precisely while distinguishing significant events from normal events; thus, alarms are sounded only when necessary. The multisensor system implements a unique mechanism for detecting human motion based on a PIR sensor, as shown in (a). The PIR sensor's sensitive zone is fan-shaped and has a maximum range of 3–4 m. The proposed system uses a rule-based approach based on human behavior to discriminate between a burglar and, for example, the homeowner's cat. If the system identifies an intruder, it sends the raw human motion data to the ThingSpeak website. As shown in (b), during testing, a person was successfully detected in every instance with a value of 1. The system uses embedded C code to preprocess and postprocess the data to implement the rule-based methodology and notify the user via the proposed app.

website. The advanced features of the ThingSpeak website allow the use of MATLAB- or C-based code for preprocessing and postprocessing the raw data [27], [28].

III. RESULTS AND DISCUSSION

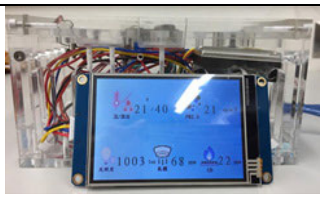
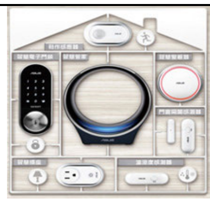
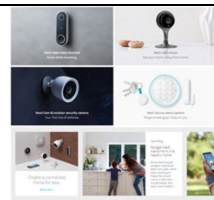
The proposed system integrates a PIR LED, a temperature and humidity sensor, a particulate matter sensor (PM2.5), a CO sensor, a gas sensor and a photoresistor running on an Arduino Yún in an integrated circuit design and includes a touch-panel TFT display (a seamless human-machine interface solution) as a standalone visual display that can be easily controlled and configured by a UART. Finally, to complete the hardware design, all components are encased in a customized transparent acrylic box (as shown in Figure 2).

In accordance with the proposed architecture, we implemented functions on the Arduino Yún to collect sensor data, upload the data to ThingSpeak via Wi-Fi, and synchronously display the data on the touch screen (as shown in Figure 4). For example, if a user wishes to view the current environmental sensor data while not connected to the network, standalone operation via the touch-screen display is available in lieu of the web service. The six icons on the TFT display correspond to the different types of sensor data. The user can touch an appropriate icon to switch to a chart-style visualization of the desired data.

The proposed system has an advanced dual-operation design that protects users from system failure. In addition to the touch display, users can perform all functions through the developed mobile app when an Internet connection is available, as shown in Figure 5. Thus, users can control and manage the home environment easily and efficiently. For example, a user can control the lights in two different ways: either through an on/off option via a smartphone or automatically based on feedback data from the PIR sensor.

Regarding the order of priority in the smart home system, security and safety requirements are satisfied first. Figure 6(a) illustrates the intelligent motion detector in the smart home system, which identifies movement reliably and precisely while distinguishing unremarkable events from significant events so that alarms are sounded only when necessary. The motion-detecting PIR sensor's sensitive zone is fan-shaped and has a maximum range of 3–4 m. Most families lead active lives; consequently, a great deal of activity occurs in a typical home. However, when the occupants leave the house, no movement occurs within the home environment—except, perhaps, from the family cat as it walks down the hallway.

TABLE 2. Comparison of the proposed system and commercial products.

Item	Proposed system	ASUS SmartHome [17]	Smart Thermostats [16]
Product			
Display on device	Color TFT	None	None
GUI	Standalone color TFT; Mobile device with app	Mobile device with app	Mobile device with app
Integration	Yes (all in one)	Separate components	Separate components
Scalability	Yes (easy to add new sensors because some GPIO pins are still unused)	Yes (new functional products developed, but new product development is not easy)	Yes (new functional products developed, but new product development is not easy)
Cost	Less than 100 USD	Gateway, 2100 USD; Motion sensor, 60 USD; Siren, 50 USD; Power, 50 USD; Temperature/humidity sensor, 50 USD	Total set approximately 1740 USD
Upgrade	Online upgrade	Online upgrade	Online upgrade
Installation	Easy	Easy	Easy
Compatibility with additional products	Easily compatible with products from different manufacturers	Commercial product and only compatible with ASUS products	Commercial product and only compatible with Nest Labs products
Addition of new sensors	Open GPIO/I2C pins	Open GPIO/I2C pins	Open GPIO/I2C pins
Customization	Open-source hardware and software; Easy to upgrade	One product with one or two sensors; Requires the use of different functional products to match requirements	One product with one or two sensors; Requires the use of different functional products to match requirements
Power consumption	750 mA	Over 1500 mA (same components)	Over 1500 mA (same components)

Other products exist on the market that can issue warnings and notifications when significant events occur, but most of these products cannot differentiate between significant and nonsignificant events because their designs are focused solely on motion detection rather than on precisely judging whether intruders or pets have been detected. Additionally, their availability is limited, and many devices are too expensive to be purchased and installed by the typical consumer. For our smart home system, we use a rule-based methodology as the basis for our intelligent motion detector, which can discriminate between a burglar and the homeowner's cat due to their respective behaviors, as shown in Figure 6(b). As shown in the figure, during testing, a person was successfully detected in every instance with a value of 1. In future research, we will demonstrate that the training data from this proposed system can be further used to train an AI to distinguish between intruder behaviors and other behaviors, which will allow the proposed system to make appropriate judgments. The system reacts in two ways when it detects an intruder: it immediately sends a notification to the app while simultaneously triggering the smoke detector alarm. Thus, users away from home are notified, and intruders may be scared off. Consequently, the homeowner can be assured that his or her home is well protected.

In the simulation testing phase, the main goals were to confirm that all sensors were operable and able to provide real-time feedback to the cloud platform. For each sensor used in the study, we used commercial equipment measuring the same parameters to conduct a comparison test. We found an average error rate of less than 8% for the sensors in our device. In addition, we found that the slowest response time was 3 seconds for the MQ7 (CO), MQ2 (gas) and GP2Y1010AU0F (PM2.5) sensors. For the PIR LED sensor, the fastest response time was 0.5 seconds, which we considered to be reliable for research purposes. Data from the comparison test are shown in Figure SM1, and the Pearson product-moment correlation coefficients for each comparison are shown in Table SM1 in the supplementary material.

In the second phase of testing, different users randomly tested our device, while commercial equipment measuring the same parameters as our sensors was used for comparison. The average error rate of our sensors was less than 5%. The improvement in error rate was due to ruling out environmental factors in the test area (Figure 6), inducible error testing and correcting for ambiguous user behaviors.

In the third phase of testing (Figure 5), we installed the proposed device in a volunteer's home, mainly in the living room area. Commercial equipment measuring the same parameters as the sensors in our device was again used for comparison. The average error rate was less than 5.5%. The error rate (err) was calculated using the following equation: err=(count(mismatch))/n, where count(mismatch) is the number of mismatch events (i.e., events showing a discrepancy between the commercial equipment and our device), and n is the total number of events detected by our device.

Although the system presented in this paper currently includes only six sensors, the system architecture is scalable and could be extended to include additional sensors for monitoring a wider variety of scenarios and achieving different goals [29]. Our system architecture allows adding or switching out sensors to accommodate other applications without extensive modifications. Comparisons to other works are shown in Table 1 [10]–[15]. Our proposed device is based on a popular IoT cloud platform, ThingSpeak, instead of an expensive customized platform (for example, IBM) [30]. Our system backbone combines ThingSpeak with a standalone system, which allows the user to operate the system even when not connected to the Internet. In addition, the advantages of using a rule-based methodology such as ours include quick response, ease of upgrading, and high scalability with limited resources [31], [32].

Table 2 shows the characteristics of the proposed system in comparison with some commercial products. Although the appearance of the proposed system, which is a laboratory prototype, is not as polished as those of the commercial products, our system is still competitive with regard to power consumption, system scalability and integration with heterogeneous information systems.

Among other advantages of the proposed system are its open-source nature and scalability. The open-source aspect is a critical issue because it can attract more developers and manufacturers to produce compatible, less expensive and more powerful sensors. The advantages of open-source firmware and APIs are expected to enable related developments and technological innovations to occur more quickly for the proposed system than for its commercial competitors. The significant features of the proposed system are its open-source hardware and software, standard IoT interface, cloud computing capabilities and scalability to include additional sensors, all of which make this proposal novel and innovative.

IV. CONCLUSION

In this study, enabled by recent advances in IoT technology, we proposed and implemented an extensive and novel architecture for a flexible, low-cost home control and monitoring system based on the Android OS that allows access to and control of the connected devices in the user's home using any Android-based smartphone. Control is possible even when a Wi-Fi connection is unavailable because the system is accessible through mobile cellular networks (e.g., 3G or 4G networks). The proposed smart home system and smart home app have been fully and successfully developed and tested to validate the research goals and system usability. The system's integrated device control and monitoring capabilities currently encompass light switches, temperature and humidity sensors, gas sensors, motion detection sensors and alarms, which are sufficient to demonstrate its feasibility and effectiveness. Moreover, the low cost and the security and surveillance capabilities of the proposed system make it unique and valuable.

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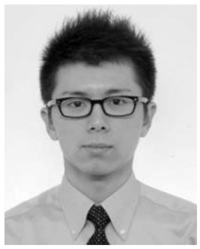

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