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Exploring Arduino-based Sensor Network for Indoor Environments: An Energy-saving Lighting and Safety Monitoring System

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Energy conservation and environmental safety are critical issues in indoor environments, where intelligent sensing and control systems can play a pivotal role. In this work, we present an Arduino-based energy-saving lighting and safety monitoring system with integrated multiple sensor modules and relevant electronic components. The proposed system employs a light intensity sensor to detect ambient light and adaptively regulate the brightness of an RGB LED matrix and automatically open or close the curtain, thereby maximizing the use of natural light and reducing power consumption. For environmental safety, a temperature and humidity sensor and a flame sensor are incorporated to monitor surrounding conditions. The system responds by adjusting fan speed based on temperature and humidity conditions to balance comfort and energy efficiency. Moreover, it responds by activating an alarm device and a warning light and opening the curtain when fire hazards are detected. In addition, an infrared receiver and a remote controller allow the manual control of these operations. Experimental results indicate the potential of the proposed system to reduce energy consumption while maintaining comfort and safety. This research highlights the practical application of sensor technologies and low-cost materials in developing a scalable, energy- and safety-aware indoor monitoring system.

1. Introduction

Since its introduction, the Arduino platform has emerged as one of the most widely adopted embedded systems, particularly in educational and prototyping contexts. Its popularity can be attributed to its several significant advantages: it is an open-source, cost-effective platform, easy to learn and use in both software and hardware, and highly versatile across a variety of applications. In recent years, with the rapid advancement of information and communication technologies (ICTs), the Internet of Things (IoT) has become a critical driver of digital transformation and industrial upgrading across a wide range of industries. IoT technologies refer

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to a collective network of interconnected ICT devices that can be equipped with diverse sensor modules, communication components, and software systems. As a result, they are widely applied in areas such as smart buildings, smart homes, smart warehouses, intelligent healthcare, intelligent agriculture, and other intelligent system applications.[1–15] Furthermore, in response to trends in industrial development, many universities and colleges have introduced elective courses to address the emerging demand for professional skills, particularly those related to IoT technologies. In this context, the Arduino platform plays a fundamental role in exploring sensor networks and has thus become the preferred choice for many educators in teaching, training, and research practices. It not only facilitates the creation of innovative solutions but also empowers both educators and students to explore diverse innovation strategies.

Arduino modules function as microcontrollers capable of performing arithmetic calculations, executing logical operations, and manipulating diverse data types.[16] They offer numerous digital and analog input/output (I/O) pins, which allow them to interface with a wide range of expansion boards, sensor modules, and controllable devices.[1,2] Accordingly, they are commonly used for data acquisition,[17] enabling the measurement and collection of real-time data from a variety of sensor modules, such as those for temperature, humidity, light intensity, different light wavelengths, flame presence, and more. The acquired data, which can be either analog or digital, are processed using user-programmed C/C++ instructions. The processed results can then be displayed on a liquid-crystal display (LCD) screen or used to control outputs such as turning on LEDs, activating motors, or communicating with other devices. To meet the demands of diverse applications, users can customize system behavior at both the software and hardware levels by integrating multiple sensor modules, controllable devices, and user-developed algorithms,[18] thereby enabling fine-grained control over sensor interactions and overall system functionality. Consequently, Arduino modules are extensively employed in the development of sensor network projects for building functional prototypes, such as indoor and outdoor environmental monitoring networks,[1,2,8,13,15] wireless automatic identification technologies,[3,9,19] biometric recognition technologies,[4,12] applications in agriculture, fishery, forestry, and livestock,[5,6,7,11] body movement control systems,[10,20] and healthcare monitoring devices.[14,21,22] Furthermore, by replacing an Arduino module with one that includes wireless capabilities, these prototypes can operate as portable sensing systems.[22,23]

Recently, energy conservation and carbon reduction have become matters of urgent global concern. As global warming and climate change intensify, implementing proactive strategies is essential to reduce greenhouse gas emissions and safeguard the environment. Among various approaches, the optimization of lighting systems presents one of the most accessible and effective methods, particularly in indoor environments where lighting contributes significantly to energy consumption. Many studies have been conducted on energy-saving lighting systems.[24–26] The majority of the approaches adopted for such systems rely on commercially available LED lighting control modules. In this work, therefore, we employ an open-source, cost-effective, and scalable Arduino board integrated with multiple sensor modules, including a light intensity sensor for adaptive lighting control, a temperature and humidity sensor for indoor environmental regulation, and a flame sensor for fire detection, together with electronic components such as an RGB LED matrix, a stepper motor, a fan motor, a buzzer, and an LED.

This integration enables the development of an energy-saving lighting and safety monitoring system, as illustrated in Fig. 1. The system supports real-time monitoring and feedback, allowing it to balance energy efficiency, environmental comfort, and safety, thereby highlighting the practical application of sensor networks in sustainable indoor environments. The remainder of this paper is organized as follows. In Sect. 2, we describe the experimental materials and methods. In Sect. 3, we present the experimental results, followed by a brief conclusion in Sect. 4.

2. Experimental Materials and Methods

Figure 2 shows the circuit diagram of the proposed Arduino-based energy-saving lighting system integrated with a safety monitoring scheme designed for indoor disaster prevention. The proposed system is designed to monitor environmental parameters and thereby control lighting and safety devices on the basis of real-time conditions. This integration enables adaptive operation that not only improves energy efficiency but also enhances indoor comfort and safety. In the following paragraph, we describe the experimental materials and methods used to develop and implement the proposed system.

Three Arduino UNO boards are employed in the proposed system, each serving as a primary microcontroller responsible for collecting and processing real-time sensor data. A push button is incorporated to switch between automatic and manual control modes. In the automatic control mode for energy-saving lighting, the analog output pin A0 of the light intensity sensor (LM393-based module) is connected to the analog input pin A0 of the first Arduino UNO board. The control input of the RGB LED matrix (WS2812) is connected to digital pin 4, whereas the control inputs of the stepper motor (28BYJ-48) and driver board (ULN2003) are connected to digital pins 5–8 of the same board. The light intensity sensor detects the ambient light level and transmits the measured analog signal to the Arduino UNO board, which digitizes and processes the incoming data in real time. The processed values are subsequently mapped from the 0–1023 range to the 0–255 range to adaptively regulate the brightness of the RGB LED matrix. From a

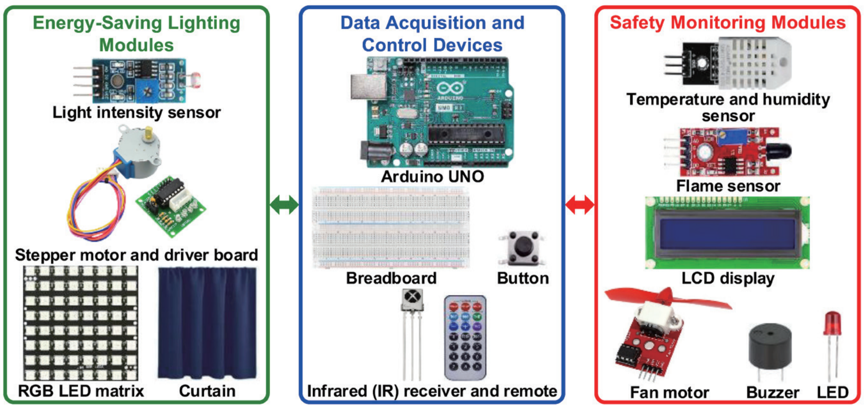


Fig. 1. (Color online) Proposed Arduino-based system for energy-saving lighting and safety monitoring.

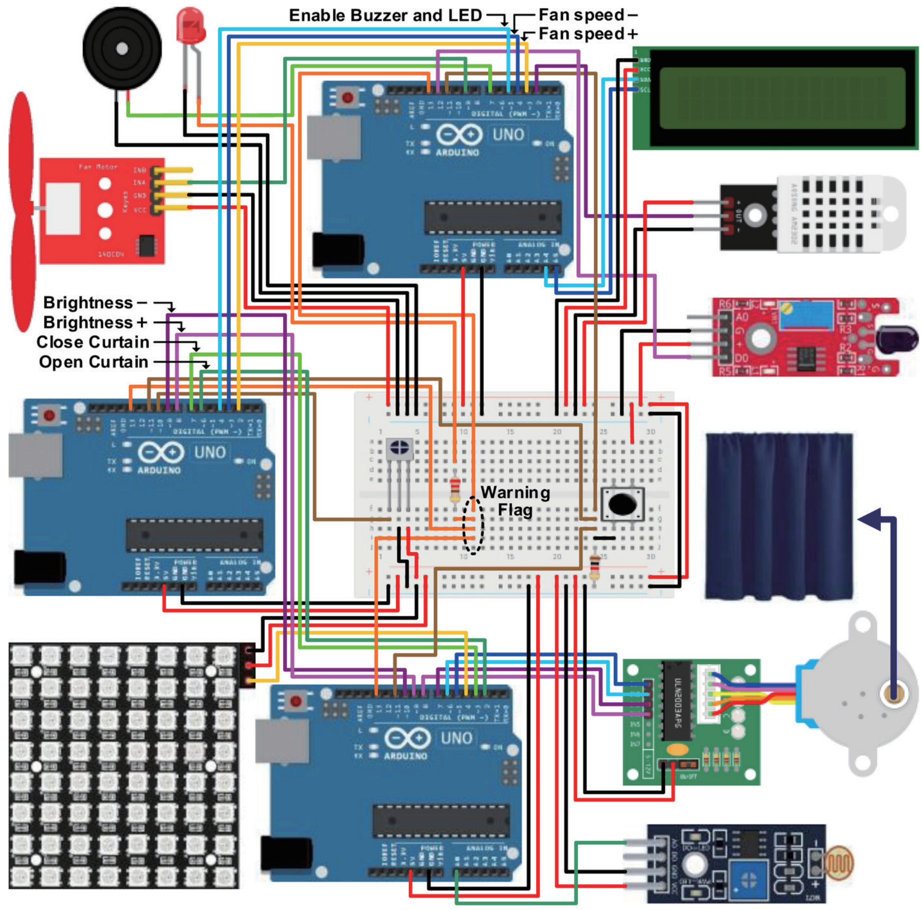


Fig. 2. (Color online) Circuit diagram of the proposed Arduino-based energy-saving lighting and safety monitoring system.

theoretical perspective, the relationship between the light intensity and the resistance of the light intensity sensor can be mathematically expressed as

$$Light\ intensity \propto \frac{1}{Resistance}. \quad (1)$$

As the ambient light intensity increases, the RGB LED matrix becomes dimmer to minimize energy use. When the ambient light intensity is at its highest, the RGB LED matrix is turned off to conserve energy, and the curtain is opened by the stepper motor via its driver board to maximize the use of natural daylight. Conversely, when the ambient light intensity drops to its minimum threshold, the RGB LED matrix is set to the maximum brightness, and simultaneously, the curtain is automatically closed. In this way, the adaptive mechanism demonstrates the potential of the proposed system to maintain energy efficiency and indoor visual comfort. Moreover, by dynamically balancing artificial lighting with natural daylight, the proposed system reduces unnecessary power consumption and contributes to sustainable development.

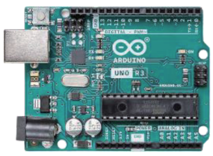
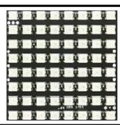
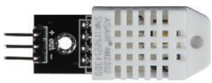
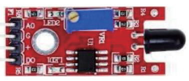
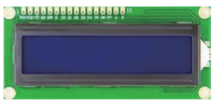
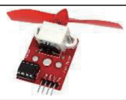
In the automatic control mode for environmental safety monitoring, the digital output pin OUT of the temperature and humidity sensor (DHT22) is connected to digital pin 2, and the digital output pin DO of the flame sensor (KY-026) is connected to the digital pin 12 of the second Arduino UNO board. This board's digital output pins 9, 7, and 13 are further connected to the fan motor (L9110 fan module), the buzzer (KY-012), and the LED, respectively, enabling the system to actively respond to detected environmental changes. The temperature and humidity sensor continuously monitors indoor temperature (TEMP) and relative humidity (RH), whereas the flame sensor detects the presence of potential fire hazards. These sensors transmit the measured data to the Arduino UNO board, which processes the incoming information in real time to determine the appropriate responses for each connected device. The processed data are also displayed on the LCD module (I2C LCD 1602) via analog pins A4 and A5, providing a continuous readout of real-time indoor TEMP and RH values for safety monitoring. When the indoor TEMP or RH reaches a predefined high threshold, the Arduino UNO board immediately activates the fan motor and sets it to operate at its maximum rotational speed to reduce TEMP and RH values, thereby mitigating potential discomfort or hazards. As the indoor TEMP and RH gradually decrease, the rotational speed of the fan is correspondingly lowered to reduce unnecessary power consumption, demonstrating an energy-aware control strategy. When the indoor TEMP and RH fall below a low threshold, the fan motor is automatically turned off to conserve energy. When a flame is detected or the indoor TEMP exceeds the maximum threshold, the buzzer is triggered as an alarm, the LED is set to blink at one-second intervals as a visual warning, and simultaneously, the curtain is automatically opened via the stepper motor and its driver board to facilitate emergency responses or evacuation. In addition to these devices mentioned above, air quality sensor modules, exhaust fans, air conditioners, windows, and other safety devices (e.g., a bell, loudspeaker, or indicator lamp) can also be integrated and automatically controlled through an electronic relay or a smart power strip.[1,2,10,18]

The third Arduino UNO board is dedicated to manual control operations. Through the infrared (IR) receiver (VS1838B) and the remote controller (Car MP3), this Arduino UNO board outputs control signals as follows: digital pins 8 and 9 for increasing or decreasing the brightness of the RGB LED matrix; pins 6 and 7 for driving the stepper motor via its driver board to open or close the curtain; pins 2 and 3 for adjusting the fan speed, either speeding it up or slowing it down via the fan motor; and pin 4 for triggering the buzzer as an alarm and toggling the LED on and off at 1 s intervals, serving as a warning light. Table 1 shows the performance characteristics of the hardware components utilized in the proposed system shown in Fig. 2.

3. Experimental Results

In this section, we summarize the experimental test results obtained from the implementation of the proposed Arduino-based energy-saving lighting and safety monitoring system. Figure 3 illustrates the prototype of the proposed system, with arrows highlighting the positions of the Arduino UNO boards, breadboards, sensor modules, and controllable devices. The proposed system was tested in an indoor environment to evaluate its functionality and reliability under

Table 1
(Color online) Performance characteristics of the experimental components used in the proposed system.

Name	Photo	Model	Function	Key specifications
Arduino board		UNO R3	Microcontroller	Microcontroller: ATmega328P Clock: 16 MHz USB interface: type B Supply voltage: 5 V Output voltage: 3.3 and 5 V Digital I/O pins: 14[*1] Analog input pins: 6
IR receiver and remote		VS1838B and Car MP3	IR signal reception and transmission	Protocol: NEC Battery type: CR2025 3V Wavelength: 940 nm Carrier frequency: 38 kHz Reception angle: ±45° Transmission distance: 8 m
Light intensity sensor		LM393-based light sensor module	Ambient light intensity detection	Output type: digital and analog Wavelength range: 400–700 nm Response time: ≤ 50 ms
Stepper motor and driver board		28BYJ-48 stepper motor and ULN2003 driver board	Curtain opening/closing actuator	Control interface: 4 pins Step angle: 5.625°/64 Resolution: ~0.088°/step Gear ratio: 1/64 Holding torque: ~300 gf·cm
RGB LED matrix		WS2812	Programmable RGB indoor lighting	Matrix resolution: 8 × 8 Color control: 24 bits Refresh rate: 400 Hz Frame rate: 30 fps
Temperature and humidity sensor		DHT22	Environmental temperature and humidity sensing	Temperature range: −40–80 °C Temperature accuracy: ±0.5 °C Humidity range: 0–100% RH Humidity accuracy: ±2.0% RH Resolution: 0.1 °C and 0.1% RH
Flame sensor		KY-026	Fire detection	Output type: digital and analog Wavelength: 760–1100 nm Viewing angle: ±60° Detection distance: 80 cm[*2] Response time: < 15 ms
LCD		I2C LCD 1602	Display for monitoring environmental parameters	Display resolution: 16 characters × 2 lines Character format: 5×8 dot characters
Fan motor		L9110 fan module	Cooling for enhanced comfort	Control interface: 2 pins Fan speed: ~4000 RPM at 5 V Speed control: PWM signal
Buzzer		KY-012 piezoelectric buzzer	Audio alert for warnings or alarm events	Sound frequency: ~2.5 kHz[*3] SPL[*4]: 85 dB at 10 cm Tone control: PWM signal

[*1]Six of them support pulse-width modulation (PWM) output.
[*2]The detection distance depends on flame size and ambient lighting.
[*3]It integrates a built-in oscillator to output a fixed 2.5 kHz frequency.
[*4]SPL stands for sound pressure level, which is a measure of sound intensity.

real-world conditions. The results verify that the proposed system can adaptively adjust the light intensity, control devices through Arduino UNO boards and sensor modules, and respond appropriately to environmental changes and potential safety hazards.

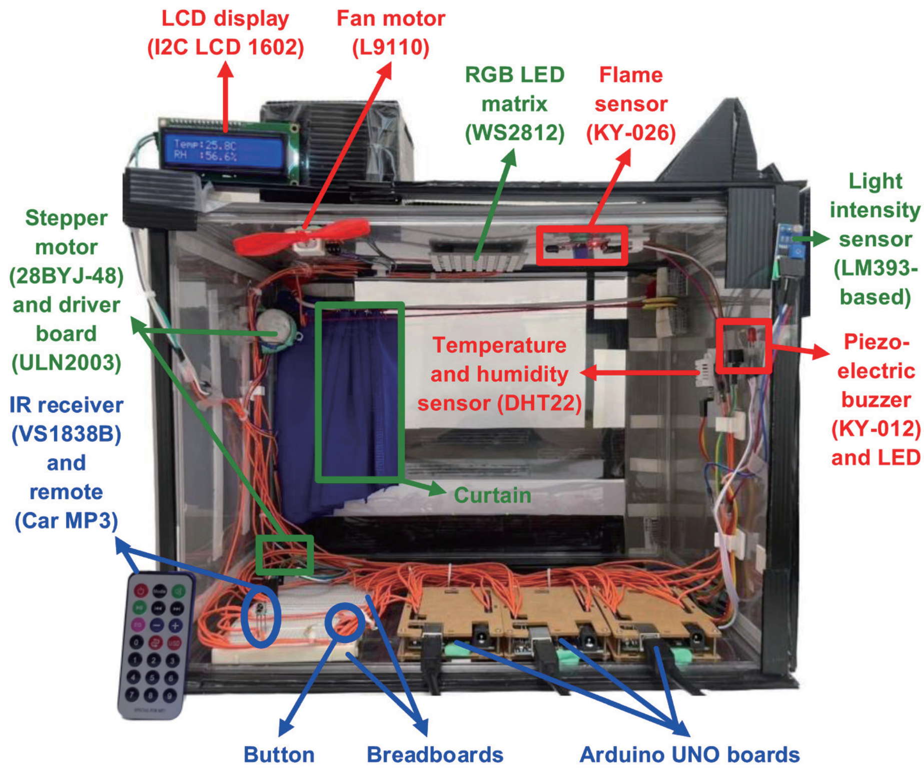


Fig. 3. (Color online) Prototype of the Arduino-based energy-saving lighting and safety monitoring system.

The flowchart illustrating the operation of the proposed system is shown in Fig. 4. After system startup and initialization, data from the sensor modules are continuously read. In automatic mode, the system controls the corresponding devices on the basis of real-time data. In manual mode, the devices are controlled by personnel using the IR receiver and remote controller. If the buzzer is triggered and the LED begins blinking, personnel intervention is required to inspect the situation and reset all devices.

Figure 5 shows the testing of the curtain opening and closing function. This function was tested by sending open and close commands via the IR receiver and remote controller in manual mode, and by triggering automatic responses based on ambient light levels in automatic mode. Figure 6 presents the performance test of the RGB LED matrix brightness regulation. The brightness adjustment capability of the RGB LED matrix was tested under varying ambient light conditions to evaluate the system's responsiveness and energy-saving potential. Figure 7 illustrates the experimental results of the fan speed control. The test was conducted to evaluate the effectiveness of the proposed system in automatically adjusting fan speed according to ambient TEMP and RH values. To test the alarm system, a smartphone flashlight was used to illuminate the flame sensor, triggering the buzzer (as an alarm), and causing the LED to blink (as a warning light). The results of this test are shown in Fig. 8.

Although this prototype does not include quantitative measurement results, the proposed system demonstrates the potential for energy savings through its adaptive control strategy. The

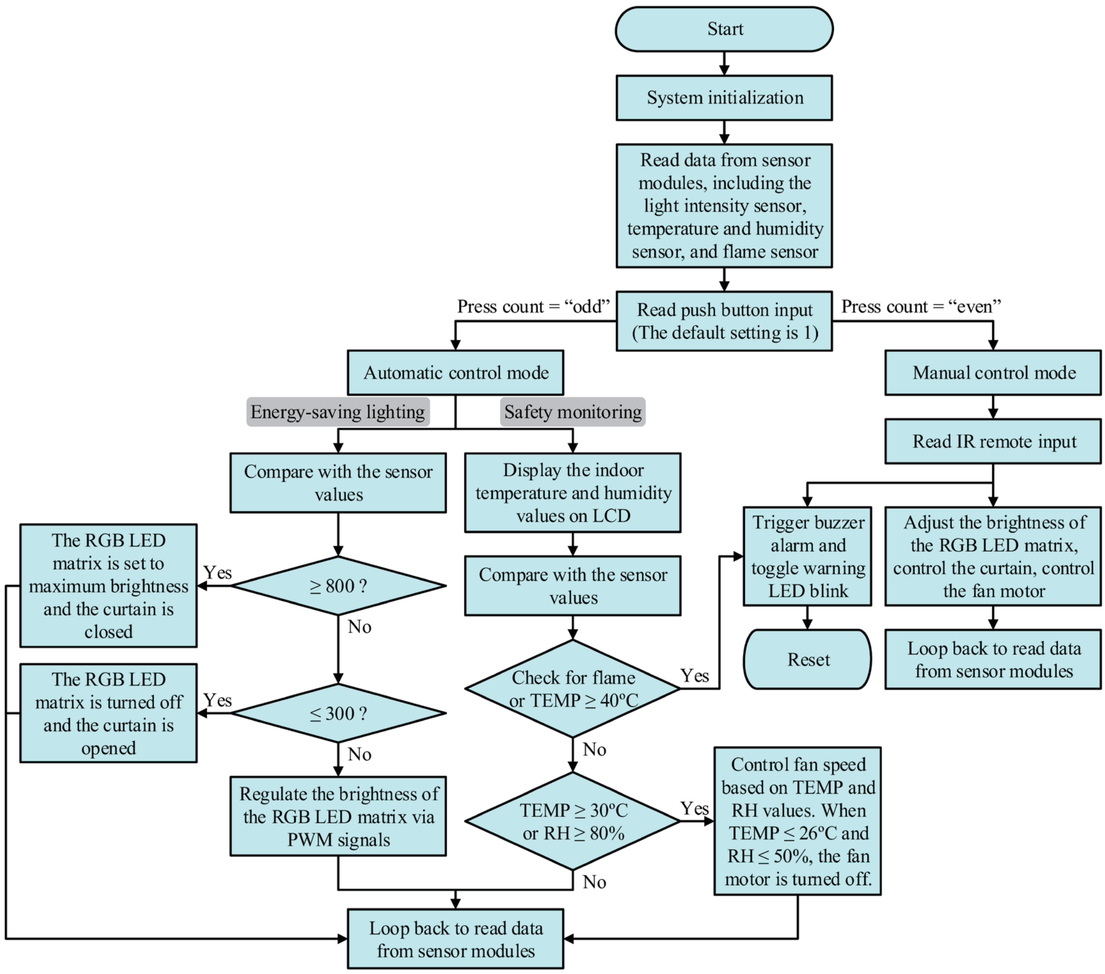


Fig. 4. (Color online) Flowchart of the proposed system's operation.

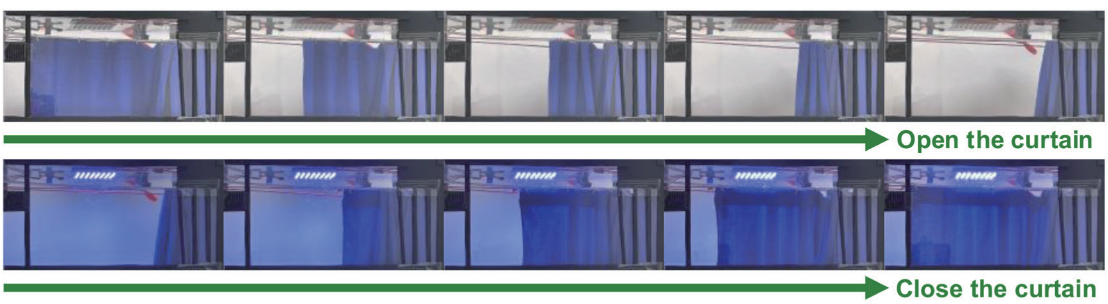


Fig. 5. (Color online) Curtain operation test: opening and closing.

lighting subsystem reduces power consumption by dimming or turning off the RGB LED matrix when sufficient ambient light is available and by opening the curtain to maximize natural daylight. Similarly, the safety monitoring subsystem operates the fan motor only when the

Fig. 6. (Color online) Brightness adjustment test of the RGB LED matrix.

Fig. 7. (Color online) Experimental results of fan speed control.

Fig. 8. (Color online) Testing of the alarm and warning light functionality.

indoor TEMP or RH exceeds a threshold and adjusts its speed to avoid unnecessary full-power operation. These features highlight the system's capability to conserve energy while maintaining both safety and comfort.

4. Conclusions

In this work, we successfully developed an Arduino-based sensor network system for energy-saving lighting and safety monitoring in indoor environments. By integrating multiple sensor modules, including a light intensity sensor, a temperature and humidity sensor, and a flame sensor, along with controllable devices such as an RGB LED matrix, a stepper motor, a fan motor, a buzzer, and an LED, the proposed system can adaptively respond to environmental changes and potential hazards. The system also supports manual operation via an IR receiver and remote control. A functional prototype was implemented to evaluate and validate the system's performance and functionality through real-world experiments. Experimental results indicate the potential of the system to enhance energy efficiency while maintaining indoor comfort and safety. The proposed system provides a cost-effective, scalable, energy- and safety-aware indoor monitoring solution. This research demonstrates how integrating sensors with controllable devices can support energy conservation goals and contribute to sustainable development.

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