IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 18, 2022, accepted March 8, 2022, date of publication March 10, 2022, date of current version March 17, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3158494

Design and Implementation of a Leader-Follower Smart Office Lighting Control System Based on IoT Technology

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This work was supported in part by the Ministry of Science and Technology (MoST), Taiwan, under Grant MOST 109-2222-E-346-001 and Grant MOST 110-2221-E-346-001; and in part by the Higher Education Sprout Project, Ministry of Education (MoE), Taiwan, under Grant MOE-110G0008-1.

ABSTRACT Most installed lighting systems are outdated and have poor energy efficiency. Therefore, there is an urgent need for smart LED lighting systems that are energy efficient, easy to install, and inexpensive. In this article, a leader-follower smart office lighting control system based on Internet of Things (IoT) technology is proposed to satisfy the goal of saving energy through the coordinated operation of a system counter and an infrared (IR) human movement sensor (passive infrared (PIR) sensor). When no one is present in the space, all indoor LED lights are turned to low-light mode. Otherwise, all indoor LED lights are turned to high-light mode together. In addition to change the brightness of LED lights in the same area at the same time to save energy, the parameters of the LED lights can be set directly through microcontrollers via the IoT and the internet. If a general 15 W T8 LED tube (noninduction light) is replaced with the proposed leader-follower office lighting system (assuming that the office is occupied for 10 hours a day and that the hourly low-light mode is 20 minutes), then the power-saving rate is as high as 28.13%.

INDEX TERMS Internet of Things (IoT), leader-follower, smart buildings, smart homes, smart lighting systems, smart offices.

I. INTRODUCTION

The rapid industrial and economic development of various countries has irreparably damaged the Earth's environment. As the Earth becomes unable to bear this load, people are becoming aware of the serious adverse effects on the climate and the environment. In turn, the importance of global warming and environmental protection issues such as energy conservation and the sustainable development of green energy are gradually being recognized by countries worldwide, and relevant protective measures have been put forward to maintain resources.

Residential electricity consumption is increasing rapidly worldwide, and energy demands are increasing daily. There is increasing interest in high-efficiency devices, particularly after the doubling of oil prices has led to rising electricity rates [1]. Population growth has resulted in a lack of natural resources. For example, manufactured resources such as electricity can no longer meet the needs of rapid population growth. In the past few decades, various measures have been taken to improve equipment and system design to improve production and transmission efficiency and to reduce power consumption [2].

In the United States, the energy consumed by buildings accounts for approximately 40% of the energy consumption, of which lighting for residential buildings accounts for approximately 10% and that for commercial buildings accounts for 20% [3]. Therefore, lighting is the most energy-consuming aspect of buildings worldwide. Reducing the energy consumption of lighting and the development of LEDs have had a significant impact on the lighting industry [4]–[5]. The use of LED technology in lighting systems can save energy [6], and LED technology development and applications continue to evolve. LED technology can be used

The associate editor coordinating the review of this manuscript and approving it for publication was Chunsheng Zhu.

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to reduce the power required for lighting and to enhance its durability and environmental protection [6], [7]–[10].

The governments of various countries are actively promoting energy efficiency campaigns. Research has found that simple lighting control using motion sensors can effectively reduce energy consumption in buildings. However, smart lighting control strategies can achieve greater energy savings and better services and provide many advantages over simple on/off control [11].

According to TrendForce's latest report, the outlook for the global LED lighting market is more optimistic than previously estimated. The global LED lighting market is estimated to grow by 5.1% in 2021. COVID-19 is spreading rapidly around the world. LED lighting products are necessary for human production and life. People stay at home, leading to higher household electricity consumption. Therefore, rigid market demand still exists. During the COVID-19 pandemic, the demand for home lighting has not decreased but rather increased, highlighting the essential nature of lighting. In addition, lighting products will further develop toward digital intelligent dimming and control lights. The lighting industry will also likely pay more attention to the intelligent systemization of products, the relationship between human health and lighting, and market demand for segmented applications in the future. TrendForce estimates that the lighting industry will reach 44.3 billion US dollars in 2025 [12].

Until now, due to the high cost of installation and maintenance and the difficulty of retrofitting, smart lighting control systems have not been very successful [13], and there is still room for improvement. Moreover, the previously used systems were expensive and required the setting up of servers, rewiring, and extensive renovation. This article proposes a low-cost, easy-to-renovate intelligent lighting control system suitable for office environments that can retain the original lamp holders without the need for wiring, server setup, and leading to energy savings. Immediately after the office space is unoccupied, it is changed to run in the low-light mode, ensuring that the office space will not turn into a dim environment during working hours.

This paper is an extended application work of [50]. Although [50] has an excellent energy-saving effect, it is only suitable for installation in public spaces such as parking lots and corridors and is not ideal for office space. The system proposed in this paper is suitable for office space through the coordinated operation of the PIR Sensor on the lamp and the system counter above the office door. When it is confirmed that no one exists in the office, all the LED lights in the room will be turned into low-light mode together, so there will be no misjudgment situation.

The rest of this article is organized as follows. Section II discusses related work. Section III introduces the proposed system. Section IV conducts and discusses energy-savings calculations related to the proposed system. Finally, we conclude the article in Section V.

II. RELATED WORK

LED lighting is environmentally friendly but is still not popular, mainly because its installation cost remains higher than that of existing lighting devices. With advances in LED manufacturing technology, this price is falling, but the overall lighting cost is still prohibitive.

Sensors and network technology are being explored to improve the economic benefits of LED lighting, and such LED lighting systems have been commercialized. When the user is not in the room or the room is too bright, these systems reduce energy consumption by reducing the output power of the lighting instead of maintaining the same brightness [14].

Byun and Shin [14] proposed an energy-efficient lighting control system, namely ESLiCoS, which considered user satisfaction. The ESLiCoS improves energy efficiency and occupant satisfaction by controlling lighting control parameters considering spatial characteristics and occupant behavior patterns.

In recent years, the lighting field's energy efficiency and control research results have been fruitful, and the various technologies and solutions that have been proposed [14]–[29] can mainly be divided into two methods: wired and wireless systems. However, the maintenance and installation costs of wired systems are relatively high, and thus, these systems are slowly being replaced by wireless technology.

Wireless sensor networks (WSNs) are an effective technology for building energy control because they are easier to implement than wired networks. Combining advanced WSN control with DC-powered LED lighting systems should achieve greater energy savings in green smart buildings [16].

In [16], artificial and daylight lighting can be measured and recorded through sensors in the local area network or a set of data logger devices to modify the light intensity and thus its energy consumption. Tang *et al.* [19] investigated a new method to perform closed-loop color control of lighting systems in smart homes using cameras available on modern smartphones.

Elejoste *et al.* [20] proposed an intelligent street light management system based on LED lights deployed in existing facilities. The proposed wireless communication technology significantly reduced the investment cost of traditional wired systems.

Uhm *et al.* [26] designed and implemented a power-aware LED light enabler with a light sensor, motion sensor, and network interface. The LED light enabler also communicates with context-aware middleware using an intelligent power gateway that uses sensing data to analyze user life patterns to determine optimal power control adaptively.

With the advancement of WSN technology, it is now easier than ever before to monitor industrial buildings, commercial buildings, and offices. Due to the flexible distribution of WSN equipment, WSNs are used in a variety of virtual applications, including industry, medical care, security, and environmental monitoring.

TABLE 1. A comparison between the proposed system and related works.

Related Work	Applicable fields	Dimming method	Server/MCU	Sensors used	IoT-based	Energy efficiency	Costs
[19]	Living room	Closed-loop color control is used	MCU	A smartphone camera	No	N/A	Low
[20]	Street	Depending on the surrounding environment of the streetlight, the brightness of the LED is adjusted.	Server	A light sensor, a humidity sensor, and a temperature sensor	Yes	Medium	High
[26]	Indoor space	The brightness of the LED is adjusted according to the sunlight in the room.	Server	A PIR sensor	No	Medium	High
[34]	Living room	Adjusting lighting based on user location and lighting preferences.	Server	Light sensor	No	N/A	High
[42]	Street	Using a sensor to control and guarantee the optimal system parameters	MCU	A PIR sensor	Yes	High	Low
[43]	Living room	Considering the illumination and uniformity of light, an intelligent lighting control algorithm based on gradient descent was designed.	Server	A PIR sensor	No	High	High
[44], [45]	Classroom	ON/OFF	MCU	A PIR sensor	No	Medium	Low
[46]	Living room	The brightness of the LED is determined according to the number of people in the space.	MCU	A PIR sensor and a temperature sensor	No	Medium	Low
[47]	Indoor space	The brightness of the LED is determined according to the number of people in the space.	MCU	Two PIR sensors	No	Medium	Low
[50]	Public space	Low-light mode is used when no people are present, and high-light mode is used when people are present.	MCU	A PIR sensor	Yes	High	Low
Proposed System	Office	Low-light mode is used when no people are present, and high-light mode is used when people are present.	MCU	Two PIR sensors	Yes	High	Low

WSNs are the backbone of cyber-physical system (CPS) applications [30]–[32]. Each device contains a network node that integrates computing, wireless communication, power management, and sensing functions to collect and process data from sensors, usually with cooperative coordination [33]. Combining WSNs with LED lights and advanced drivers can greatly reduce lighting power consumption in multiple applications [21].

Recently, WSNs have been applied to energy savings, such as light control [34], [35]. In [34], light control was used to study the trade-off between energy consumption and user satisfaction. A utility function that considers the user's location and lighting preferences was used to adjust the lighting to obtain the most benefit. However, this function does not consider that people may need different lighting levels when performing different activities.

FIGURE 1. A new type of LED sensor light (T8 LED light tube) [48].

Lighting in an office space or home is usually directly controlled by an on/off switch. Of course, users can connect lighting equipment to a personal computer (PC) to remotely turn on or off lights, but this PC must control the operation 24 hours a day, leading to high costs and the consumption of a considerable amount of electricity [36]–[39]. In some designs, specific hardware and software must be installed to control the lights, resulting in unacceptable costs. In addition, this type of system cannot detect human body temperature or indoor light intensity [40], [41].

Kaleem [42] studied an outdoor lighting system based on ZigBee. Sensors controlled the system parameters. Experiments showed that the system reduced energy use by 70.8% in outdoor street environments. Wang [43] studied a WSN-based smart lighting control system. Based on the illuminance and uniformity of the light, he designed a smart lighting control algorithm that can be stepped down.

References [44] and [45] presented a system composed of an infrared human motion sensor (passive infrared (PIR) sensor), Arduino Uno, and a 2-channel relay module that used the PIR sensor to detect motion and control light through computer processing. The function of this system is to automatically turn on the lights when someone enters the classroom and to automatically turn off the lights when no one is there. Wahyuni & Irawan [46] studied a similar intelligent lighting system in which the PIR sensor detects the presence of people through body temperature and the movement of people in the room.

Mohamed *et al*. [47] studied the use of two PIR sensors to detect the entry and exit of people at the entrance and then determined the brightness of the lighting according to the number of people in the space. The more people there are, the higher the brightness, thereby avoiding energy waste. However, there is a problem with this system. When the number of people is small, the space's lighting is obviously insufficient, and the number of people should not determine the brightness of the lighting.

The most significant problem with current smart lighting systems is that although they can reduce energy, they are usually costly and difficult to install and are mostly used in simple spaces such as toilets and corridors. They are not widely used in complex spaces such as offices that include complex tasks. Therefore, this article proposes a leader-follower smart office lighting control system based on Internet of Things (IoT) technology that is very suitable for office spaces.

The proposed system is a low-cost, wireless, easy-to-install, and adaptable leader-follower smart LED lighting system. When the system's counter is zero and the infrared human body movement sensor (PIR sensor) cannot detect people, the system turns all the indoor LED lights to "low-light mode." In contrast, when the counter is not 0, the system turns all the indoor LED lights to a "high-light mode."

In addition to change the brightness of the LED lights in the same area at the same time to save energy, the LED lights can be directly parameterized through the IoT. Table 1 compares the proposed system and related works.

Previously, we developed a new type of LED sensor light with a low-light mode [48]. We changed the full-dark mode of the general sensor light to a low-power low-light mode for standby, which solved many problems with the general sensor light. When a person approaches the sensor light, their eyes will not feel uncomfortable due to strong light, and the sensor light is in a weak light state when no one is passing by. People who return at night no longer need to face dark corridors, achieving multiple purposes.

In addition, the power consumption of the new sensor light in low-light mode is only 1/10 of that in high-light mode, but its brightness is only half of that in high-light mode. It is very suitable for sensor lighting in building parking lots, corridors, stairwells, or toilets.

The original light tube can be directly replaced without changing the light fixture, and the basic brightness can be maintained, as shown in Fig. 1 [48]. This work is based on the system described in [48] and transforms it into a low-cost, easy-to-renovate smart lighting control system suitable for office environments.

Furthermore, the main idea and goal of [50] are regionalized synchronization, while the proposed system is designed for smart office lighting applications. Through the PIR sensor on the lamp, the energy-saving lighting in the space works in conjunction with the system counter above the office door. The LED lights in the room switch to the low-light mode together only when it is confirmed that there is no one in the office, so there is no misjudgment in the proposed system unlike for the system in [50].

III. THE PROPOSED SYSTEMS

A. THE DESIGN CONCEPT

The design concept of this work is based on [48], modified its algorithm for calculating the number of people in space regarding [47], and [50] to design and implement a leader-follower smart lighting control system suitable for the office environment. The design concept is introduced in detail sequentially.

In an office, busy schedules and hard work sometimes result in people forgetting to turn off lights, which ultimately results in a waste of electricity. The office lighting system we propose can reduce power consumption and optimize power. Fig. 2 shows an application scenario of the proposed system installed in an office. Fig. 2 (a) is a side view, and Fig. 2 (b) is a top view.

There are two PIR sensors above the office door. The sequence of the two PIR sensors is used to determine whether

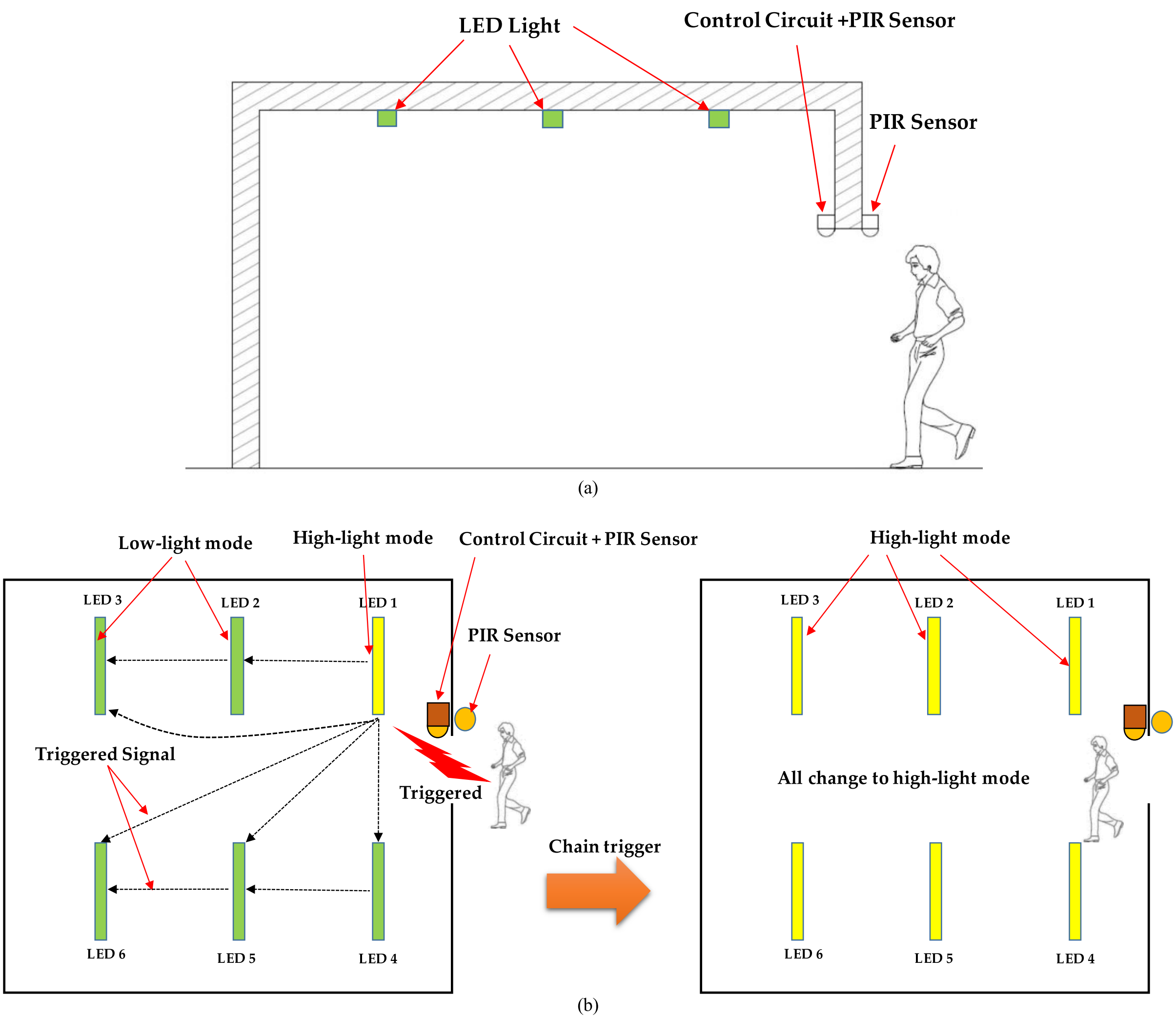

FIGURE 2. An application scenario of the proposed system installed in an office. (a) Side view. (b) Top view.

a person is entering or exiting the office. If the PIR sensor outside the door senses the person's presence first, then the person is judged to be "entering", and the system counter is increased by 1. Otherwise, if the PIR sensor inside the door senses the person's presence first, then the person is judged to be "exiting", and the system counter is decreased by 1.

In the beginning, the system counter = 0; when someone enters the office from outside, the counter increases by 1, and LED 1 closest to the door is also triggered as long as the LEDs in the same office (area) are on the same channel (only the LED lights of the same channel can send signals to or receive signals from each other, as explained in detail in the next section). At this time, trigger signals are transmitted to the other LED lights in the same area through the Wi-Fi wireless transmission module. The LED lights in the same area all simultaneously change to the high-light mode.

In Fig. 2, when someone approaches LED 1, LED 1 immediately transmits the trigger signal to LEDs 2 to 6. There are two ways to receive the signal: one is directly receiving the signal sent by LED 1, and the other is receiving a signal sent by the other LEDs that received the signal earlier.

Take LED 6 as an example. It can receive the signal sent by LED 1 or the trigger signal sent by LED 5 (whichever signal arrives first). After the trigger signal of LED 1 (as a leader) is received, LED 2 to LED 6 (as followers) immediately operate in high-light mode, so LED 1 to LED 6 change to the strong light mode nearly simultaneously. Different areas are defined by different channel settings. LEDs in different areas are not triggered. The user can set the areas to which the LEDs belong according to the environmental requirements. When LED lights are set to the same area, they act synchronously.

The LED light used in the proposed smart office lighting system in this paper is similar to the induction light proposed in [1] (it is equipped with a PIR sensor), so the strong light lasts for T seconds (the parameter T can be set through IoT; the default value is 30 seconds). When the PIR sensor of the previous LED light cannot detect a person, the lights automatically change to low-light mode, but the system is modified

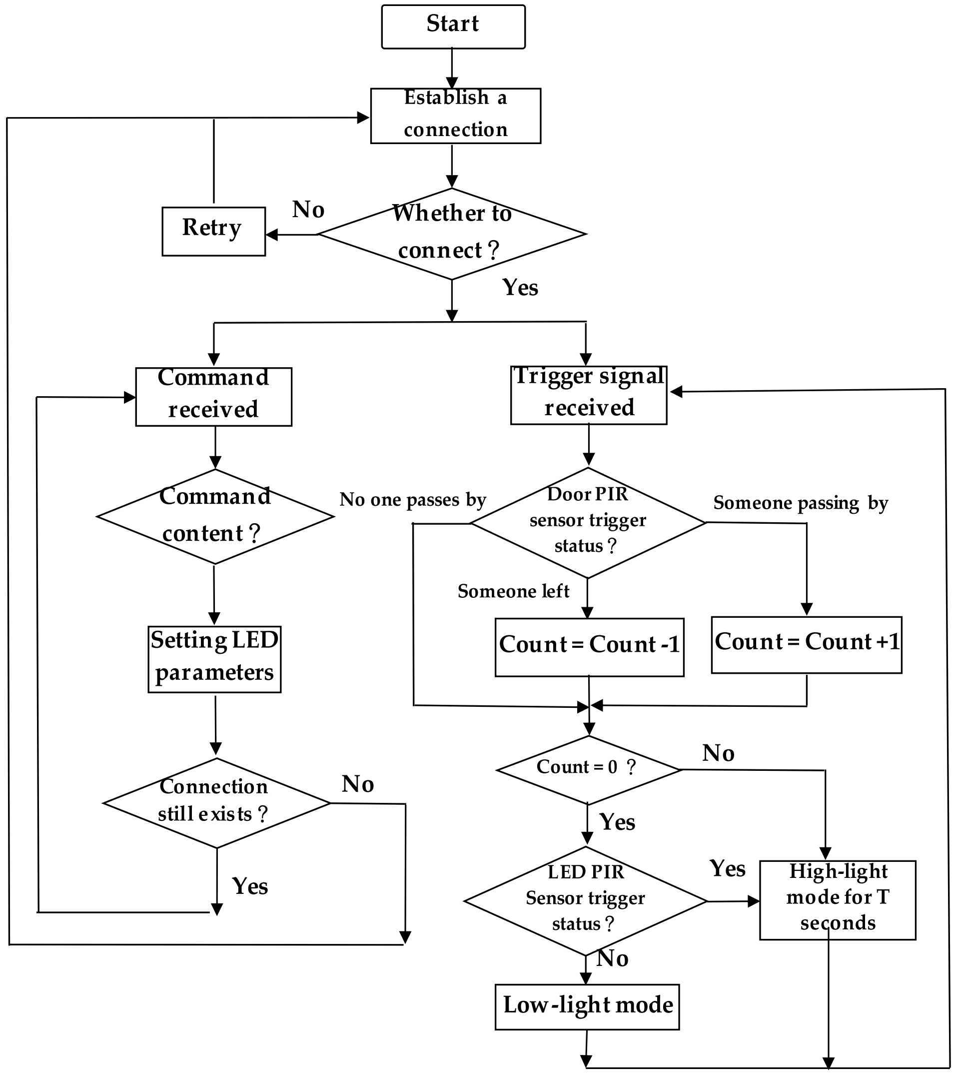

FIGURE 3. Flow chart of the proposed system.

to the requirements that the PIR sensor cannot detect people and the system counter = 0.

These two conditions must exist at the same time for the LEDs to be turned to low-light mode. This method prevents system misjudgment and clearly prevents turning off of lights when someone is there. Because people in a space may stay still for a long time, the PIR sensor alone cannot detect them, and misjudgment can occur.

Therefore, when someone is present in the office, a person entering only increases the system counter by 1 and does not cause the LED lights to change (because the high-light mode is maintained); if someone exits the office, this only decreases the system counter by 1 and does not change the system to low-light mode (because the counter is not equal to zero). Only after the last person in the office leaves for T seconds (the default value is 30 seconds) do all LED lights change to low-light mode.

Because the proposed system does not require the replacement of the light fixtures of the original LED lights, we can directly replace old LED tubes or fluorescent tubes in the office with new sensor lights and then install PIR sensors inside and outside the door. Hence, the installation is simple; there is no need for wiring and no need to set up a server, and the original light fixtures can be used, allowing the smart LED lighting control system to reduce energy consumption.

Furthermore, we take [26] as an example. In this article, the energy-savings concept is the same, but a server and complicated wiring must be set up to control the brightness of each LED light and the route that people pass by. It takes considerable time and money to achieve a 58% energy-savings effect. In our design, as long as the general T8 LED tube is replaced with a new induction light, no server or wiring is required, and good energy-savings effects can be achieved. We use the proposed system in Fig. 2 as an example. Each lamp tube costs NT\$800, and the door control circuit and PIR sensor cost NT\$1,200. The total cost is $800 \times 6+1{,}200 =$ NT\$6,000 (approximately US\$241.29).

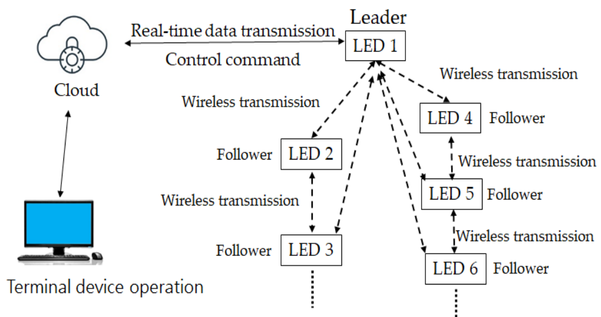

FIGURE 4. System architecture of the proposed system.

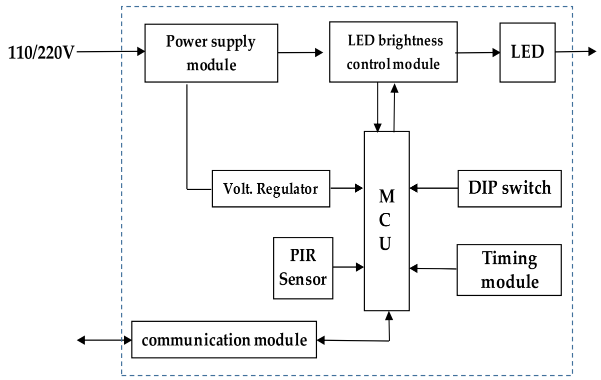

FIGURE 5. Hardware block diagram of the proposed system.

B. THE PROPOSED SYSTEM FLOWS AND ARCHITECTURE

A flow chart of the proposed system is shown in Fig. 3. The proposed system first establishes a connection with the cloud server. When there is no connection, the proposed system repeatedly tries to establish a connection. After the connection is established, the proposed system waits for a command from the application and starts to receive external triggers. The command of the application program is to set the LED parameters (e.g., high-light duration T, high-light mode power %, and low-light mode power %). Then, the proposed system checks whether the connection is continuous and repeats the whole system flow.

The proposed system first receives the trigger of the door PIR sensor. If the entry of a person is detected, the system counter increases by 1; if the exit of a person is detected, the system counter decreases by 1; if no one enters or exits, the counter remains unchanged, and then the proposed system judges the value of the counter. If the counter is not 0, all LEDs are set to high-light mode.

The time continues for T seconds. If the counter = 0, the system immediately checks whether the PIR sensor of each LED has been triggered (indicating that there are still people in the office); if so, all the LEDs are set to high-light mode. If the PIR sensor of the LED is not triggered, then the counter = 0, and no one is in the office at this time. Therefore, all LEDs are set to low-light mode (we wait until the T-second countdown of the high-light mode expires before turning to low-light mode).

TABLE 2. Parameters of preset values and settable ranges of the proposed system.

	Settable ranges	Present values
Duration of high-light mode (T)	10 – 60 s	30 s
Power of high-light mode (W_H)	80–100%	100%
Power of low-light mode (W_L)	10–30%	10%

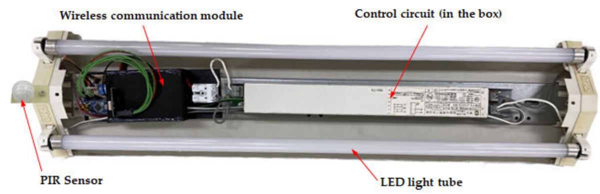

FIGURE 6. Photograph of a prototype of the proposed system.

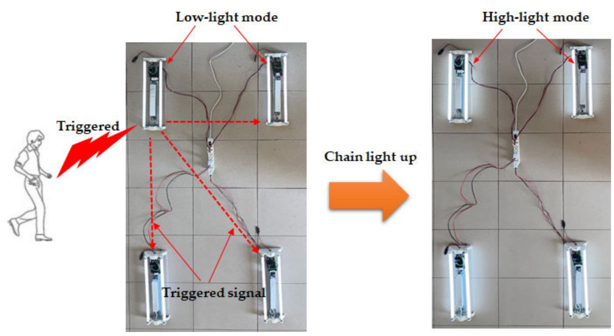

FIGURE 7. Photograph of a prototype of the proposed system.

Therefore, when the counter > 1, a person entering only increases the counter by 1. If someone exits the office, it only decreases the counter by 1, and the LED lights remain in high-light mode. All the LED lights change to low-light mode only when the last person in the office leaves, T seconds have elapsed, and the PIR sensor of the LED has not been triggered.

When the PIR sensor of the LED light cannot detect anyone and the system counter = 0 simultaneously, the LEDs are changed to low-light mode. This method can prevent many situations of misjudgment. For example, if there is no one in the office at the beginning, the counter will erroneously be set to 1 if two people simultaneously enter side by side. When one person walks out of the office, the counter will change to 0, but the PIR sensor of the LED light will detect that there are people in the office at this time.

Therefore, the LED lights are not changed to low-light mode, and when the last person leaves the office, the counter remains at 0 (we set the counter to never become negative), and the LED lights change to low-light mode. Previous systems reported in the literature have installed only a system counter or used only a PIR sensor for detection. Under these conditions, it is very easy to misjudge the number of people, resulting in malfunctions (the lights are turned off when someone is present or are still on when no one is present).

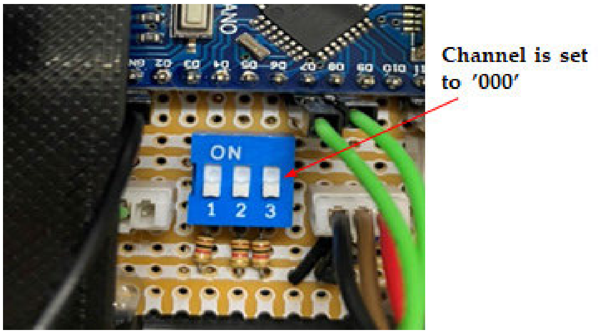

FIGURE 8. A LED light with the channel set to '000'.

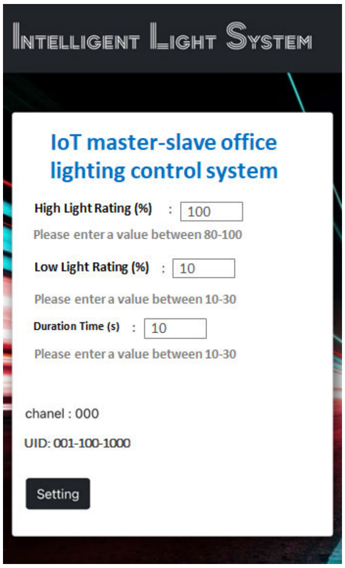

FIGURE 9. Settings screen of the mobile device app.

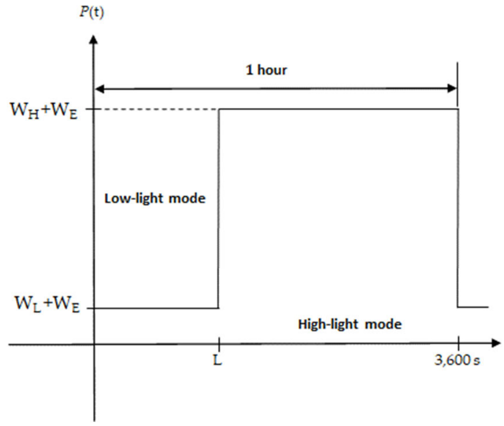

FIGURE 10. Hourly power consumption curve of the new LED induction light.

The architecture of the proposed system is shown in Fig. 4. The proposed system can upload the LED high-light duration, high-light mode power %, low-light mode power %, and other parameters, and the leader-follower mode control data are sent to the cloud through Wi-Fi wireless transmission.

The terminal device performs parameter settings. The terminal device can be a mobile phone, tablet, or computer. When the leader LED light receives commands from the cloud, it immediately transfers the command to other follower LED lights via Wi-Fi wireless transmission. The parameters of the LED lights in the same area can be easily set together instead of individually setting them.

C. HARDWARE IMPLEMENTATION OF THE PROPOSED SYSTEM

Fig. 5 shows the hardware block diagram of the proposed system. The power supply module is 110/220 V universal voltage. The microcontroller unit (MCU) sends commands to the LED brightness control module according to the parameter values sent by the communication module to determine the power ratio of the LED high-light and low-light modes and the duration of the high-light time. The communication module is a Wi-Fi wireless transmission module responsible for data transmission with the cloud and transmission between smart LED lights based on the IoT.

The settable range and preset value of the LED light parameters of the proposed system are shown in Table 2. The parameters that can be set are the duration of high light T, the power of the high-light mode W_H, and the power of the low-light mode W_L. These parameters are all set. The default values are suitable for office lighting. The user can connect to the LED lights to modify them through the internet. The setting range is shown in the table. The modified parameter values are also uploaded to the Wi-Fi wireless transmission module. The cloud platform is used for big data analysis and suggestions for setting parameter values in the future. A prototype of the proposed system is demonstrated in Fig. 6.

The LED lights in the office operate in low-light mode at the same time when there is no one present. When any of the LED lights in the office detect people passing by (as shown in Fig. 7), it transmits the trigger signals through the Wi-Fi wireless transmission mode to the other LED lights in the same area and simultaneously adjusts the brightness to the high-light mode instead of sequentially lighting up the LED lights one by one.

The communication module in Fig. 6 is a Wi-Fi wireless transmission module responsible for the data transmission to the cloud and transmission between the LED lights. In the transmission method between the LED lights, the LED lights set to the same channel send signals to or receive signals from each other. For example, the channel of the leader LED light in Fig. 8 is set to '000' (the dual inline package (DIP) switch is set to '000').

We use Wi-Fi wireless transmission to transfer the set parameters of 000 to other channels and to the follower LED lights. This information cannot be received by the other channels. This is a function designed for a large field because, in a large field, there may be hundreds of LED lights that need to be set. Setting so many LED lights is a very large project, so the channel value of the light can simply be set the same.

Take the office in Fig. 2 (b) as an example. We can set the channel of all LED lights in the same office to '001' and those in different offices to different channels so that a large number of LED lights can be set easily. The user can set the area of the LEDs according to the environmental requirements, and when the LED lights are set to the same area, they act synchronously. In addition to the various parameters set through the DIP switch of the LED control circuit, parameters can be set via the mobile device app, as shown in Fig. 9.

In this work, a Wi-Fi wireless transmission module is adopted as the communication module in Fig. 5. Moreover, this Wi-Fi wireless transmission module can be replaced with ZigBee, Bluetooth, LTE, *etc.*, according to different field conditions. We note that the communication module should support universal asynchronous receiver/transmitter (UART) interfaces for communication with the MCU module used in the system proposed in this work.

The data transmission method of the Wi-Fi communication module can generally be divided into two types: message queuing telemetry transport (MQTT) and HyperText Transfer Protocol (HTTP). In this article, we adopt the MQTT architecture [51]. Compared to the HTTP architecture, the MQTT architecture can reduce power consumption during transmission, and the proposed system will synchronize the time with the primary server every minute, avoiding the problems caused by time out of synchronization and data delay [2], as follows.

1) The finite element machine architecture is adopted to write programs, and the device will automatically ignore it to avoid errors when assisting false data injection [52].
2) A timestamp is adopted for the data recognition judgment, so that the same timestamp will only recognize one piece of data, and the data with errors due to delay will be ignored.
3) Due to the solution of the first two problems, system resources can be prevented from being exhausted due to multiple occupation.

IV. ENERGY SAVINGS CALCULATION AND DISCUSSION

Each LED induction lamp calculates the energy consumption per hour and year. Then, it is compared with the non-induction LED light to calculate its energy-saving rate (ESR), the number of electricity consumption savings, cost savings, reduced carbon emissions, *etc*. The proposed office lighting system's LED lights have high-light and weak light modes, so it is more complicated to calculate the power consumption, unlike ordinary non-induction LED lights.

Factors that affect the power consumption include the frequency of people entering and leaving the office, the duration of high-light T, the power of high-light mode W_H, the power of low-light mode W_L, the presence or absence of continuous triggering. To facilitate the deriving of the formula, we refer to calculation methods [2], [48], [49] of power consumption. Finally, consider a company as an example to calculate the total savings for all of its offices.

TABLE 3. E_{ph}, E_{py}, ESR, D_{py}, M_{py}, C_{py} values of each LED light with different L values.

L (Sec)	E_{ph} (kW·h)	E_{py} (kW·h)	ESR (%)	D_{py} (kW·h)	M_{py} (NT$)*	C_{py} (kgCO2e)
0	0.0160	58.400	0.00%	0.000	0.000	0.000
120	0.0156	56.758	2.81%	1.643	6.570	1.023
240	0.0151	55.115	5.63%	3.285	13.140	2.047
360	0.0147	53.473	8.44%	4.928	19.710	3.070
480	0.0142	51.830	11.25%	6.570	26.280	4.093
600	0.0138	50.188	14.06%	8.213	32.850	5.116
720	0.0133	48.545	16.88%	9.855	39.420	6.140
840	0.0129	46.903	19.69%	11.498	45.990	7.163
960	0.0124	45.260	22.50%	13.140	52.560	8.186
1,080	0.0120	43.618	25.31%	14.783	59.130	9.209
1,200	0.0115	41.975	28.13%	16.425	65.700	10.233
1,320	0.0111	40.333	30.94%	18.068	72.270	11.256
1,440	0.0106	38.690	33.75%	19.710	78.840	12.279
1,560	0.0102	37.048	36.56%	21.353	85.410	13.303
1,680	0.0097	35.405	39.38%	22.995	91.980	14.326
1,800	0.0093	33.763	42.19%	24.638	98.550	15.349
1,920	0.0088	32.120	45.00%	26.280	105.120	16.372
2,040	0.0084	30.478	47.81%	27.923	111.690	17.396
2,160	0.0079	28.835	50.63%	29.565	118.260	18.419
2,280	0.0075	27.193	53.44%	31.208	124.830	19.442
2,400	0.0070	25.550	56.25%	32.850	131.400	20.466
2,520	0.0066	23.908	59.06%	34.493	137.970	21.489
2,640	0.0061	22.265	61.88%	36.135	144.540	22.512
2,760	0.0057	20.623	64.69%	37.778	151.110	23.535
2,880	0.0052	18.980	67.50%	39.420	157.680	24.559
3,000	0.0048	17.338	70.31%	41.063	164.250	25.582
3,120	0.0043	15.695	73.13%	42.705	170.820	26.605
3,240	0.0039	14.053	75.94%	44.348	177.390	27.628
3,360	0.0034	12.410	78.75%	45.990	183.960	28.652
3,480	0.0030	10.768	81.56%	47.633	190.530	29.675
3,600	0.0025	9.125	84.38%	49.275	197.100	30.698

*Note: US$1=NT$28.

A. CALCULATION OF THE POWER CONSUMPTION AND ENERGY-SAVINGS RATE (ESR)

Fig. 10 shows the hourly power consumption curve of the new LED induction light. We can use this graph to illustrate how to calculate the hourly power consumption of the new LED induction light.

P(t) is used to describe the hourly power consumption change of the new LED induction light. The meanings of the other parameters are as follows:

L: The cumulative number of seconds per LED light per hour in low-light mode.

W_H: The power of the LED light in high-light mode. The default power in this work is 15 W (the default value is 100%).

W_L: The power of the LED light in low-light mode. The default power in this work is 1.5 W in low-light mode (default value is 10%)

W_E: The average power consumption of the LED light circuit (including the power consumption of the control circuit and PIR sensor); the W_E value in this work is approximately 1 W.

Fig. 10 shows that the use of the new type of LED light sensor maintains the activated state within 1 hour (the life cycle state is the low-light mode state, not the 0-second low-light mode). There are 3,600 L seconds to maintain the high-light mode status, so we use the method for calculating the area to simulate and calculate the energy Eph consumed by the new LED induction light:

$$\begin{aligned} \mathrm{E_{ph}} &= (\int_0^L P(t)dt + \int_L^{3600} P(t)dt)\mathrm{J} \\ &= (\int_0^L (W_L + W_E)dt + \int_L^{3600} (W_H + W_E)dt)\mathrm{J} \\ &= (\mathrm{L}\times(W_L + W_E) + (3600 - \mathrm{L}) \times (W_H + W_E))\mathrm{J} \\ &= (\mathrm{L}\times(W_L - W_H) + 3600 \\ &\quad \times(W_H + W_E))/3.6 \times 10^6 kW \cdot h \end{aligned} \tag{1}$$

In addition, we assume that the new type of LED sensor light in a company's office is turned on for 10 hours a day, for a total of 10 × 365=3,650 hours in a year. Therefore, the annual electric energy $\mathrm{E_{py}}$ consumed by each new type of LED sensor light is as follows:

$$\mathrm{E_{py}} = \sum E_{ph} = 3,650 \times \mathrm{E_{ph}}\mathrm{kW \cdot h} \tag{2}$$

Because noninductive LED lights are always in the starting state, the electric energy $\mathrm{F_{py}}$ consumed by each LED light per year compared with noninductive LED lights is (where $\mathrm{F_{ph}}$ is the electric energy consumed by noninductive LED lights per hour):

$$\begin{aligned} \mathrm{F_{py}} &= \sum F_{ph} = 3,650 \times \mathrm{F_{ph}}\mathrm{kW \cdot h} \\ &= 3,650 \times ((W_H + W_E)/1000) \\ &= 3.65 \times (W_H + W_E)\mathrm{kW \cdot h} \end{aligned} \tag{3}$$

Next, we can calculate the ESR if the general noninductive LED lights in all offices of a company are replaced by the proposed new type of LED induction lights in the proposed smart office lighting system. In addition, for each new LED, we can calculate the amount of electricity saved by the induction light in one year $\mathrm{D_{py}}$, the amount saved in one year $\mathrm{M_{py}}$ (assuming 4 NT$ per kilowatt-hour of electricity), and the carbon emission reduction $\mathrm{C_{py}}$ in one year as follows (assuming each kilowatt-hour (kW·h) can produce carbon emissions of 0.623 $kgCO_2e$):

$$\begin{aligned} \mathrm{ESR} &= (\mathrm{F_{ph}} - \mathrm{E_{ph}})/\mathrm{F_{ph}} \times 100\% \\ &= (((W_H + W_E)/1000) - \mathrm{E_{ph}})/((W_H + W_E)/1000) \\ &\quad \times 100\% \\ &= ((W_H + W_E) - 1000 \times \mathrm{E_{ph}})/(W_H + W_E) \times 100\% \end{aligned} \tag{4}$$

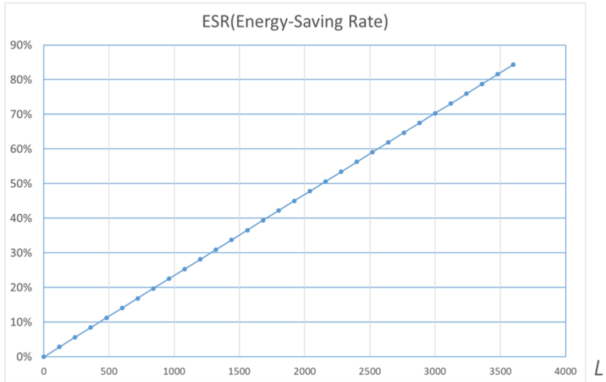

FIGURE 11. Relationship between ESR and L.

$$\begin{aligned} \mathrm{D_{py}} &= \mathrm{F_{py}} - \mathrm{E_{py}} = 3.65 \\ &\quad \times((W_H + W_E)) - 1000 \times \mathrm{E_{ph}})\mathrm{kW \cdot h} \end{aligned} \tag{5}$$

$$\mathrm{M_{py}} = (\mathrm{F_{py}} - \mathrm{E_{py}})\mathrm{kW \cdot h} \times 4\ dollar/\mathrm{kW \cdot h} \tag{6}$$

$$\mathrm{C_{py}} = (\mathrm{F_{py}} - \mathrm{E_{py}})\mathrm{kW \cdot h} \times 0.623\ kgCO_2e/\mathrm{kW \cdot h} \tag{7}$$

B. ESR DISCUSSION

Since the ESR of the new type of LED sensor light is closely related to the number of seconds L accumulated in low-light mode per LED light per hour, this subsection explores the relationship between *ESR* and the number of seconds L accumulated in low-light mode per hour and calculates the maximum and minimum *ESR*.

First, (4) shows that ESR is inversely proportional to the electrical energy $\mathrm{E_{ph}}$ consumed by the new LED induction light per hour. From (1), $\mathrm{E_{ph}}$ is inversely proportional to L (because (W_L-W_H) must be negative), so *ESR* is proportional to L. The more seconds accumulated in low-light mode, the better ESR is.

Next, to calculate the ESR, the actual power values of W_H, W_L, and W_E must be determined. The power of the LED light in high-light mode is 15 W, the power W_L in low-light mode is 1.5 W, and the average power consumption of the circuit W_E is approximately 1 W. Below, we bring different L values into the formula for $\mathrm{E_{ph}}$ to calculate the $\mathrm{E_{py}}$, *ESR*, $\mathrm{D_{py}}$, $\mathrm{M_{py}}$, and $\mathrm{C_{py}}$ values of each new type of LED sensor light with different L values (compared with those of nonsensing LED lights). In Table 3, due to space, only the important parameters are listed (the T value is listed at intervals of 120 seconds).

Table 3 shows that the maximum *ESR* of 84.38% occurs when L = 3,600 (indicating that the new LED sensor lights are in low-light mode within 1 hour, that is, there is no light in high-light mode in the entire office within 1 hour); the same is true for $\mathrm{D_{py}}$, $\mathrm{M_{py}}$, and $\mathrm{C_{py}}$. The *ESR* is smallest when L is zero (ESR=0%) and linearly increases with increasing L. When L = 3,600 seconds, the *ESR* rises to 84.38%. Fig. 11 shows the relationship between *ESR* and L.

In Fig. 11, ESR is the energy-saving rate, L is the number of seconds accumulated per hour in the low-light mode for each

TABLE 4. A satisfaction analysis form.

Question item	Average value	Standard deviation	Number	Average rank
2. The respondent thinks that this office lighting system can operate in low-light mode when there is no one in the office space and does not allow the office space to become totally dark during working hours.	4.9	0.486	180	1
1. The respondent thinks that the low-light mode function of this office lighting system is very energy-efficient.	4.85	0.528	180	2
4. The respondent thinks that this office lighting system can confirm that no one is present in the space and turn all the LED lights in the room to low-light mode together and that there is no misjudgment.	4.74	0.568	180	3
8. The respondent would recommend this office lighting system to others.	4.37	0.708	180	4
3. The respondent thinks that when the office lighting system turns the sensor lights on, my eyes are not uncomfortable due to sudden bright lights.	4.36	0.685	179	5
7. The respondent thinks this office lighting system waits 30 seconds before turning all the LED lights to low-light mode when no one is in the office space. This function is very suitable.	4.32	0.704	180	6
6. The respondent thinks that the sensitivity and response distance of this office lighting system is moderate.	4.3	0.702	180	7
5. The respondent thinks that the brightness of the low-light mode of this office lighting system is just right.	4.3	0.678	178	8

LED lamp, and the relationship between the two is linear. A greater number of accumulated seconds in low-light mode corresponds to a higher the energy-saving rate (no one in the office) so that the system will run in low-light mode only when at the appropriate time to save energy.

C. ENERGY-SAVINGS CASE CALCULATION

We use a company as an example to calculate the total cost savings and energy savings of all its offices. Assume that the company has 16 offices and that each office has 12 LED lights. There are a total of 192 LED lights. For the new type of LED induction light, we have demonstrated its energy-savings effects and expected results from reducing electricity consumption over the same period of the year. Because our new LED sensor light can uniformly set the parameters of each LED light in the office through the Wi-Fi wireless transmission module, there is no need to waste effort to individually set them.

We use 192 LED lights to estimate the reduced power consumption over the same period of the year. The following assumes that the lights in the office are turned on for 10 hours a day and that the hourly time of the new LED sensor light mode is 1,200 seconds. We assume that the office is occupied for 1,200 seconds and that otherwise no one is there.

We can directly refer to Table 3 to calculate the related values (directly taking the E_{py}, D_{py}, M_{py}, C_{py} values of L=1,200 seconds) and conduct the analysis as follows:

1) Power consumption of 192 LED lights (the E_{py} value of $L = 1{,}200$ is 41.975): $41.975 \times 192 = 8{,}059.2$ kW·h.
2) One-year power consumption of 192 noninductive LED lights (only run in high-light mode): $650 \times 0.016 \times 192 = 11{,}212.8$ kW·h.
3) Reduced power consumption in a year (the D_{py} value of $L = 1{,}200$ seconds is 16.425): $16.425 \times 192 = 3{,}153.6$ kW·h.
4) Cost reduction in one year (the M_{py} value of $L = 1{,}200$ seconds is 65.700): NT\$65.70 $\times$ 192 = NT\$12,614.40.
5) Reduction in carbon emissions in a year (the C_{py} value of $L = 1{,}200$ is 10.233): $10.233 \times 192 = 1{,}964.736$ $kgCO_2e$.

Therefore, as long as we change all 192 LED lights in the office of the company to the new type of LED sensor light, we can obtain the following expected results (assuming that the office is occupied for 10 hours a day, that the hourly time of the new type of LED sensor light in low-light mode is 1,200 seconds, that NT\$4 is saved per degree calculation, that the power W_H of the high-light mode is 15 W, that the power W_L of the low-light mode is 1.5 W, and the average power consumption of the circuit W_E is approximately 1 W):

D. USER SATISFACTION ANALYSIS AND DISCUSSION

A total of 180 respondents completed questionnaires in this study, of which 51.7% were males and 48.3% were females.

TABLE 5. A comparison of existing two smart lighting bulbs with the system proposed in this work.

Related work	Philips Hue smart lighting bulb [53]	VOCOline smart lighting bulb [54]	**This work**
Applicable fields	Living room	Living room	Office
PIR sensor adoption	No	No	Yes
IoT-based	Yes	Yes	Yes
Power consumption	10 W	9.5 W	14 W
Dimming	Freely dimmable	Freely dimmable	Processing in low-light mode when there is no one (Brightness can be adjusted)
Situational lighting	It can be changed in full color according to the situation.	It can be changed in full color according to the situation.	No.
Communication protocol	ZigBee	Wi-Fi 2.4G Hz	Wi-Fi 2.4 GHz
Google Home/Apple Home kit supported	Yes	Yes	No
Regional chain response	No	No	LED lights in the same region can be brightened at the same time.
Price	NT$1,764 (About US$63)	NT$950 (About US$33.9)	NT$800 (About US$28.6)

The analysis results are shown in Table 4. The overall average ranking of the satisfaction found that the top three satisfaction levels for sensor light settings are "The respondent thinks that this office lighting system can operate in low-light mode when there is no one in the office space and does not allow the office space to become totally dark during working hours ($m = 4.9$)," with the highest score; "The respondent thinks that the low-light mode function of this office lighting system is very energy-efficient ($m = 4.85$);" and finally "The respondent thinks that this office lighting system can confirm that no one is present in the space and turn all the LED lights in the room to low-light mode together and that there is no misjudgment ($m = 4.74$)."

This satisfaction analysis was conducted at Cheng-Shiu University, Kaohsiung, Taiwan. Currently, the proposed system is installed in the life creative building of the school and has been used for nearly half a year. Currently, we are evaluating whether the office lighting system of the whole school has been fully renovated.

Furthermore, the reliability of the proposed system is as high as 95% after the actual test. Errors occur only in rare cases. Generally, errors occur when two people enter side by side at the same time. The proposed system counter and PIR sensor must confirm that no one is in the state before changing to the low-light mode. However, if the person in the office is entirely still, the PIR sensor still cannot sense it. Currently, this is the major problem that must be resolved.

Finally, comparing to the related works, the differences and advantages of the proposed method are summarized as follows.

1) When the office space is unoccupied, the system operates in low-light mode and does not allow the office space to become totally dark during working hours.
2) Through the coordinated operation of the system counter and the infrared human body movement sensor (PIR sensor), when it is confirmed that no one is present in the space, all the indoor LED lights are turned to low-light mode, and there is no misjudgment.
3) The original light fixtures can be retained, with no wiring and no need to set up a server, and the energy-savings purposes of smart lighting in the office can be achieved.
4) The parameters of LED lights can be set directly through the IoT.
5) If a general 15 W T8 LED tube (nonsensing light) is replaced with the proposed office lighting system (assuming that the office is occupied for 10 hours a day and that the hourly low-light mode is 20 minutes), the power-saving rate is as high as 28.13%.

Finally, there are some existing smart lighting control products on the market. They are also similar to the proposed system. Hence, we also compare our system to them. Table 5 compares the system developed in this work with two popular smart lighting bulb products: Philips Hue full-color ambient light bulbs [53] and VOCOline smart lighting bulbs [54].

V. CONCLUSION

This article proposes an energy-saving, easy-to-install, wireless, low-cost IoT-based leader-follower smart office lighting control system that is very suitable for installation in the office of a large company or factory. It uses a system counter and an infrared human motion sensor (PIR Sensor) working in coordination; only when no one is in the space do all the LED lights in the room enter low-light mode together, and there is no misjudgment.

The system can easily achieve energy savings and convenient control of a large-scale smart LED lighting system. Moreover, the cost of this system is only 1/10 that of installing a smart system, and there is no need to replace the original LED lights. The original light fixtures can be used in the system without additional wiring or setting up a server.

In addition to directly setting the parameters of LED lights through the IoT, unlike general induction lights, the recommended office lighting system operates in low-light mode instead of total darkness when there is no one in the office space. Taking a general 15 W T8 LED tube (induction light) as an example, if users switch to the recommended office lighting system (assuming that the office is occupied for 10 hours a day and that the hourly low-light mode time is 20 minutes), the power-saving rate is as high as 28.13%.

In addition, when the system counter is 0, but people are still present in the office, the PIR sensor is still unable to sense if the people in the office are completely still. Therefore, in the future, we will fine-tune the strategy and add a judgment condition that the count is set to be 0, but when the PIR sensor senses that people are still present in the office many times, the counter will be changed to a policy of 1, solving this problem. Furthermore, in future work, we plan to focus on considering the lighting effects of natural light so as to obtain increased energy savings and make the system more efficient.

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