The Design of Building Management Platform Based on Cloud Computing and Low-Cost Devices

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Abstract -

Indoor environment monitor and control are important aspects of reducing building energy consumption and maintaining occupants' visual and thermal comforts. Previous research showed that the lots of buildings were not able to provide designed service level in the daily operation and the feedback from occupants showed that the predetermined service level sometimes did not match occupants' desire. However, most of existing buildings and residential buildings did not have building management systems that can systematically monitor the indoor environment, collect occupants' feedback, and fine-tune built-in control logic when the occupants' needs could not be met. An easy-to-build and easy-to-use build management system can help researchers, engineers, and occupants themselves to identify the issue.

The goal of this study was to develop a building management platform with the functions of indoor environment data collection (temperature, relative humidity, solar radiation, etc.), remote control (air conditioner, window, shading), occupants' feedback collection (set point, status of building components, etc.), and user interface for retrieving the data and modifying control logic. The platform was developed using Arduino-based and Raspberry Pi-based microcontroller board, low-cost sensors, 3D printing technology, and cloud computing technology. The stored data can serve for personal behavior/comfort analysis, components efficiency analysis, and advanced control logic development. This last part of this paper demonstrated the ability of the developed platform and exhibited the potential application. In the end, we provided further discussion about the potential challenges we might face when developing building management systems in other existing spaces/buildings.

Keywords –

Building Management Platform; Cloud Computing; Low-Cost Devices

1 Introduction

A considerable portion of energy consumptions in buildings are from satisfying occupant' needs and providing human-beings a better life. Researchers try to reduce the energy usages by setting up efficient automated control algorithms for building components such as lighting, shading, heating ventilation and air conditioning (HVAC) system using strategies. However, these newly developed control algorithms may sometimes cause displeased indoor environments since sometimes the algorithms were set too high or too low in an attempt to save more energy and occupants might have different thermal preferences. When occupants took the business on their own and took unexpected actions to control the indoor environment manually, it may result in interfering the designed energy-saving strategies and goals. For example, the HVAC system might experience a startup peak caused by occupants setting the set point too low during the cool down process from the initial state.

To overcome these issues, researchers are paying more and more attention to occupants' behavior and their reactions to automated control recently. One particular challenge of collecting occupants' feedback, is that most of the existing buildings do not have built-in building automation and management system. While the concept, some companies have been promoting intelligent building energy management systems for years[1], the market has not fully accepted these products because of its price and the installation labor works. For most of the prototypes in existence now, the installation and the system integration task are a laborious, ad-hoc process. Adding each new device/features into the building or zone requires a great deal of work. After getting the orders, the engineers must research that targeted buildings' characteristics, operation, protocols of existing devices in the buildings, determining how to integrate new components into the existing system, where to install, how to configure it and how to interface with it. On the other hand, the cost is usually one of the priorities for people when investing in a new system. An easy-to-build and easy-to-use building management system can help researchers, engineers and occupants themselves identify the issue.

The goal of this research is to develop a building management platform in an existing space with the functions of indoor environment data collection (temperature, relative humidity, solar radiation, etc.), remote control (air conditioner, window, shading), occupants' feedback collection (set point, equipment status, etc.), and user interface for retrieving the data and deploying control logic interface.

2 Literature Review

Human's lifestyle is constantly changing along with the development of technology. In Teichroew [2]'s paper from 1971, they already started to talk about the importance of home automation. Murata [3] introduced a system that can control home computer, television, audio and video entertainment with verbal commands. Ryan [4] designed a system using cordless humidity sensors and temperature sensor to control the heater remotely by occupants. The smart building concept has become very more popular recently. Lots of researchers have started to investigate how to improve the energy efficiency of buildings and how to improve the indoor environment we live in.

To run a smart building systematically, a building management system (BMS) or a building energy management system (BEMS) is essential. Without a good building management system, it is hard for the building manager to find out the issues, for the devices to communicate with each other, and for occupants to provide feedback. Not to say, it would be very challenging for engineers to deploy newly developed control logic and to add new technology into an existing system. Building management system has been installed in more and more newly constructed buildings, especially after some researchers have pointed out that its potential for energy saving.

Rotger-Griful et al. [5] present a multi-modal building energy management system for capturing residential demand response. They set a testbed where they collected indoor environment data from sensors and power meters in order to analyze the occupant's demand response. According to the study, the energy saving potential of a building to be 7.4 MWh/year. Macarulla et al. [6] present the procedure of implementing a predictive control strategy in a commercial BEMS for boilers in buildings based on a neural network that turned on the boiler each day at the optimum time, according to the surrounding environment, to achieve thermal comfort levels at the beginning of the working day. The results showed that the implementation of predictive control in a BEMS for building boilers could reduce the energy required to heat the building by around 20% without compromising the user's comfort. However, as the introduction section points out, it is especially tricky for existing building/space regarding system integration and cost.

Low-cost developmental systems such as Arduino and Raspberry Pi are widely used for developing prototypes of smart building applications [7] since it is capable of serving as a data acquisition system and is also capable of being a controller [8].

Data collecting and monitoring is the core of a building energy management system, and lots of advanced control algorithms are relying on accurate and reliable data sources. Researchers tried to cut the cost of data collecting. Li et al. [9] developed a low-cost real-time data logger with PM sensor, an Arduino Nano ATmega328, and an XBee radio to measure particulate matter. Habibi et al. [10] developed a smart system prototype based on Arduino microcontroller which can obtain and monitor environmental data (light, sound pressure/mic, temperature, and humidity) in real-time. Jin [11] developed a similar system to monitor IEQ. Rajalingam and Malathi [12] used an Arduino system as a smart controller for home power management. Lovett et al. [13] present an approach minimized the cost of sensing by inferred performance metric (e.g., high CO2 levels may indicate poor ventilation). They designed a process for grouping sensor sets to capture energy events in buildings. While these techniques are being widely studies, the accuracy and reliability of these low-cost sensors have not thoroughly been studied.

Research communities and companies started from developing systems and interfaces that allow the occupants to control lighting, shading, and HVAC system remotely. Gill et al. [14] developed a home automation system based on ZigBee to control lighting system and radiator. Occupants can control the lights and the radiator through any device supporting Wi-Fi and Java. Piyare et al. [15] developed a Bluetooth based home automation on a Symbian OS mobile phone for controlling lamps remotely. Al-Ali et al. [16] developed a JAVA based home automation interface that can control lighting, fan, and oven through a local web page. Later on, the research scope was extended. Advanced automated control by analyzing sensors' feedback was studied and implemented. Kuo et al. [17] developed an automatic shading control system using photometer, 3D-printing component, and support vector machine algorithm for learning an individual's lighting preference. Cheng et al. [18] developed a satisfaction based Q-learning system which integrated lighting and blind control by gathering occupants' feedback. Tang et al. [19] used smartphone and light sensors to perform daylight harvesting while maintaining occupant desired light color. Compared to the original control mode, the power savings were up to 54.7%. Fewer studies were published about the HVAC system since the system is generally more complicated, but it had huge energy saving potential. Rashid et al. [20] retrofitted the functionality of the HVAC system by using the existing distributed heating/cooling infrastructure in buildings to provide a low-cost centralized command and control mechanism namely. The paper targeted buildings in developing countries that lack the necessary infrastructure of a traditional HVAC system. The result showed it could save approximately 45% of the total energy consumption of the air conditioner (AC) on a day.

From reviewing past studies, we can find that the benefits brought by building management system are valuable. More and more researchers started to develop a low-cost smart control and monitor system and building management system for existing buildings. However, the integration of protocols from different appliances and different manufacturers has not been discussed. In the past, we usually control each component separately. While more and more studied indicated – HVAC system, lighting system, shading system, and window system are related and should be considered together in order to achieve [21].

Moreover, the impact of occupants' inputs and feedback were skimmed. This paper aims to address some of the issues mentioned and to present an overview of an integrated building management system that can facilitate further research about occupants behavior and advanced control.

3 Methodology

This section described the system we developed and the method we used to overcome the existing conditions. This system was specifically designed for the test space described in next session. The design plan was carried out according to the current situation and the characteristics of existing building components (HVAC system, lighting system, and shading system).

3.1 System Structure

Figure1 showed the overall system structure which included four groups: the user interface, the cloud platform, the processing units, and the sensors and controllers.

There were two types of front-end components in the structure, environmental sensors, and controlled objects. Sensors collected environmental conditions that helped the controllers to provide appropriate environmental control. Meanwhile, the collected data helped the researchers to understand the conditions when occupants provided certain feedback (i.e., interact with building components) and for other research purposes. Sensors installed for monitoring the indoor and outdoor environment include thermocouples, temperature sensors, humidity sensor, light sensors, illuminance sensors, and pyranometers, and so on. Extra sensors such as and pyroelectric infrared detectors (PIR) were for detecting occupancy, and infrared receivers were for capturing remote controllers' signals. In the developed system, there were two controlled objects – shading systems and mini-split air conditioner. In the future, its scope would be expanded to other common building components in the spaces.

The processing unit was the medium of sensors, controllers, and database. For gathering environmental data from sensors, we used two types of systems (sensors + processing unit) in this study. The low-cost ones were there for the targeted system and data collected through this system was directly used for control. The high-end sensors and processing unit (mainly DAQ system) were set up in order to validate the readings collected by low-cost sensors. Both systems were integrated into the overall system frame, and the data was sent to a cloud database.

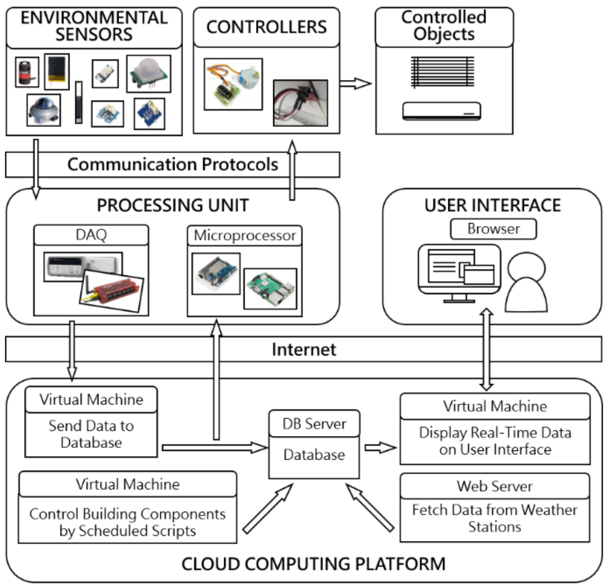

Figure 1. The overall system structure of developed building management platform

For low-cost data gathering, we chose Arduino and Raspberry Pi microcontroller boards as our processing unit. Both boards were capable of decoding communication protocols such as UART, I^2C, Modbus, and other communication protocols, which allowed better flexibility. Both boards supported Wi-Fi, which was critical to the existing space. Although communication through physical wires might be more reliable, it would increase the overall installation cost and workload. The data gathering program was running on the boards directly. After gathering the reading from sensors, it sent POST requests with the readings to a cloud server running a custom database and PHP application.

High-end system's processing units consisted of several different data acquisition systems which connected to sensors with voltage outputs, current outputs, etc. Instead of installing a program into the packaged DAQ system, the data gathering was running on the cloud server which sent signals to communicate with the DAQ system while the DAQ system communicates with sensors through its internal protocol. The data collected by the cloud server were sent and stored in the database directly.

Some microprocessors served for control purpose. The details would be present in 3.2 and 3.3. The typical way to interact with components in daily life were kept while the occupants' action being recorded. The web-based user interface also allowed engineers and occupants control the system remotely and to set up more complicated control algorithm.

The user interface of our system is web-based. The website present real-time information such as temperature, humidity from weather stations and sensor data, components' status, and occupancy status. We can also download CSV data for a customized period from the website.

The cloud computing platform was the core of the system. It was set up on the cloud instead of on-site to increase the computational efficiency, and to save the cost and space and can be accessed by people with access right from anywhere. Tasks hosted by cloud computing platform include hosting database, hosting PHP server that passed data to the database, performing data gathering programs, fetching data from weather stations, hosting user interface websites, and running control scripts on the virtual machines. New control algorithms would be deployed from the cloud computing platform. The expandability of the platform would give us the flexibility to add more functions and to add more computational capacity to the system in the future.

3.2 Thermal Environment Control

The section describes how our system control the thermal environment for the targeted space according to occupants' actions or control algorithm commands while capturing occupants' feedback. The structure of how the system executes thermal environment control is shown in Figure2.

The air conditioner demonstrated, in this case, was a mini-split system. Typically, it was controlled by occupants through the factory remote controller. However, it did not keep when and the conditions when occupants took a control action. The developed system kept the original way to control and added a web-based user interface that allowed both users and system to control the air conditioner from outside of the space. The original factory controller communicated with air conditioner through infrared signals, so we installed an Arduino Yun microprocessor with infrared receiver right next to the air conditioner signal to capture and decode the infrared signal sent by the controller in order to record occupants' actions. The remote controller sent out a specially timed sequence of pulses to transmit data. The infrared sequence consisted of a set of marks and spaces referred to as a "frame" of data. The receiver captured the whole sequence and determined critical time intervals (space) to decode the set point temperature and wind speed the controller was trying to tell the air conditioner. For realizing the control from outside of the space, an infrared transmitter and a WEMOS D1 mini pro microprocessor with a built-in web server were set up and aimed to the receiver in order to pass the infrared signal according to users' command through the website instead of factory remote controller. One of the most challenging parts was to decode the signals before setup the extra receiver and transmitter. In order to differentiate from the signals sent from the factory remote controller and signals sent by the website, we altered the small part of the signal.

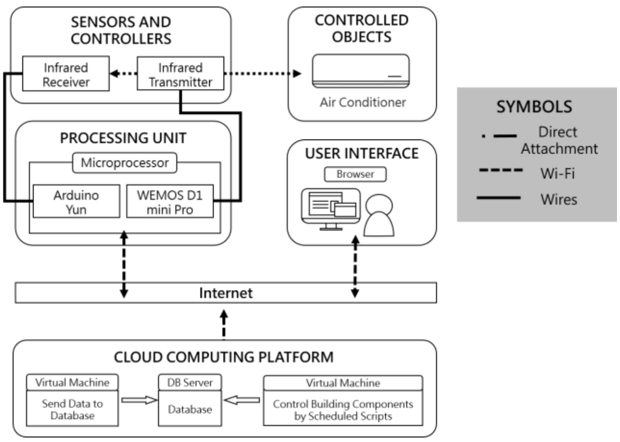

Figure 2. The system structure of thermal environment control

The user interface displayed the latest air conditioner temperature set point and wind speed. When changes were made, the code will swap out the characteristic time intervals to regenerate the corresponding infrared signal. It then emitted it through the infrared LED transmitter, and the signals were expected to be captured by the air conditioner and the Arduino Yun. After decoding and filtering the signal, the code on Arduino Yun then POST sensor reading to another web server on the cloud computing platform. The targeted website server would execute a PHP code that reads the information containing in the URL string and passed the sensor readings to the database.

Other than establishing the ability to control from outside of space and gathering occupants' action records, we also deployed multiple thermocouples and other sensors to gather indoor environment data as described before, so we knew what the indoor environmental condition was when the occupants happened to take the actions. The beeper in the air conditioner was replaced with a blue LED to avoid the disturbance caused by automated control.

3.3 Shading Control

The targeted shading system in our study was Venetian blinds which controlled the amount of sunlight entering the environment and controlled the glare by its slats. Venetian blinds system consist of slats, gears, a fixed frame, a drawstring, and a rotating rod. The drawstring's function was for adjusting the height of the blinds. When released, the louver would cover the entire window. In this study, we fixed the blind's height to the full-covered position in order to reduce the complexity of the shading control system. The rotating rod's function was for adjusting the angle of the slats, which would also change the amount of sunlight entering the space. The slats angle was the primary control variable in this system.

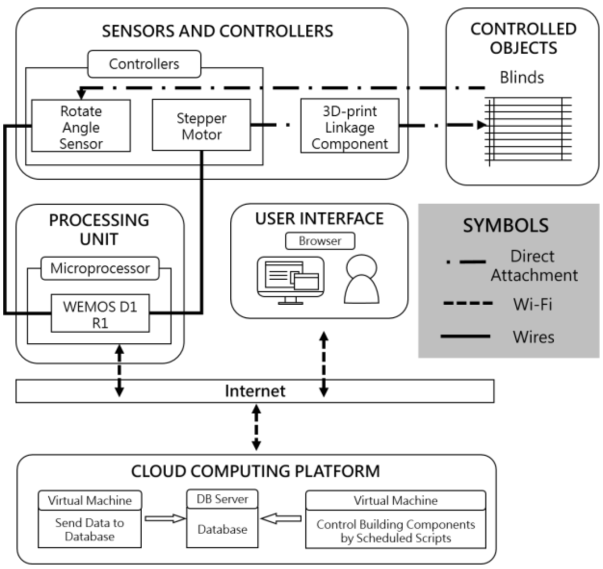

Figure 3. The system structure of shading control

Figure3 shows the system structure of shading control. We connected the rotating rod of the shades to a stepper motor by a customized 3D printed device. Then in the same WEMOS D1 R1 microprocessor, we installed an angle sensor and put it on top of the slats to measure the three axial displacements. The readings from the angle sensors were used to tell the stepper motor when to stop. The slats angle operation procedure is shown in Figure 4.

A web server was also hosted on this WEMOS D1 R1 board. By accessing the web server, the users and the system can control the shading system directly. When a command was sent, WEMOS D1 R1 would execute the code to trigger the motor, and it would stop when the slats reached the desired angle. At the same time, an URL containing the desired angle was POST to the cloud server. An infrared receiver was also installed, and programmed to couple with a remote controller and to provide another control option. Consequently, the shades can be controlled by either infrared signals or web commands.

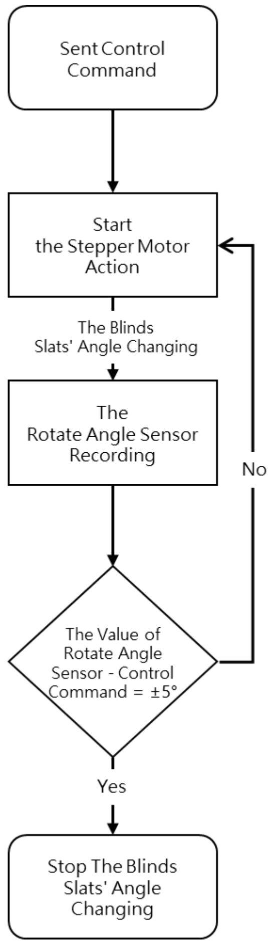

Figure 4. The slats angle operation procedure

4 Case Demonstration

In this section, we demonstrated the system's capabilities by deploying it into an existing space. The following session showcased the function of the current building management platform, the control implementation, and the environmental data and the occupants' feedback can be collected by the system.

4.1 Introduction The Testbed Environment

The testbed was set up in Taipei, Taiwan. The city is located 121 degrees east longitude and 25 degrees north latitude, with an average annual temperature of 23.6 ℃ and an average annual average relative humidity of 76%. The climatic conditions are classified into a subtropical monsoon climate, which means high temperature and rain in summer and warm and humid in winter than in the same latitude.

Figure 4 presents the configuration of the testbed. The size of the testbed was 6.1 m × 2.4 m × 2.6 m (length × width × height). The testbed had a door (90 × 200cm) and three windows on the west wall and three windows on the east wall. Each window is 110 × 90cm. The window to wall ratio for east wall and west wall is around 18.8%.

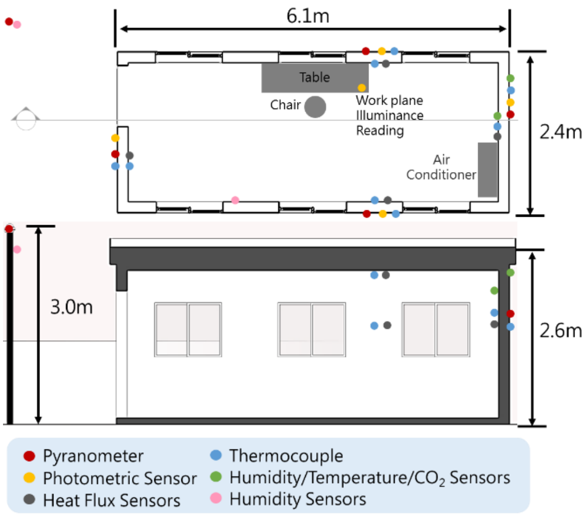

Figure 5. The Testbed Environmental Sensors Arrangement Position

The existing components targeted in this study were a split air conditioner and Venetian blinds. Only the west side of windows and blinds can be altered, while the shades on the east side were all closed during the experiments period in order to simulate the situation of a typical individual office. The table for the occupant was placed in front of the middle west window, and there was a photometric sensor to read work plane illuminance on the table.

We recruited several occupants to test the environmental comfort in the testbed. In order to observe the occupants' activities and actions, we maintained testbed's starting conditions similarly before the occupant entered the testbed by automated control. For this purpose, we set up a virtual machine program to execute the control sequence at 01:00 am every day, so the Venetian blinds would be fully open, and the air conditioner would be off when occupant entered the room. Before the test, we told the occupant that we gave him/her the full control of targeted building components.

4.2 Occupant's Behavior Related Thermal Comfort

We designed a test to gather occupants' response to the changes in the indoor environment and to demonstrate the system's capability to control from outside of the space. Figure 6 shows a comparison between a day with the air conditioner on (top) and a day with the air conditioner off (bottom). The vertical axis on the left side indicated the temperature, and the vertical axis on the right side indicated the passive infrared (PIR) sensor - value 0 indicates occupant was not there, value one indicates occupant was in the space. In the case with the air conditioner on, it was evident that the air conditioner is hunting the set point in comparison to the case with the air conditioner off – which has a smooth curve. Therefore, sometimes we do not need action response sensors to capture occupant behavior. The virtual sensor can be developed by analyzing the data.

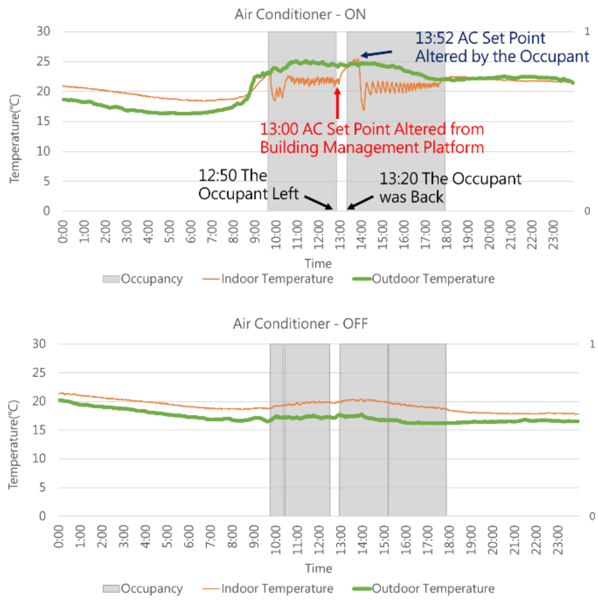

Figure 6. Occupant and Air Conditioner Interactions

The test process was to adjust the temperature setpoint while the ambient temperature is stable in order to recognize their thermal tolerance and to develop energy-saving strategies. Figure 6 (top) shows that the adjustment was sent at around 13:00 when occupant left for lunch but forgot to turn off the air conditioner. The system raised the set point by 4 degrees. The occupant was not happy about this adjustment. While when the occupant came back, the temperature set point of the air conditioner was not immediately adjusted, the occupant decided to lower the setpoint 30 minutes after entering the room. From the case where the air conditioner was off, we can find that the occupant's preferred temperature range is approximately between 21 and 23 degrees. The energy-saving adjustment, unfortunately, caused the occupant discomfort and resulted in occupant's unexpected action by adjusting the set point to somewhere even lower than the set point before adjustment. The presented result was a compelling case that the control algorithm developer should pay attention to. It also demonstrated the importance of building management system and its remote control function.

4.3 Occupants' Behavior Related to Visual Comfort

This session demonstrates the capability of the system's shade adjustment and feedback from occupants. Figure 7 shows the results of shade status and occupant's behavior on a sunny day and a cloudy day. The vertical axis on the left is the illuminance level, and the vertical axis on the right is the slat angle. The gray block was the interval that the occupant was in the space.

In the sunny day case, the system read the report from weather prediction and knew that the day was sunny beforehand. It then adjusted the slat angle to 40 degrees in advance through the management platform before the occupant entered the testbed for capturing the occupant's reaction. Note that: the slat angle is zero degrees when the slat is horizontal, -70 degrees when it rotated towards the ground and 70 degrees when it rotated towards the sky.

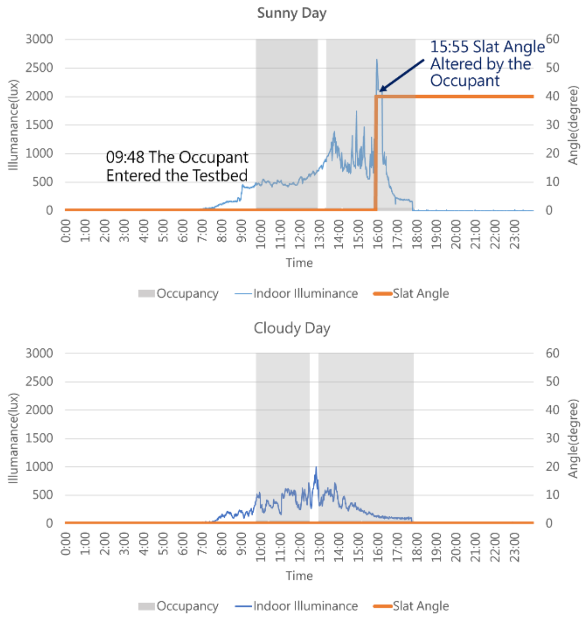

Figure 7. Occupant and Air Conditioner Interactions

From Figure 7, we knew that once the occupant entered the space, the occupant found that the indoor light is insufficient. The good news is that instead of turning on the light, this occupant chose to change the slat angle to 20 degrees. The occupant adjusted the slat angle again at 15:55 to reduce the amount of light coming in and maintain visual comfort because it is the time when direct light can transmit through the gap between the slats from what we found in Figure 7. Unfortunately, the sensor here was placed on the work plane instead of the vertical plane. It was a lesson learned from testing and can be used to adjust the set up for control.

5 Discussion

Although this system is designed to be easy to build and easy to use, there are still some challenges to overcome when adapting our system to other cases.

We need a knowledge base for setting up remote and automated control for different existing building components. There are many different types of building components with different communication protocols and different shapes, and the component with the same communication protocol might adopt different ways to decode the signal. For example, the infrared signals differ from one air conditioner to another air conditioner. 3D printed adapter for connecting step motors and rod also needs to be redesigned for different rod shape.

After all, we are looking forward to expanding our system to include more building components such as fans, stand-alone heaters, etc. The industry standard should be established in the future, and a more natural way to build accessories such as 3D printed adapter should be studied. We also need to find a more efficient way to deploy the control logic that requires less experiencing on programming.

6 Conclusion

We built a building management platform in an existing space to verify the feasibility and effectiveness of the overall system structure. The preliminary results and demonstration provided a crucial foundation for the subsequent implementation of intelligent systems and equipped a testbed that can be used for other behavior studies and control studies in the future.

The building management platform is composed of many different hardware devices and software services. The low-cost sensors and microprocessors were selected to reduce the implementing cost. The demonstration showed that the low-cost hardware devices could be used as a good terminal device for intelligent systems and carefully designed and commissioned devices could achieve good stability and accuracy. The low-cost concept would benefit buildings that are in the operation and maintenance phase, and make the system more acceptable in the market.

The concept of getting feedback from occupants can help the manager and research communities understand occupants' need better. The continuous monitor of the indoor environment can help the managers check if the building components such as air conditioner and the blind system can achieve designed service level. The cloud-based platform makes the commission process and other services more flexible.

In the past, the control of the building environment and the management and maintenance of building components strongly depend on the experience of the building managers, which usually led to an unnecessary waste of energy and increased the difficulty to deploy new control algorithms. This study showed that we have the potential to learn more and occupants and to run advanced energy saving control logic by introducing the cloud-based building management platform into the existing building space.

Acknowledgments

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