Occupancy Estimation in Smart Building using Hybrid CO_2/Light Wireless Sensor Network

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Abstract: Smart building, which delivers useful services to residents at lowest cost and maximum comfort, has gained increasing attention in recent years. A variety of emerging information technologies have been adopted in modern buildings, such as wireless sensor networks, internet of things, big data analytics, deep machine learning, etc. Most people agree that a smart building should be energy efficient, and consequently, much more affordable to building owners. Building operation accounts for major portion of energy consumption in the United States. HVAC (heating, ventilating, and air conditioning) equipment is a particularly expensive and energy consuming of building operation. As a result, the concept of "demand-driven HVAC control" is currently a growing research topic for smart buildings. In this work, we investigated the issue of building occupancy estimation by using a wireless CO_2 sensor network. The concentration level of indoor CO_2 is a good indicator of the number of room occupants, while protecting the personal privacy of building residents. Once indoor CO_2 level is observed, HVAC equipment is aware of the number of room occupants. HVAC equipment can adjust its operation parameters to fit demands of these occupants. Thus, the desired quality of service is guaranteed with minimum energy dissipation. Excessive running of HVAC fans or pumps will be eliminated to conserve energy. Hence, the energy efficiency of smart building is improved significantly and the building operation becomes more intelligent. The wireless sensor network was selected for this study, because it is tiny, cost effective, non-intrusive, easy to install and flexible to configure. In this work, we integrated CO_2 and light senors with a wireless sensor platform from Texas Instruments. Compare with existing occupancy detection methods, our proposed hybrid scheme achieves higher accuracy, while keeping low cost and non-intrusiveness. Experimental results in an office environment show full functionality and validate benefits. This study paves the way for future research, where a wireless CO_2 sensor network is connected with HVAC systems to realize fine-grained, energy efficient smart building.

1. INTRODUCTION

According to U.S. Department of Energy (DOE), annual energy cost of buildings in United States reaches 200 billion. Much of building energy is consumed in heating, ventilation and air conditioning (HVAC) processes. It has been reported that 30% of building energy dissipation is inefficient and unnecessary. Moreover, energy usage in residential buildings will rise 27% by the year 2025. Despite technology advance in HVAC equipment such as variable speed fan and blower, there is still plenty of room left to optimize energy efficiency of building and drastically cut energy bill. For instance, regardless building vacancy or occupancy, current HVAC systems usually operate on a fixed schedule (e.g., ON mode from 8AM to 5PM). It is common that HVAC systems keep running in active ON mode, while certain thermal zones or even the entire building is empty. In order to avoid this kind of energy waste, researchers have proposed to match HVAC operation schedule with working schedule of building users (Yang, 2014) (Leavey, 2015).

To promote building energy efficiency, U.S. government and national laboratories have launched a series of research initiatives and projects to establish smart building. Smart building, often referred to as intelligent building, is a multidisciplinary research topic. It involves cutting-edge techniques and innovations from fields of civil, mechanical, electrical, and computer engineering. The ultimate goal of smart building research is to provide the lowest energy usage, the highest service and quality of life to building users or residents through the use of emerging technologies, such as wireless sensor network, big data analytics, deep machine learning, or internet of things (IoT), smart grid, and so on. The success of smart building leads to more comfortable and healthy environment, and improves creativity and productivity of building occupants.

In addition to accommodation, smart building also provides extra high-end services to satisfy residents' needs. For example, indoor positioning technique estimates location and trajectory of each occupant, and then guesses what activity is going on and what expected service would offer. Based on preference of each building user, human-oriented service is triggered, such as intelligent lighting/temperature/door/window/household appliance control. For instance, in shopping centers, Wi-Fi based indoor localization technology has been used for shopping assistance and goods recommendation (Chon, 2011). Recently, a Li-Fi assisted calibration approach has been proposed to refine the accuracy of Wi-Fi based indoor localization method (Huang, 2016). A number of high-tech companies are working on smart building systems and applications, such as Johnson Controls, GE, IBM, Google, Samsung, Intel. It is estimated that that in the next decade, most of new homes will come equipped with certain intelligence in areas of HVAC automation and internet of things.

Among all aforementioned technologies, wireless sensor network is of particular significance. As foundation of smart building, it is closely related with other emerging technologies. Wireless sensor network is composed of numerous distributed autonomous sensor nodes. Each node monitors or senses ambient environment, such as humidity, temperature or air quality. Ambient information collected from each node is transmitted to a central computer via a wireless communication protocol, such as Zigbee or Z-Wave. Through collaborative manner, hundreds or thousands of sensor nodes are able to perform a variety of fine-grained environmental sensing tasks, such as building temperature monitoring (Huang, 2010) (Huang, 2011), building fire hazard detection (Huang, 2012), indoor air quality monitoring (Bhattacharya, 2012), or building energy monitoring (Tachiwali, 2007) (Magpantay, 2014). Due to the huge amount of data points acquired from fine-grained instrumentation, wireless sensor network helps to understand dynamics of indoor temperature or air quality, and sustains machine learning and big data analytics, which applies statistical theory to extract inherent features or characteristics of building operation behavior (Huang, 2012)(Alsheikh, 2014). Besides, wireless sensor network is indispensable to connect household meters, instruments and appliances to internet of things (IoT).

Wireless sensor network has several distinctive advantages over traditional wired infrastructure. First, wireless sensor network is cost effective, since there is no need of purchasing or installing long connection wires or cables. Particularly, labor cost for cable installation or construction work is eliminated, which is usually more expensive than the cost of cable itself. As the implementation cost of a smart building greatly depends on what smart functions a user would like to have, a low cost infrastructure is attractive. Second, as being composed of commercial-off-the-shelf devices, wireless sensor network is easy to install, configure, expand and update. After reading an instruction manual, users can set up the entire system without any special training or expertise. Because data communication is carried out through radio frequency electromagnetic wave, system reconfiguration or expansion does not need to cut old connection cables or route new cables. Third, due to technology advancements in semiconductor fabrication and electronics design, nowadays the size of a wireless sensor node is miniature in the range of a few cm^2 or cm^3. Therefore, the presence of indoor wireless sensor network is not noticeable, and hence does not cause much inconvenience or discomfort to the daily life of building residents (Lu, 2010). Last but not least, wireless sensor network is well applicable in existing old buildings, where it is hard or even impossible to setup wired sensor infrastructure due to the prohibited cost of required construction work. Alternatively, wireless sensor network provides a feasible and inexpensive to retrofit existing energy-inefficient buildings.

Nowadays, a wireless sensor node typically consists of four main elements: sensor, microprocessor, radio transceiver, and power supply. Sensor performs dedicated sensing task and outputs measurement results to microprocessor. Microprocessor is a powerful control unit that manipulates data processing and coordinates the entire system. Radio transceiver is a block that receives and transmits data packets via a RF antenna. Battery is usually chosen as power supply to offer electrical energy to sensor, microprocessor and radio transceiver. Prior researchers have studied to utilize energy harvesting techniques to prolong the lifetime of wireless sensor node (Niyato, 2007) (Lu, 2011). Energy harvesting techniques convert environmental energy into electrical energy to replenish power supply. For example, wireless sensor network has been demonstrated to be driven by indoor lighting energy and thermal gradient in buildings without any battery integration (Huang, 2010) (Huang, 2011).

It is widely admitted that the number of occupants is critical to the success of demand-driven HVAC. As will be reviewed in next section, although a variety of room estimation or reasoning approaches have been presented for smart buildings, so far, there is no viable solution available to satisfy all requirements of low cost, high accuracy and non-intrusiveness. To deal with this design challenge, this work aims to develop and implement a combination of hybrid sensors. In this work, a miniature CO_2 sensor and light sensor are integrated with a wireless sensor platform from Texas Instruments. Both hardware configuration and software programming are involved. Our proposed scheme is not intrusive, hence greatly protects privacy of building users. The entire system implementation is versatile and flexible, ease of functional expansion and communication to existing HVAC operation systems.

The rest of this paper is organized as follows. Section 2 reviews related works of building occupancy detection/estimation methods. Section 3 describes the proposed system architecture, characteristics of each building block and experimental results. In addition, a comprehensive discussion and comparison with related references in literature is elaborated. Finally, Section 4 concludes the paper.

2. RELATED WORKS

Effectiveness of demand-driven HVAC control heavily depends on accurate occupancy information and measurement. Occupancy information has a big impact on dynamic optimization of HVAC operation parameters and set points. Numerous types of sensors have been used in literature in the past decade to detect occupancy information. In this section, we will briefly overview the advantages and drawbacks of these existing approaches.

Passive Infrared (PIR) motion sensor is popular, due to its low cost and high reliability. PIR sensors are commonly used for automatic lighting control. Through infrared light radiation, it detects if a person has moved in or out of an area. Unfortunately, PIR sensors cannot detect actual occupancy (Emmerich, 2001) (Lam, 2009) (Agarwal, 2010). Later, RFID technology is proposed for building occupancy detection (Lee, 2008) (Li, 2012). Experimental results have validated this idea with a good detection accuracy. However, since each RFID tag is associated with a specific person, the location and trajectory of an occupant wearing a RFID tag is easily observed and tracked. Hence, one major short-coming of this approach is occupants' willingness to wear RFID tags due to privacy and security concerns (Ekwevugbe, 2013). Furthermore, researchers reported detection accuracy of using RFID tags is coarse-grained (Li, 2012). Alternatively, when a person stays in a room, noise or sound is usually made. Therefore, voice recognition is another potential technique to predict building occupancy information. For example, a high-performance acoustic processing unit has been developed (Kattanek, 2014). It is a dedicated field-programming gate array (FPGA) running acoustic recognition and processing algorithms. A variety of acoustic recognition algorithms has been implemented for energy-efficient smart buildings (Uziel, 2013) (Kelly, 2014) (Huang, 2016). Audio-based occupancy processing is not expensive, since the basic hardware resource is composed of a microphone and a microcontroller. Because no RFID tags are required to wear, it is non-intrusive and user-friendly. The drawback is its detection performance largely depends on the environment where this technique is applied. Detection is more accurate in quiet office buildings than noisy supermarket or restaurant environments. Besides, when people keep silence and no acoustic signal is collected, these audio-processing algorithms are ineffective. Video/image cameras have been presented in monitoring building occupancy of smart buildings (Erickson, 2009) (Benezeth, 2011) (Ahmed, 2013). Yet, cameras cannot be placed in arbitrary locations due to the constraint of line of sight. The resultant high hardware cost and user privacy concern severely impede its wide deployment. Last but not least, the observation of indoor carbon dioxide level has been proposed to predict room occupancy information (Sun, 2011) (Nassif, 2012). This method is low cost and not intrusive. CO_2 levels represents a roughly linear relationship with the number of occupants in a space. One drawback of this method is that CO_2 level fluctuates with HVAC operational condition (Labeodan, 2015), so the exact relationship between CO_2 level and occupancy information varies case by case. This drawback degrades the accuracy of occupancy detection using CO_2 sensors.

The growing popularity of smart buildings and increasing concerns on personal privacy, are expecting new low-cost, high-accuracy, and non-intrusive occupancy detection schemes to meet these rigid requirements. To address this goal, we propose a hybrid detection method using the combination of CO_2 and light sensors. Unlike video/image cameras, light sensors only report the illuminance level of light situations, and hence privacy concern is completely gotten rid of. With the assistance of light sensor, the hybrid detection method achieves better accuracy than using CO_2 sensor alone. We integrate this hybrid sensor with a wireless sensor node, and collect and visualize the measurement data for performance analysis.

3. SYSTEM ARCHITECTURE AND MEASUREMENTS

The proposed hybrid CO_2/light sensor network is shown in figure 1. Entire system consists of a few proposed hybrid sensors and a central control computer. The measurement results of CO_2 and light levels are transmitted to the central control computer via wireless communication. The wireless sensor node is a commercial-off-the-shelf device from Texas Instruments (TI). This wireless sensor node consists of a low power microcontroller (MSP430™) and an analog-to-digital converter (ADC). The output pins of CO_2 and light sensors are connected with user input pins of wireless sensor node. Thus, the measurement data are given to the internal ADC and microcontroller of wireless sensor node, and then are sent out to the central control computer through the radio transceiver. Miniature CO_2 sensor from COZIR and light sensor from Adafruit are selected for the proposed system. The details of CO_2 and light sensors will be described later.

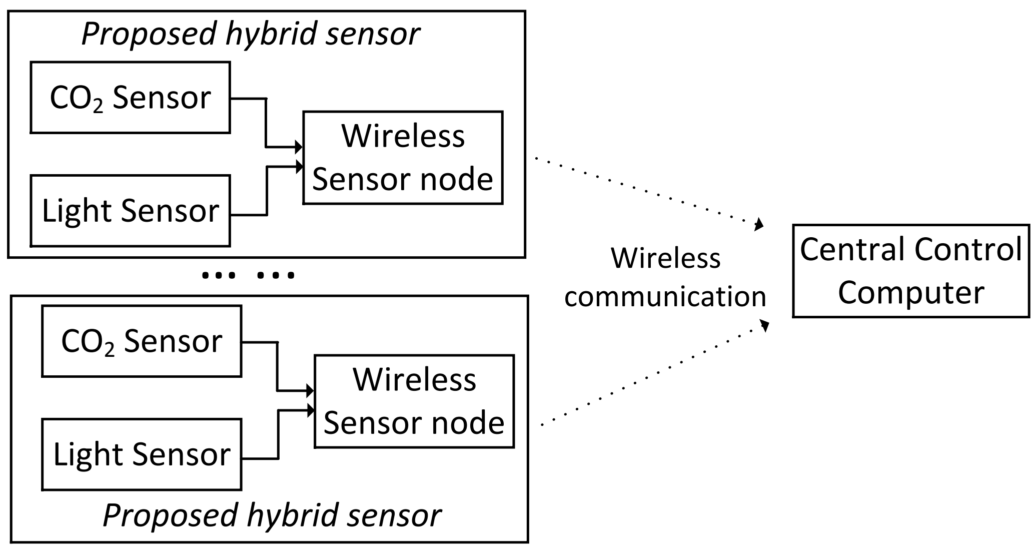


Figure 1. Conceptual system architecture for building occupancy estimation

Figure 2 depicts the prototype implementation of the proposed system architecture. It is obvious that the CO_2 and light sensors are connected with TI wireless sensor node through wires. The control computer receives the measurement results via 2.4GHz wireless channel. Note the central control computer does not have to be placed very close to the sensor node. According to prior measurement data (Huang, 2010), wireless transmission distance between this sensor node and central control computer can reach up to 16 meters.

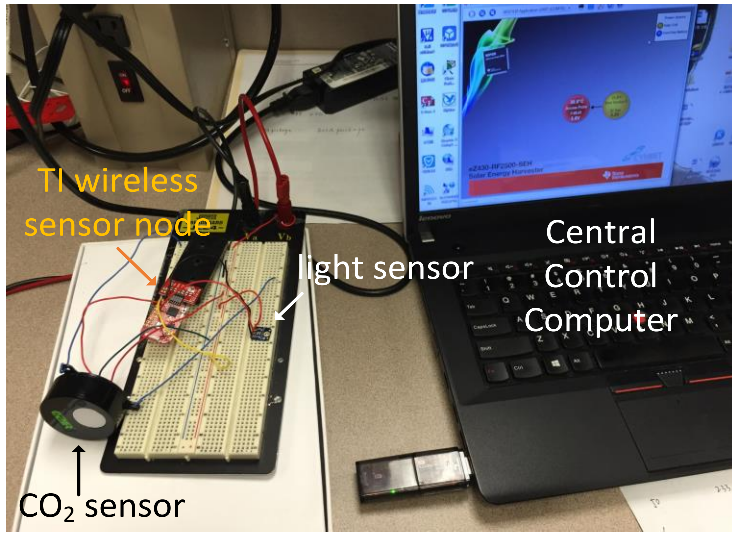


Figure 2. Prototype implementation of the proposed system architecture

This CO_2 sensor is battery powered and has a wide-rage of 0-5,000 ppm. Its output is an analog voltage, which linearly varies with sensed CO_2 level. As a result, output voltage of this CO_2 sensor precisely indicates ambient CO_2 level. Figure 3 plots how the output voltage of a CO_2 sensor responds to timing-varying room occupancy.

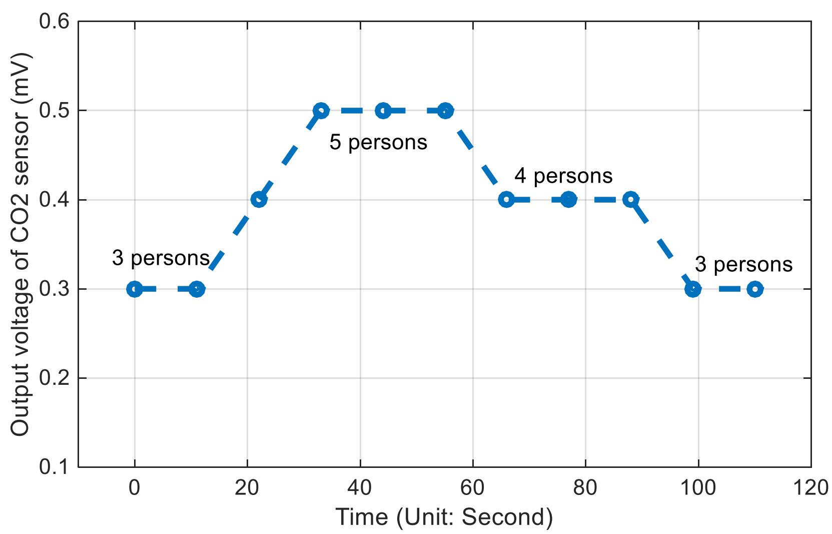
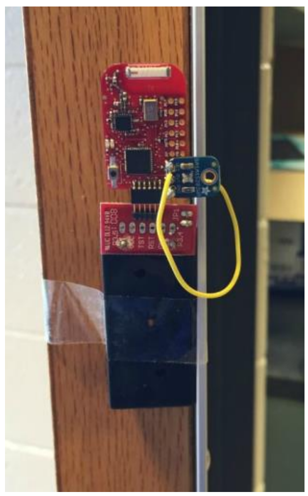
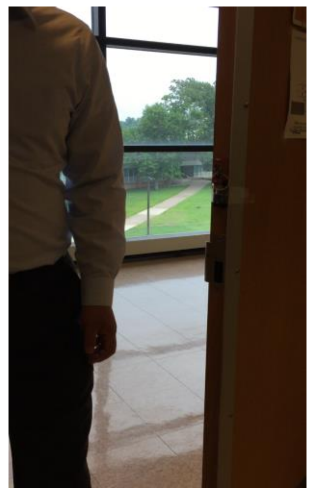


Figure 3. Output voltage of CO_2 sensor vs. time when room occupancy varies 3->5->4->3

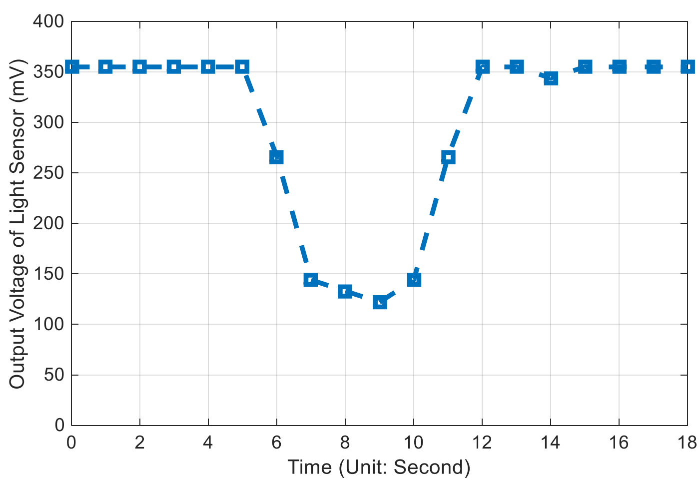
Output voltage of a light sensor represents nearby illumination level in a wide-rage of 0.1 to 40,000 Lux. Its output is a log-scale analog voltage, which changes with illumination level. Thanks to the adoption of a light sensor instead of a video/image camera, users' concern of personal privacy or security is no longer a problem. As shown in Figure 4, when a light sensor is taped on a door frame, once a person walks through the door and blocks lighting, the light sensor will output a deep pulse response to this entrance or exit event.



(a)



(b)



(c)

Figure 4. (a) Experimental setup of a light sensor on the door frame (b) A person walking and passing the door frame (c) Measurement response of a light sensor response to a passing event

In practice, the distance between light sensor and walking person is different. To investigate impacts of this phenomenon, we setup test instruments as shown in Figure 5. A LED lamp is used to mimic lighting source near door frame. The proposed hybrid sensor and a digital illuminance/Lux meter are vertically attached to a hardboard. When distance between the LED lamp and the hardboard is adjusted, ambient lighting condition changes as well as output voltage of the light sensor. Figure 6 plots how the output voltage of light sensor varies with illuminance. It is evident that this curve looks like a logarithmic relationship, which matches the expected log-scale characteristics as mentioned earlier. When lighting is blocked by a person passing through a door frame, the resultant illuminance is very low and hence the output response of a light sensor rapidly drops to around 100mV.

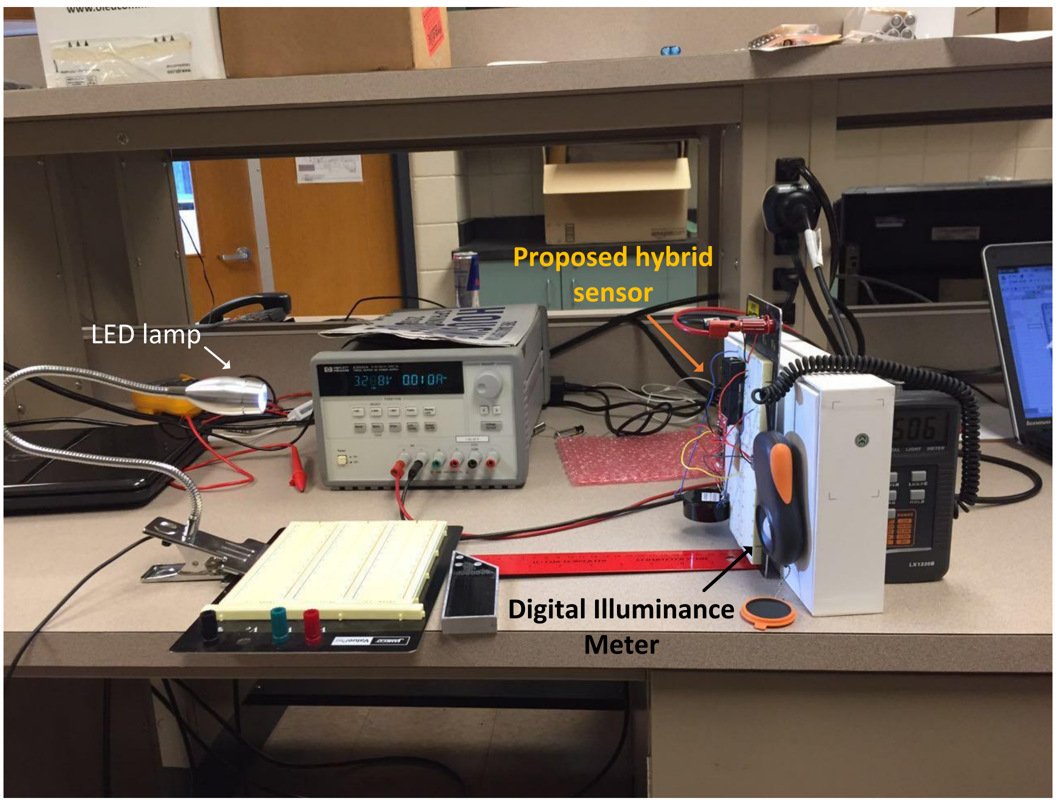


Figure 5. Experimental setup to check response of light sensor under different illuminance conditions

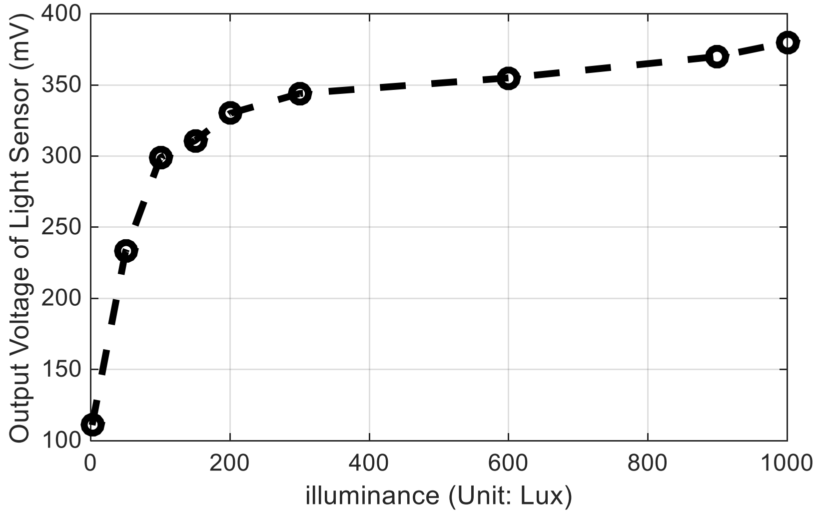


Figure 6. Measured output of light sensor vs. ambient illuminance condition

To verify the proposed hybrid detection method, we carried out experiments in an office building. As shown in Figure 7, once a person walks in or out of a room, the light sensor outputs a pulse response. At *t*=100 second, one person walked into the room, therefore, the measured CO_2 level quickly rose from its baseline. At *t*=900 second, another person entered. At *t*=1000 second, CO_2 level reached its peak point. From *t*=1000 to *t*=1500 second, two persons left this room. Consequently, two pulses were observed and the CO_2 level gradually dropped back to its baseline. It is apparent that the presence of a light sensor refines the detection accuracy, since temporal fluctuations of CO_2 level (e.g., the spikes between 600 to 900 second in Figure 7) may trigger a false estimation. Because these temporal fluctuations do not trigger a pulse response of light sensor, temporal fluctuations will be viewed as noise and ignored. In this way, the proposed hybrid CO_2/light sensor leads to more accurate occupancy detection than only using CO_2 sensor.

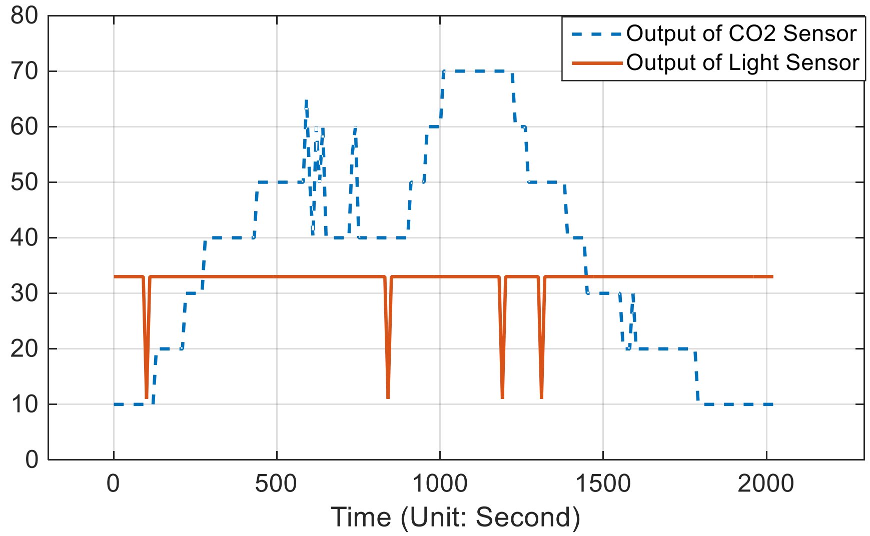


Figure 7. Measured response of hybrid sensors when two occupants walk in and out of a room

Table 1 summaries the existing building occupancy detection mechanisms in literature. These established approaches include passive infrared (PIR), radio-frequency identification (RFID), acoustic recognition, image camera, and CO_2 sensor. PIR sensor and image camera involve high expense. RFID and image camera are not user-friendly in terms of privacy and security. Detection performance of standalone acoustic recognition or CO_2 sensor varies with enviroment and suffers from large uncertainty due to temporal noise or fluctuations. In contrast, our proposed hybrid design is low cost, since the price of a light sensor is less than \$5. A light sensor successfully collaborates with a CO_2 sensor and avoids false reasoning of occupancy information. A light sensor is also non-intrusive, since its output only reports ambient lighting condition and no any image or video is captured.

Table 1. Summary of common building occupancy methods

References	Mechanism	Cost	Intrusive	Occupancy Detection Performance
(Emmerich, 2001) (Lam, 2009) (Agarwal, 2010)	Passive infrared	High	Yes	Failure
(Lee, 2008) (Li, 2012)	RFID	Low	Yes	Coarse-grained
(Uziel, 2013) (Kelly, 2014) (Huang, 2016)	Acoustic recognition	Low	No	Varying with environment Failure when people keep silence
(Erickson, 2009) (Benezeth, 2011) (Ahmed, 2013)	Image camera	High	Yes	Failure when line of sight is not satisfied
(Sun, 2011) (Nassif, 2012) (Labeodan, 2015)	CO_2 sensor	Low	No	Accuracy depends on case by case, false detection may exist due to CO_2 level fluctuation
This work	CO_2 + Light	Low	No	Improved accuracy with the assistance of light sensor

4. CONCLUSION

Smart building has great potential to increase comforts and quality of life, while significantly reducing energy usage and cost. Room occupancy is important information, which helps to realize energy-efficient demand-driven HVAC operation. Existing building occupancy detection or estimation methods can not meet all the requirements of low cost, high accuracy and privacy. Therefore, in this work, a hybrid CO_2/light sensor is proposed for more accurate occupancy estimation. Our proposed solution is cost-effective, non-intrusive and suppresses temporal disturbances. The entire system has been assembled and tested experimentally in an office building. The measurement results validate the functionality and benefits.

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