Experimental evaluation of occupancy lighting control based on low-power image-based motion sensor

Takuya Futagami and Noboru Hayasaka

Department of Engineering Informatics, Osaka Electro-Communication University, Neyagawa, Japan

ABSTRACT
Occupancy lighting control, which is used to turn lights on/off based on the occupancy state measured by an occupancy sensor, is a popular and effective type of automatic lighting control. This paper clarifies the effectiveness of occupancy control based on a low-power image-based sensor, which measures only the occupancy state by applying an image processing technique to visible images, implemented on a low-cost single-board computer. We found that the rated power consumption of the low-power image-based sensor was 69.50% or less than that of commercial image-based sensors. In addition, the low-power image-based sensor increased the total comprehensive energy-saving rate of the occupancy control by 5.38% or more compared with a commercial PIR sensor and commercial image-based sensor. Further analysis of the effectiveness of the low-power image-based sensor is provided herein.

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1. Introduction
Lighting accounts for a considerable portion of global energy consumption, comprising 10% or more of the total energy consumed in residential and non-residential environments in the United States [1,2]. Therefore, the energy consumption from lighting should be reduced to achieve zero energy homes and buildings [3,4].

A popular and effective lighting control is occupancy control, in which lights are turned on/off based on the presence of the occupants (workers or residents in a room) as measured by an occupancy sensor (e.g. passive infrared (PIR) or image-based sensors) [5,6]. A PIR sensor, which is widely used owing to its cost effectiveness, measures the changes in infrared radiation received through a Fresnel lens [7].

The occupancy control turns on the lights when the sensor detects occupants and turns off the lights after the sensor detects that no occupants have been continuously present for a preset time. Because an occupancy sensor cannot perfectly measure an occupancy state, a time delay between the detection of no occupants and the turning off of the lights is required to avoid a false-off (i.e. turning off the lights in an occupied room) [5,6]. However, the time delay decreases the energy-saving effect of the occupancy control because the light remains turned on for a preset time in an unoccupied space. Thus an occupancy sensor that can decrease the time delay while avoiding a false-off is required if we want to increase the energy-saving effect [5].

Image-based sensors, which apply an image processing technique to visible images [8–10], are expected to increase the energy-saving effect by decreasing the time delay while avoiding a false-off. Two widely applied image processing techniques for the occupancy measurement are motion detection, which tracks the change in appearance in an image [11,12], and image-recognition, which utilizes a classifier based on machine learning [13,14]. Frame difference, background subtraction, and optical flow are well-known motion detection methods, whereas classifiers such as a support vector machine (SVM) or deep neural network (DNN) are primarily used to construct image recognition.

The measurement accuracy for occupants depends on the image processing technique that is used. However, commercial image-based sensors utilize frame difference, which calculates the differences between consecutive captured images [10]. This utilization is based on the fact that the frame difference, which is categorized as a simple and fast method, can be easily implemented on a low-power and low-cost embedded board compared with other image processing techniques [15]. On the basis of such commercialization trends, in this work, we assume that image-based sensors utilize the frame difference.

The time delay of an image-based sensor tends to be set to a smaller value (e.g. 5 min) than that of a
PIR sensor (e.g. 15 min) [6,9,16–18]. This tendency mainly stems from the image-based sensor increasing the measurement accuracy for occupants with slight motions [19].

However, the rated power consumption of a commercial image-based sensor is considerably greater than that of a PIR sensor [17,20]. In [17], it is suggested that, compared with commercial PIR sensors, commercial image-based sensors do not decrease the comprehensive energy saving, which is based on the energy consumption of both the lights and the sensors. Focusing on the specifications in [21–23], commercial image-based sensors typically measure not only the state of occupancy but also the number of occupants or their activity level. Measurements that are not used in the occupancy control might increase the rated power consumption of the commercial image-based sensor. While there have been previous studies on occupancy control that evaluated the energy-saving effect of the commercial image-based sensor, the energy-saving effect of a low-power image-based sensor that measures only the occupancy state has not been sufficiently examined. It is important to evaluate the energy-saving effect of the low-power image-based sensor so as to develop and commercialize the next generation of image-based sensors that can increase the comprehensive energy saving. Thus, in this study, we clarify the energy-saving effect of occupancy control based on the low-power image-based sensor.

In [24], an image-based sensor was implemented on a Raspberry Pi, which is a single-board computer. Furthermore, an occupancy sensor implemented on a single-board computer is expected to be widely utilized for occupancy control owing to its cost effectiveness and energy efficiency [5]. Therefore, on the basis of a literature review, we utilize a low-cost and energy-efficient single-board computer to implement the low-power image-based sensor and achieve the aforementioned purposes of the present study.

Because a single-board computer has limited computational power [25], it is important to evaluate the computational time when conducting an occupancy state measurement. However, the computational time of the occupancy state measurement implemented on a single-board computer was not evaluated in [24]. Therefore, we conducted an experiment to carefully examine the computational time of the occupancy state measurement implemented on a single-board computer.

In Section 2 of this paper, we provide an overview of the conventional occupancy control based on PIR sensors. In Section 3, we discuss the low-power image-based sensor. In Section 4, we report the experiment we conducted in an actual home environment and discuss the results, and in Section 5, we broaden the discussion for greater generalizability. We conclude in Section 6 with a brief summary and mention of future work.

2. Conventional occupancy control

This section describes the conventional occupancy control based on PIR sensors. Sections 2.1 and 2.2 overview and review the occupancy control and the PIR sensor, respectively.

2.1. Occupancy control

Occupancy control is used to turn lights on/off based on the occupancy state measured by the occupancy sensor, as depicted in Figure 1. In practice, the occupancy sensor tends to be mounted on the ceiling but not the wall, as ceiling-mounted sensors are not obstructed by furniture or occupants [26].

Figure 2 shows a flowchart of the occupancy control system, which turns on the light when the sensor detects an occupant and turns off the light after the
sensor has detected that no occupants have been continuously present for a preset time. Because the occupancy sensor cannot perfectly measure the occupancy state, a time delay between the detection of no occupants and the turning off of the lights is required to avoid a false-off [5,6].

A shorter time delay causes a false-off, which decreases the visual comfort of the occupants [5], whereas a longer time delay decreases the energy-saving effect by increasing the time during which the light remains on in an unoccupied space. Thus time delay is an important parameter in terms of both the visual comfort of the occupants and the energy-saving effect. Because the time delay needed to avoid a false-off depends on the measurement accuracy of the installed occupancy sensor, the accuracy should be increased to enhance the energy-saving effect without incurring a false-off.

2.2. PIR sensor

PIR sensors measure the occupancy state based on the change in infrared radiation emitted by the human body [7]. The PIR sensor is widely utilized as an occupancy sensor owing to its cost effectiveness and power efficiency. However, it suffers a decreased measurement accuracy of occupants with small (arm- and hand-level) motions [27–29]. For example, in [29], it was observed that the PIR sensor detects the arm-level motion at a rate of only 35% on a median. To enhance the energy-saving effect without a false-off, an occupancy sensor that can decrease the time delay without a false-off is required [10,16,19].

3. Low-power image-based sensor

This section describes the low-power image-based sensor, the effectiveness of which we evaluate in comparison with the commercial PIR sensor and commercial image-based sensor. The low-power image-based sensor measures only the occupancy state and is implemented on a single-board computer so as to decrease the power consumption compared to a commercial image-based sensor. Sections 3.1 and 3.2 overview and review the occupancy state measurement algorithm of the low-power image-based sensor and single-board computer, respectively.

3.1. Occupancy state measurement algorithm

Image-based sensors measure the occupancy state based on the images captured by a visible camera [8–10]. As an occupancy state measurement algorithm, the commercial image-based sensor typically uses the frame difference [10]. Thus the low-power image-based sensor also utilizes the frame difference as the occupancy state measurement algorithm.

The frame difference proposed in [8] is assumed to be applied for the occupancy control. In addition, since this frame difference is implemented on a single-board computer in [24] to provide a real-time occupancy measurement, we expect it to be effective. Thus the frame difference [8] is assumed to be utilized for the low-power image-based sensor. Note that the commercial image-based sensor is also assumed to utilize this frame difference.

The motion of the occupant incurs a difference in the appearance between the previous and current images (Figure 3 a and b, respectively). The frame difference focuses on the subtracted image (Figure 3 c), which compares the current image with the previous image. The intensity of the subtracted image at pixel position $n$ is represented by

$$x'_n = |x_{n-1}^t - x_n^t|,$$

where $x_{n-1}^t$ and $x_n^t$ denote the luminance value of the previous and current images, respectively. The pixel positions with luminance values that are sufficiently different between the previous and current images are indicated by the thresholded subtracted image, as shown in Figure 3(d). The intensity of the thresholded subtracted image is given by

$$\bar{x}_n = \begin{cases} 1 & (x'_n \geq T_x) \\ 0 & \text{(Otherwise)} \end{cases},$$

where $T_x$ denotes the threshold parameter to determine whether the luminance values are sufficiently different between consecutive images. The occupancy state is determined on the basis of the ratio of the number of pixels with luminance values that are sufficiently different between consecutive images to the number of all pixels. The ratio is represented by using the thresholded
subtracted image as

\[ r = \frac{\sum_{n=1}^{N} \tilde{x}_n}{N}, \]

where \( N \) denotes the number of all pixels. When the ratio is larger or smaller than a threshold value \( T_r \), the low-power image-based sensor determines the occupancy state as occupied or unoccupied, respectively.

### 3.2. Single-board computer

A single-board computer is built on a single circuit board and provides the basic features of a computer. Ever since the Raspberry Pi was commercialized in 2012 [30], the single-board computer has been widely used in control and monitoring applications [31], and its lower cost and superior power effectiveness compared to smartphones, laptops, and desktop computers have been demonstrated [32].

Although there are several types of single-board computer currently on the market, including Raspberry Pi, Orange Pi, and BeagleBoard, the Raspberry Pi tends to be superior in terms of cost, power consumption, and computational power [33]. Furthermore, the frame difference [8] has been effectively implemented on a Raspberry Pi 3 model B, which was commercialized in 2017 [34], in [24]. Therefore, in this study, we also implement the frame difference on a Raspberry Pi 3 model B to construct the low-power image-based sensor. The Raspberry Pi 3 model B has an ARM Cortex-A53 of a quad core CPU and 1.0 GB of RAM [34].

### 4. Experiment

In this section, we evaluate the effectiveness of the low-power image-based sensor implemented on a single-board computer, which measures only the occupancy state, through experiments in an actual home environment using the data recorded in [19] and compare it with the commercial PIR sensor and commercial image-based sensor. Sections 4.1 and 4.2 discuss the experimental conditions and results, respectively. Since some of the experimental results in [19] are used in this evaluation, the experiment described therein is referred to as the "preliminary experiment," the findings of which are summarized in Section 4.2.1 to identify the differences from the present evaluation.

#### 4.1. Experimental conditions

##### 4.1.1. Environment

We conducted the experiment in a living room (shown in Figure 4) used by two residents. An LED light (CL6D-5.0 produced by Iris Ohyama, Inc.), the details of which are provided in [35], was mounted on the ceiling. The rated power consumption, which shows the maximum power consumption, of a CL6D-5.0 is 33.00 W.

We built a sensing device that records the data of both the sensing results of a PIR sensor module and QVGA sized images (320 × 240 pixels) captured by a camera module at a cycle time of 100 ms. An inter-frame time, which denotes the gap of time while capturing the previous and current images of the frame difference [8], was also set to the value of the cycle time. These settings for the recording image size and the inter-frame time were chosen because they are the most frequently utilized ones and provide the best performance in occupancy activity analysis. Specifically, the QVGA sized images are the most common ones for the recording images of surveillance cameras, as discussed in [36], and the inter-frame time of 100 ms provides the best performance in occupancy activity analysis, as discussed in [37].

The PIR sensor module contained an LHI778 pyroelectric sensor (produced by PerkinElmer, Inc.) and the camera module contained an OV5647 CMOS sensor (produced by OmniVision, Inc.). Because viewing angles of the PIR sensor module and camera module are 120 and 130 degrees, respectively, both the modules are classified as a wide-angle type. We carefully confirmed that the field of views of both the modules included the entire living room. Further details of the two are provided in [38,39]. The sensing device was mounted on the ceiling at the height of 2.15 m and was pointed downward for the reason described in Section 2.1. The sensing results by the PIR sensor module and images recorded by the camera module were used to simulate the occupancy measurement of the commercial PIR sensor and both the commercial and low-power image-based sensors, respectively. The frame difference [8] was utilized as the occupancy state measurement algorithm of the commercial and low-power image-based sensors for the reason discussed in Section 3.1.

To evaluate the occupancy control, we set two types of time delay in the occupancy sensors: a practical time delay \( t_p \) and a minimum time delay \( t_m \). The practical
time delay shows a value that is most frequently used in an actual environment, whereas the minimum time delay shows a minimum value to avoid a false-off during the experiment. The practical time delays for the PIR and image-based sensors were set to 15 and 5 min, respectively, as in prior studies \([6,9,16–18]\). The minimum time delay was determined on the basis of the preliminary experiment results described in Section 4.2.1. In addition, the parameters for the sensitivity of each sensor were determined experimentally on the basis of an adjustment test, which was conducted for 8 h before this experiment. The determined parameters were fixed throughout the experiment.

Table 1 shows the experimental schedule, where the sensing device recorded data for 76.5 h over a period of 8 days. A portion of the data was excluded from the evaluation at the request of the residents. The length of the data was considered sufficient to evaluate the occupancy control because it is 36.5 h longer than the experiment conducted in [17], where the effectiveness of the lighting control was evaluated in an actual office environment.

### 4.1.2. Evaluation methodology

The preliminary experiment evaluated an occupancy measurement accuracy based on F-measure, which is defined as

\[
F\text{-measure} = \frac{2 \cdot \text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}},
\]

\[
\text{Precision} = \frac{\text{True-positive}}{\text{True-positive} + \text{False-positive}},
\]

\[
\text{Recall} = \frac{\text{True-positive}}{\text{True-positive} + \text{False-negative}},
\]

where the true-positive denotes the number of correct determinations as an occupied state. In addition, the false-positive and false-negative, respectively, denote the number of correct and erroneous determinations as an unoccupied state. Because the precision and recall are in an unavoidable tradeoff, the \(F\)-measure, which denotes the harmonic mean of them, is employed as the comprehensive metric. The preliminary experiment also compared time during which the light was turned on (hereafter called “lighting time”) between the sensors.

After the preliminary experiment, we evaluated the low-power image-based sensor, which measures only the occupancy state. The low-power image-based sensor was implemented on the Raspberry Pi 3, which is a low-power and cost-effective single-board computer (as discussed in Section 3.2). However, whether or not the single-board computer has the computational resources to perform the frame difference \([8]\) for QVGA sized images within less than 100 ms has not been verified in the literature. This verification is important given that we want to see if the low-power image-based sensor can be constructed on the single-board computer under the most frequently utilized and best-performance settings, as discussed in Section 4.1. Hence, our experiment measures the computational time of the frame difference on the single-board computer. In addition, the power consumption of the low-power image-based sensor has not been measured in the literature. Thus our experiment evaluates the power consumption of the low-power image-based sensor compared with that of the commercial image-based sensor so as to clarify how much the power consumption decreases. This evaluation is also important to discuss the comprehensive energy-saving rate of occupancy control based on the low-power image-based sensor. On the basis of aforementioned aspects, we determined the evaluation items of the experiment (but not the preliminary experiment), which are listed in the following.

First, we evaluated the computational time of the occupancy state measurement by running the low-power image-based sensor for 8 h. This evaluation is important given that we want to see if the low-power image-based sensor can be constructed on a single-board computer under the most frequently utilized and best-performance settings.

Second, we evaluated the power consumption of the low-power image-based sensor by running it for 8 h. The power consumption was measured by a CT-2 (produced by AVHzY, Inc.), which is a USB power meter. We then compared the measured power consumptions with the rated power consumption of the commercial PIR sensor and commercial image-based sensor on the basis of Table 2, which summarizes the minimum and maximum rated power consumptions of the commercial PIR sensor and commercial image-based sensor produced by a manufacturer that develops both types of sensors. The rated power consumption, which is used to evaluate the comprehensive energy-saving rate, of the low-power image-based sensor was set on the basis of the maximum value of the measured power consumption, since the rated power consumption shows the maximum power consumption.

| Date  | Start time | End time | Data length (h) |
|-------|------------|----------|-----------------|
| D-1   | 8:00 a.m.  | 10:30 p.m. | 13.00          |
| D-2   | 1:00 p.m.  | 6:00 p.m.  | 5.00           |
| D-3   | 6:00 p.m.  | 11:15 p.m. | 5.25           |
| D-4   | 8:00 a.m.  | 11:00 p.m. | 14.50          |
| D-5   | 0:30 p.m.  | 10:15 p.m. | 9.50           |
| D-6   | 1:00 p.m.  | 7:30 p.m.  | 6.50           |
| D-7   | 9:00 a.m.  | 9:30 p.m.  | 12.00          |
| D-8   | 10:00 a.m. | 8:45 p.m.  | 10.75          |

| Sensor | Min (W) | Max (W) |
|--------|---------|---------|
| PIR sensor | 1.0 | 2.0 |
| Image-based sensor | 4.0 | 6.0 |
Third, we evaluated the comprehensive energy-saving rate, which is also used in [17], by comparing the energy consumption between the occupancy control and the scenario in which the light is continuously turned on. The comprehensive energy-saving rate of the occupancy control is determined by

\[
E(d_{\text{all}}, d_{\text{oc}}, l, p) = \frac{d_{\text{all}} \cdot l - (d_{\text{oc}} \cdot l + d_{\text{all}} \cdot p)}{d_{\text{all}} \cdot l}, \tag{7}
\]

where \(d_{\text{all}}\) and \(d_{\text{oc}}\) denote the time during which the light is turned on under scenarios in which the lights are continuously on and when occupancy control is applied, respectively. In addition, \(p\) and \(l\) denote the rated power consumption of the occupancy sensor and light, respectively. The effectiveness of the low-power image-based sensor is discussed in terms of the comprehensive energy-saving rate of the occupancy control compared with the commercial PIR sensor and commercial image-based sensor. The minimum measured power consumption of the low-power image-based sensor was 1.22 W, respectively. Thus the rated power consumption of the low-power image-based sensor was set to 1.22 W, as discussed in Section 4.1.2. Although the rated power consumption of the low-power image-based sensor was larger than the minimum rated power consumption of the commercial PIR sensors in Table 2, it was 2.78 W (corresponding to 69.50%) smaller than the minimum rated power consumption of commercial image-based sensors. Thus the power consumption of the commercial image-based sensor can be decreased by implementing only the occupancy state measurement on the single-board computer.

### 4.2. Experimental results

#### 4.2.1. Preliminary results

This section summarizes the experimental results obtained from [19], which we regard as the preliminary experiment in this paper. The preliminary experiment showed that the commercial image-based sensor and low-power image-based sensors increased the \(F\)-measure by 21.7% compared with the commercial PIR sensor. The minimum time delays of the commercial PIR sensor and both image-based sensors were 10.58 and 2.66 min, respectively. Both image-based sensors decreased the lighting time by 8.9% compared with the commercial PIR sensor.

#### 4.2.2. Computational time

The minimum, average \(\pm\) standard deviation, and the maximum computational time of the frame difference on the single-board computer were found to be 3.30, 5.51 ± 1.35, and 12.82 ms, respectively. These findings show that the frame difference using QVGA sized images, which are commonly utilized as the recording image size of surveillance cameras, can be performed within less than 100 ms, which provides the best performance in occupancy activity analysis, on the single-board computer. Hence, the image-based sensor, which achieves the results described in Section 4.2.1, can be implemented on the low-cost single-board computer under the most frequently utilized and best-performance settings, as discussed in Section 4.1.

#### 4.2.3. Measured power consumption

The minimum, average \(\pm\) standard deviation, and the maximum measured power consumption of the low-power image-based sensor were 1.01, 1.04 ± 0.01, and 1.22 W, respectively. Thus the rated power consumption of the low-power image-based sensor was set to 1.22 W, as discussed in Section 4.1.2. Although the rated power consumption of the low-power image-based sensor was larger than the minimum rated power consumption of the commercial PIR sensors in Table 2, it was 2.78 W (corresponding to 69.50%) smaller than the minimum rated power consumption of commercial image-based sensors. Thus the power consumption of the commercial image-based sensor can be decreased by implementing only the occupancy state measurement on the single-board computer.

#### 4.2.4. Comprehensive energy-saving rate

Table 3 shows the comprehensive energy-saving rate of the occupancy control based on the commercial PIR sensor, commercial image-based sensor, and low-power image-based sensor using practical and minimum time delays. The total comprehensive energy-saving rate was obtained from the occupancy control for all the times listed in Table 1. The ranges of the comprehensive energy-saving rate by the commercial sensors were provided by those of the rated power consumption as presented in Table 2. The minimum and maximum values were given by commercial sensors which have maximum and minimum rated power consumption, respectively. On the other hand, since

| Date | C*-PIR sensor | C* | LP* |
|------|---------------|----|-----|
| D-1  | 2.00 to 5.03  | −4.46 to 1.60 | 10.02 |
| D-2  | −5.09 to −2.06| −15.11 to −9.05| −0.62 |
| D-3  | 2.11 to 5.15  | −1.27 to 4.79  | 13.22 |
| D-4  | 21.46 to 24.49| 17.93 to 23.99 | 32.41 |
| D-5  | −4.38 to −1.35| −12.53 to −6.47| 1.95 |
| D-6  | 61.86 to 64.89| 54.18 to 60.24 | 68.67 |
| D-7  | −0.45 to 2.58 | −10.89 to −4.83 | 3.59 |
| D-8  | 20.53 to 23.56| 19.72 to 25.78 | 34.21 |
| Total| 11.74 to 14.78| 5.68 to 11.74  | 20.16 |

| Date | C*-PIR sensor | C* | LP* |
|------|---------------|----|-----|
| D-1  | 3.00 to 6.93  | −2.19 to 3.88 | 12.30 |
| D-2  | −3.62 to −0.59| −14.00 to −7.94| 0.48 |
| D-3  | 6.82 to 9.85  | 6.77 to 12.84  | 21.26 |
| D-4  | 25.41 to 28.44| 23.71 to 29.77 | 38.19 |
| D-5  | −1.27 to 1.76 | −10.13 to −4.07| 4.36 |
| D-6  | 64.13 to 67.16| 55.38 to 61.44 | 69.87 |
| D-7  | 1.89 to 4.92  | −5.02 to 1.04  | 9.47 |
| D-8  | 26.33 to 29.36| 26.97 to 33.03 | 41.45 |
| Total| 15.00 to 18.03| 10.12 to 16.18 | 24.61 |
the rated power consumption of the low-power image-based sensor was determined uniquely in Section 4.2.3, the comprehensive energy-saving rate does not have the range.

When the minimum time delay was set, the comprehensive energy-saving rate provided by each sensor increased compared with the practical time delay. For example, the total comprehensive energy-saving rate provided by each sensor increased by 3.25% or more when the minimum time delay was set. These results stemmed from the fact that the minimum time delay of the commercial PIR sensor and both image-based sensors decreased by 4.42 and 2.34 min, respectively, compared with the practical time delay, as shown in Section 4.2.1.

The total comprehensive energy-saving rate provided by the commercial PIR sensors ranged from 11.74% to 14.78% and from 15.00% to 18.03% when the practical and minimum time delays were set, respectively. The total comprehensive energy-saving rate provided by the commercial image-based sensors ranged from 5.68% to 11.74% and from 10.12% to 16.18% when the practical and minimum time delays were set, respectively. The total comprehensive energy-saving rate provided by the low-power image-based sensors was 20.16% and 24.61% when the practical and minimum time delays were set, respectively. The results in Table 3 suggest that the commercial image-based sensors could not decrease the total comprehensive energy-saving rate of the occupancy control compared with the commercial PIR sensor that had the minimum rated power consumption. Thus, the power consumption of the commercial image-based sensor should be decreased so as to increase the total comprehensive energy-saving rate compared with the commercial PIR sensor. On the other hand, the low-power image-based sensor could increase the total comprehensive energy-saving rate of the occupancy control by 5.38% or more and 8.42% or more compared with the commercial PIR sensor and commercial image-based sensor, respectively.

The commercial image-based sensor decreased the comprehensive energy-saving rate compared with the commercial PIR sensors at D-1, D-2, D-5, D-6, and D-7. However, the low-power image-based sensor was found to increase the comprehensive energy-saving rate compared with the commercial PIR sensors on all days. This was evidenced by the fact that the rated power consumption of the low-power image-based sensor was reduced compared to that of the commercial image-based sensor.

5. Discussion

This section offers an additional practical discussion of the low-power image-based sensor and the findings of our experiment. In Section 5.1, we discuss further improvement of image-based sensor in the comprehensive energy-saving rate and in the occupancy measurement accuracy, and in Section 5.2, we discuss an application situation of each sensor. In Section 5.3, we present more generalizable findings by assuming that a living room is mounted with a different LED light, and in Section 5.4, we discuss the scope of our experiment, which was designed to provide more general experimental results.

5.1. Further improvement

5.1.1. Energy-saving rate

The single-board computer consumes energy even when it is in an idle state because it typically runs an operating system (OS) [40]. The Raspberry Pi, which we used as the single-board computer to implement the low-power image-based sensor, also runs the Linux-based Raspbian OS.

Therefore, the power consumption of the low-power image-based sensor might be reduced if we implement it on a processor without the OS. This section describes an estimate of the comprehensive energy-saving rate of the occupancy control based on the image-based sensor, which measures only the occupancy state, implemented on a processor without the OS (hereafter called “OS-free image-based sensor”).

The rated power consumption of the OS-free image-based sensor \( p_n \) can be estimated by subtracting the rated power consumption of the single-board computer during an idle state \( p_\text{s} \) from that of the low-power image-based sensor \( p_\text{i} \), as

\[
p_n = p_\text{i} - p_\text{s}. \tag{8}
\]

Because the rated power consumption of the single-board computer in an idle state and the low-power image-based sensor was 0.72 and 1.22 W, respectively, that of the OS-free image-based sensor was estimated to be 0.50 W by applying the above equation.

Table 4 shows the comprehensive energy-saving rate of the occupancy control based on the OS-free image-based sensor, which had the rated power consumption estimated using Equation 8. Here, we discuss the effectiveness of the OS-free image-based sensor compared with the other sensors from Table 3. In contrast to the comprehensive energy-saving rate provided by the other sensor, which was not positive at D-2 when the practical time delay was set, that provided by the OS-free image-based sensor was 1.56% or more. In addition, the total comprehensive energy-saving rate provided by the OS-free image-based sensor was found to be 22.34% and 26.79% when the practical and minimum time delays were set, respectively. This finding demonstrates that the OS-free image-based sensor increased the total comprehensive energy-saving rate by 2.18% or more compared with the other sensors.
Table 4. Comprehensive energy-saving rate (%) from occupancy control based on OS-free image-based sensor.

| Date | Practical time delay | Minimum time delay |
|------|-----------------------|--------------------|
| D-1  | 12.20                 | 14.48              |
| D-2  | 1.56                  | 2.66               |
| D-3  | 15.40                 | 23.44              |
| D-4  | 34.60                 | 40.38              |
| D-5  | 4.14                  | 6.54               |
| D-6  | 70.85                 | 72.05              |
| D-7  | 5.78                  | 11.65              |
| D-8  | 36.39                 | 43.64              |
| Total| 22.34                 | 26.79              |

5.1.2. Occupancy measurement accuracy

The inter-frame time of the frame difference was set to 100 ms in the experiment, since this setting is expected to provide the best performance in the occupancy activity analysis. When the inter-frame time is increased, the small motion is easier to be detected, because the obvious difference in the appearance can be found between previous and current images. Thus we picked up a scene (4:00 p.m. to 5:00 p.m. at D-2), in which the occupant continuously performed the finger- and hand-level motion to control a mouse and to type a keyboard of the computer for 22 min, so as to discuss the measurement accuracy for the small motion.

Figure 5 represents the precision, recall, $F$-measure provided by the frame difference at different inter-frame time. The transition of the recall indicates that the false-negative was decreased at larger inter-frame time just as expected. However, the false-positive, which causes the lights to remain turned on in the unoccupied space, was found to be conversely increased from the transition of the precision. The maximum $F$-measure of 92.71% at 2300 ms inter-frame time was higher than that of 71.07% at 100 ms by 21.64%. Hence, these results suggest that the inter-frame time is required to be tuned carefully for the occupancy measurement, especially for that to the small motion.

In addition, we consider that the threshold parameters of the frame difference should be determined adaptively on the basis of the environment as in [41]. However, because the algorithm of the adaptive thresholding is more complicated, the effectiveness is required to be checked at various conditions.

5.2. Application situation

Our experiment demonstrated the effectiveness of the low-power image-based sensor compared with the commercial PIR sensor. The results show that the low-power image-based sensor is expected to increase the comprehensive energy-saving rate under the room where the occupants perform the small motion such as living rooms and offices.

However, the image-based sensor may not increase the comprehensive energy-saving rate compared with the PIR sensor under the condition that the minimum time delay cannot be considerably decreased. To verify this statement, we picked up a scene (6:00 p.m. to 7:00 p.m. at D-2), in which the occupants most frequently entered or left the room once a minute on average, and evaluated the comprehensive energy-saving rate. The minimum time delays of the commercial PIR sensor and both image-based sensors were required to be set to 66.41 s and 43.81 s, respectively. The difference in the minimum time delays was not large compared with that in Section 4.2.1 due to frequent and large motion provided by repeatedly entrancing and leaving.
the room. When these minimum time delays were set, the comprehensive energy-saving rate of the commercial PIR sensor, the commercial image-based sensor, and the low-power image-based sensor were 42.13% to 45.16%, 30.96% to 37.02%, and 45.45%, respectively. These results suggest that the low-power image-based sensor was not always effective in the rooms, in which the frequent and large motion is expected to be found, such as a corridor, because it increased the comprehensive energy-saving rate only by 0.29% compared with the commercial PIR sensor that had the minimum rated power consumption in this scene.

In addition, an acceptability of the image-based sensor is lower, because it raises significant privacy and security concerns of the occupants. Thus the image-based sensor is difficult to be introduced to lavatory or locker room, in which the privacy is explicitly protected. On the other hand, the PIR sensor has been introduced to these rooms due to its privacy and security preserving capability.

5.3. Application of other lights

This section discusses the total comprehensive energy-saving rate under the condition where other LED lights were installed in a room of the same size as the living room (see Figure 4). We surveyed the power consumption of the currently available LED lights produced by four manufacturers and found that the minimum and maximum rated power consumptions ($l_{\text{min}}$ and $l_{\text{max}}$, respectively) of the LED lights were 21.30 and 39.00 W, respectively.

Table 5 shows the total comprehensive energy-saving rate of the occupancy control for the currently available LED lights. Although the total comprehensive energy-saving rate of the commercial image-based sensor decreased compared with the commercial PIR sensor when a lower power light was mounted, that of the low-power image-based sensor increased the total comprehensive energy-saving rate by 5.02% or more compared with the commercial PIR sensor. From these comparisons, we conclude that the low-power image-based sensor should be developed and commercialized to increase the comprehensive energy-saving rate.

The total comprehensive energy-saving rate provided by the low-power image-based sensor was larger than that by the PIR sensor when lights with a power consumption of more than 3.57 W were applied, which is 17.73 W or more under the rated power consumption of the currently available LED lights.

5.4. Scope of this experiment

The effectiveness of the low-power image-based sensor discussed in this paper may not be the same in other environments, as the experiments we conducted were based only on the sensing data obtained from a single Japanese home for 76.5 h over eight days. However, our experiment was designed to enable a discussion of the effectiveness of the low-power image-based sensor in a wide variety of environments.

For example, we selected a Japanese living room in a home occupied by two residents as the experimental field, as the average number of private household members in Japan was 2.3 as of 2019 [42]. Moreover, we focused on the living room because occupants tend to spend most of their time in the living room in the evening, which is when lights are typically turned on [43]. In addition, we chose settings in which the low-power image-based sensor applies frame difference to QVGA sized images at 100 ms inter-frame time. We assume these settings are frequently selected for image-based sensors because QVGA sized images are commonly utilized by surveillance cameras. Moreover, occupancy activity analysis has demonstrated that the best performance is achieved at the inter-frame time of 100 ms.

Furthermore, we have discussed the effectiveness of the low-power image-based sensor compared with the commercial PIR sensor and commercial image-based sensor, which are currently available, under additional conditions in which the living room was mounted with different LED lights or in which the occupants entered and left the room most frequently. Our objective with this was to provide broader findings by avoiding a discussion of only one condition.

Although our experiment and discussion were designed to examine the effectiveness in as wide a variety of environments as possible, it did not cover all potential conditions and scenarios. For example, it would be beneficial to examine other room types to provide a more general discussion, since occupancy patterns (e.g. the frequency and size of the motion), which affect the occupancy measurement accuracy of the sensors, may be different for different rooms. In short, further experimentation is required to clarify the effectiveness of the low-power image-based sensor.

Table 5. Total comprehensive energy-saving rate from occupancy control for currently available LED lights (\(l\) denotes the power consumption of a light, \(C^*\) and \(LP^*\) represent "commercial" and "low-power", respectively).

| Practical time delay | Image-based sensor | C*-PIR sensor | C* | LP* |
|----------------------|--------------------|---------------|----|-----|
| $l_{\text{min}}$    | 8.42 to 13.11      | −4.31 to 5.08 | 18.13 |
| $l_{\text{max}}$    | 12.68 to 15.24     | 8.47 to 13.60 | 20.73 |

| Minimum time delay | Image-based sensor | C*-PIR sensor | C* | LP* |
|-------------------|--------------------|---------------|----|-----|
| $l_{\text{min}}$ | 11.67 to 16.36      | 0.14 to 9.53  | 22.58 |
| $l_{\text{max}}$ | 15.93 to 18.49      | 12.92 to 18.05 | 25.18 |
6. Conclusion

In this study, we evaluated the effectiveness of occupancy lighting control based on a low-power image-based sensor, which measures only the occupancy state, implemented on a single-board computer. Experimental results demonstrated that the single-board computer has sufficient computational resources to perform the frame difference algorithm under the most frequently utilized and high-performance settings of the image size and frame rate. In addition, we found that the rated power consumption of the low-power image-based sensor was 1.22 W, which is 2.78 W (corresponding to 69.50%) less than that of a commercial image-based sensor.

Our experiment was conducted in an actual living room where a light with the rated power consumption of 33.00 W was mounted for 8 days. As the results of the experiment indicate, the commercial image-based sensor could not decrease the total comprehensive energy-saving rate, which is based on the energy consumption of both the light and the occupancy sensor, as much as the commercial PIR sensor did. In contrast, the low-power image-based sensor increased the total comprehensive energy-saving rate by 5.38% and 8.42% or more compared with the commercial PIR and image-based sensors, respectively.

We further discussed the effectiveness of the low-power image-based sensor to provide more general findings. First, the comprehensive energy-saving rate provided by the low-power image-based sensor implemented on a processor without an OS was 2.18% or higher than that provided by the commercial PIR sensor and commercial image-based sensor. Second, the low-power image-based sensor increased the total energy-saving rate compared with the PIR sensor under a light with a power consumption of 3.57 W or more, which covers the range of rated power consumption of the LED lights currently available for use in a living room. Our experiments and discussion suggest that the rated power consumption of the commercial image-based sensor should be decreased in order to increase the comprehensive energy-saving rate of the occupancy control compared with that based on the commercial PIR sensor.

However, our discussion suggested that the low-power image-based sensor was not always effective in the room where the occupants perform the frequent and large motion. Although our experiment was designed to examine the effectiveness in as wide a variety of environments as possible, further experimentation is required to cover additional conditions and scenarios. In addition, we found that the parameters of the image-based sensor should be tuned or determined adaptively to increase the occupancy measurement accuracy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Takuya Futagami received his BS, MS, and PhD degrees from Osaka University, Suita, Japan, in 2013, 2015, and 2021, respectively. He has been a visiting researcher at Osaka Electro-Communication University, Neyagawa, Japan, since 2018. His current research interests include image processing and lighting control.

Noboru Hayasaka received his BS, MS, and PhD degrees from Hokkaido University, Sapporo, Japan, in 2002, 2004, and 2007, respectively. At present, he is an associate professor at Osaka Electro-Communication University, Neyagawa, Japan. His current research interests include speech processing and recognition.

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