Verification of a Seat Occupancy/Vacancy Detection Method Using High-Resolution Infrared Sensors and the Application to the Intelligent Lighting System

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Abstract— *We have conducted research on the Intelligent Lighting System that realizes illuminance demanded by a worker at minimum power. In real office the system realized to improve in office workers comfort and to reduce the power consumption. In the system, workers are necessary to change the occupancy/ vacancy status. However some workers didn't change appropriately it. Thus there were lights that provided brightness more than required even though there were no workers. Consequently, we propose a method for automatically controlling changes in the occupied/ unoccupied status of a worker's seat. This study uses high-resolution infrared sensors that can detect temperature. The method detects the occupied/ unoccupied status of a worker's seat by using temperature values output by high-resolution infrared sensors and their differences. We confirmed that the system incorporating the proposed method detects the occupied/ unoccupied status and realizes illuminance demanded by a worker and reduces the power consumption.*

Keywords: infrared sensor, optimization, energy conservation, lighting control

1. Introduction

It has been demanded in recent years to improve intellectual productivity and creativity of workers in an office environment. It has also been reported that improving office lighting environment enhances workers' intellectual productivity[1]. In particular, there have been extensive studies on the impact of office lighting environment on workers' comfort, and it has been clarified that providing each individual with the optimal brightness for their work leads to an improvement in their comfort[2].

Against such a backdrop, we have conducted research on the Intelligent Lighting System which realizes illuminance demanded by a worker at minimum power[3]. The intelligent lighting system realizes the target illuminance for each worker. The target illuminance refers to brightness desired by a worker and is set by the illuminance sensor button on the PC on his/ her desktop or the physical button installed on an illuminance sensor. The effectiveness of the Intelligent Lighting System has been verified so far[4]. As its effectiveness was acknowledged, demonstration tests have been conducted in real office environments.

The Intelligent Lighting System judges that it is not required to provide illuminance to an area unoccupied by any worker. When turning off the lighting fixture providing illuminance to the area in question, the system dims or turns off surrounding lighting in order not to affect working space of other workers, thereby realizing even higher energy saving. The results of demonstration tests at real offices, however, showed that workers did not appropriately change the occupied/ unoccupied status. Those results confirmed that there were lighting fixtures which provided brightness more than required even though there were no workers. Therefore we propose a method for automatically controlling changes in the occupied/ unoccupied status of a worker's seat. This is expected to improve the power consumption reducing effect.

This study proposes a method for detecting the occupied/ unoccupied status of a worker's seat by installing infrared sensors, which are generic. Existing methods using infrared sensors control lighting on the basis of two values: whether a person is or is not in the detection range of infrared sensors. With the Intelligent Lighting System, however, it is required to identify the detailed state of occupancy by workers because multiple workers are in the detection range. Consequently, we propose and verify a method for detecting occupancy or vacancy using high-resolution infrared sensors that can detect temperature for each of 256 pixels corresponding to the same number of sections of the detection range.

2. Intelligent lighting system

2.1 Configuration of Intelligent Lighting System

An Intelligent Lighting System is a lighting control system to realize illuminance demanded by a worker(target illuminance) at minimum power. It consists of lighting fixtures, control devices, illuminance sensors, a power meter and a network to connect them. Fig. 1 shows the configuration of the Intelligent Lighting System.

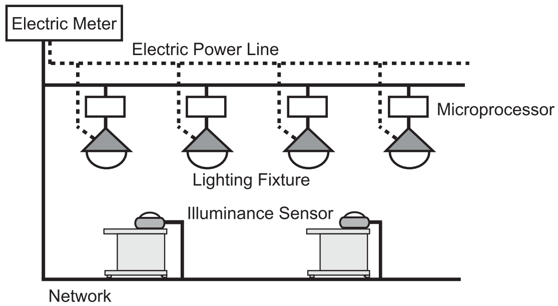

Figure 1: Configuration of the Intelligent Lighting System

As shown in Fig. 1, control devices acquire the illuminance information, the target illuminance information and the occupancy/ vacancy information. From these information, the control device controls the luminance of lighting fixtures using an optimization method. By this control, the system realizes the target illuminance required by each worker and saves power consumption.

2.2 Illuminance control algorithm

An Intelligent Lighting System uses an Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC) based on Simulated Annealing (SA). The system solves an optimization problem in an autonomous distributed style. In this algorithm the luminance of each lighting fixture is the design parameter, the target illuminance of each illuminance sensors is the constraint and the total power consumption of the lighting is the objective function. Thus, the system derives the luminance of each lighting fixtures to realize the target illuminance for each worker and the reducing of power consumption. the system learns the effect of each lighting fixtures on each illuminance sensors using a regression analysis and varies appropriately the luminance of each lighting fixture. In this way, the system can realize the optimal luminance. The flow of control by the Intelligent Lighting System using ANA/RC is shown below.

1) Set the target illuminance of each illuminance sensor.
2) Turn on each lighting fixture at the initial luminance.
3) Obtain values measured by illuminance sensors and a power meter.
4) Calculate the values of the objective function.
5) Determine the next luminance in accordance with illuminance/ luminance influence factor and turn on each lighting fixture at the next luminance.
6) Obtain values measured by illuminance sensors and a power meter.
7) Calculate the values of the objective function referred to in step (5) under the new lighting condition.
8) Conduct a regression analysis with changes in luminance of each lighting fixtures and changes in the illuminance of each illuminance sensor to estimate illuminance/ luminance influence factor.
9) If the value of the objective function is improved, accept the next luminance. Otherwise, revert to the original luminance.
10) Go back to step (3).

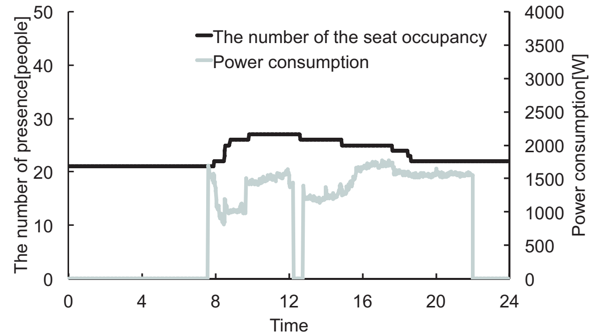

Figure 2: History of the number of the seat occupancy and power consumption of the Intelligent Lighting System

The objective function is indicated in the Ecuation(1).

$$f_i = P + \omega \times \sum_{j=1}^{n} g_{ij} \quad (1)$$

$$g_{ij} = \begin{cases} 0 & (Ic_j - It_j) \geq 0 \\ R_{ij} \times (Ic_j - It_j)^2 & (Ic_j - It_j) < 0 \end{cases}$$

$$R_{ij} = \begin{cases} r_{ij} & r_{ij} \geq T \\ 0 & r_{ij} < T \end{cases}$$

i:lighting ID , j:illuminance sensor ID, P:power consumption [W], ω:weight[W/lx^2]
Ic:current illuminance [lx], It:target illuminance [lx], r:regression coefficient, T:threshold

As shown in Fig. (1), the objective function f consists of power consumption and illuminance constraint. Illuminance constraint g_{ij} which set target illuminance of each illuminance sensors as constraint is changed by illuminance/ luminance influence factor r_{ij}. The objective function f operates to emphasize illuminance constraint as illuminance/ luminance influence factor is larger. The algorithm also can restrict lighting fixtures affect an illuminance sensor to lighting fixtures near the illuminance sensor by setting a threshold. Therefore the system controls lighting fixtures far from the illuminance sensors as a purpose only minimization of power consumption.

2.3 Issues Regarding Occupancy and Vacancy in the Intelligent Lighting System

The Intelligent Lighting System judges that space does not need brightness if it is not occupied by a worker. It is possible to reduce unnecessary brightness by treating the target illuminance for an unseated worker as 0lx. A change in the occupied/ unoccupied status is made by each worker by the occupied/ unoccupied button in the web user interface or the physical button installed on the illuminance sensor.

When the system was introduced to a real office, however, the occupied/ unoccupied status was not appropriately changed. Fig. 2shows the number of seated workers and the transition in the power consumption of the Intelligent Lighting System on January 15, 2011 in the Tokyo Building, in which the Intelligent Lighting System was introduced. The number of workers was 42 in the area in the Tokyo Building to which the Intelligent Lighting System was introduced.

Fig. 2 indicates that, for about 20 workers, the occupied/ unoccupied status was always indicated as "occupied" on the system regardless of a period of time. It also shows that the percentage of workers who changed the occupancy status was 10% of all workers. Power consumption declined temporarily in the morning during which the number of seated workers increased. This is considered to be because the impact of light from outside was so great as to suppress the luminance of lighting fixtures as it was fine in Tokyo on that day. It is also found that power consumption increased after 15:00 due to the smaller impact of light from outside resulting from a reduction in solar radiation. It is found that the light was turned off at 22:00 as power consumption became 0 at 22:00.

Assuming that the number of workers increases linearly from 8:00 to 9:00, during which period workers come to the office, and decreases likewise from 18:00 to 22:00, during which period they leave the office, power consumption is also considered to increase/ decrease linearly in the same manner. Because of workers who do not change the occupied/ unoccupied status, however, brightness more than necessary was provided even though the space was unoccupied by a worker. The occupied/ unoccupied status was not changed either when workers temporarily leave their seat for attending a meeting or going out. It can be said to be important to grasp the occupied/ unoccupied status of a worker's seat correctly from the perspective of energy saving in lighting.

One cause cited for the fact that the occupied/ unoccupied status is not changed appropriately is that changing it is somewhat bothersome because it is required to start up a web browser or press the button attached to the illuminance sensor. Therefore, this study proposes a method for reducing power consumption further by using high-resolution infrared sensors to detect the occupied/ unoccupied status of workers' seats and setting the target illuminance for a worker not occupying their seat as 0.

Table 1: Specification of the high-resolution infrared sensor

Measurement	MEMS Thermal IR Sensor
Element Type	16×16 pixels
Detection Range	3.6 m × 3.6 m (3 m detection length)
View Angle	90 °
Temperature Range	5 − 50 °C
Temperature Resolution	0.15×10^{-2} °C

3. Occupancy/vacancy Detection Using High-resolution Infrared Sensors Method

3.1 Outline of a High-resolution Infrared Sensor

A high-resolution infrared sensor is a noncontact temperature sensor that combines a wide range of visual field and high-precision area temperature detection. Table. 1 gives the specifications of a high-resolution infrared sensor.

The difference between existing infrared sensors and the high-resolution infrared sensor is that the latter can roughly identify the number of persons in the detection range of a sensor. Existing infrared sensors cannot identify the number and locations of persons because they detect a person in the detection range bivalently: whether there is a person or not. On the other hand, the high-resolution infrared sensor can grasp the number and locations of persons since it can detect the temperature of every part of the detection range. The high-resolution infrared sensor outputs the average temperature in each of 256 sections of the detection range corresponding to the same number of pixels on the sensor.

3.2 Occupancy/vacancy Detection Algorithm

We propose a method which detects the occupancy/ vacancy status of a worker's seat by using temperature values output by high-resolution infrared sensors and their differences. The flow of the occupancy/ vacancy detection procedure is shown below. Let T be the threshold temperature for distinguishing heat sources, ΔT be the temperature difference threshold for determining whether a seat is occupied or unoccupied by a person, and N be the number of adjacent pixels required for detecting occupancy.

1) Assign the value "unoccupied" to all pixels in their initial condition.
2) Obtain the difference between the temperature t seconds ago and the present temperature.
3) Assign the value "occupied" to the pixel representing the section for which temperature difference is ΔT °C or greater with temperature being T °C or above.
4) Assign the value "unoccupied" to a pixel representing the section for which temperature difference is $-\Delta T$ °C or less with temperature being T °C or below.

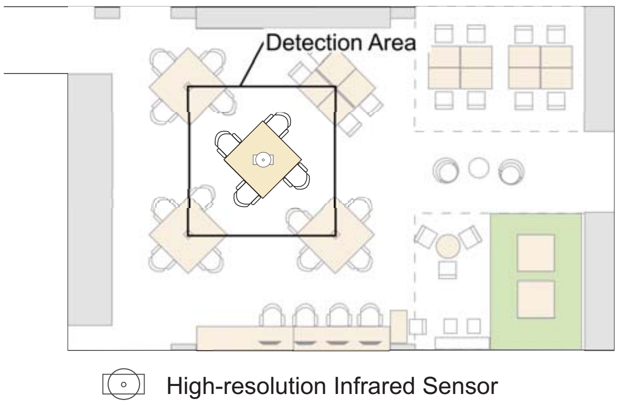

Figure 3: Experiment environment of the seat occupancy detection verification

5) Detect a pixel the number of whose adjacent occupied pixels is N or greater and classify it as occupied.
6) Detect a pixel the number of whose adjacent occupied pixels is less than N and classify it as unoccupied.

By repeating steps (2) to (6) every second, it is detected whether a seat is occupied or unoccupied by a worker. As noted above, a pixel representing a section with a large positive temperature difference is classified as occupied, and a pixel representing a section with a large negative temperature difference is classified as unoccupied. Each pixel is classified as either occupied or unoccupied. Because of the nature of this method using temperature difference, pixels are classified as unoccupied in their initial condition. If the temperature difference $\Delta T'$ is such that $-\Delta T < \Delta T' < \Delta T$, the previous occupied/ unoccupied status of the relevant pixel is retained unless the relevant temperature falls below the threshold T.

4. Verification Experiment for the Occupancy/Vacancy Detection Method Using High-resolution Infrared Sensors

4.1 Outline of Verification

We verified the effectiveness of the system detecting occupancy/ vacancy by using a high-resolution infrared sensor. Fig. 3 shows the experimental environment. A high-resolution infrared sensor was placed directly above the center of the desk in the center shown in Fig. 3. In this experiment, assuming PC work, 4 seats shown in Fig. 3 were sometimes occupied and sometimes not during 20 minutes. Occupancy or vacancy was detected every second to output the value 1 when a seat was occupied and the value 0 when it was unoccupied. Detection precision was confirmed by visual inspection using log data based on camera images.

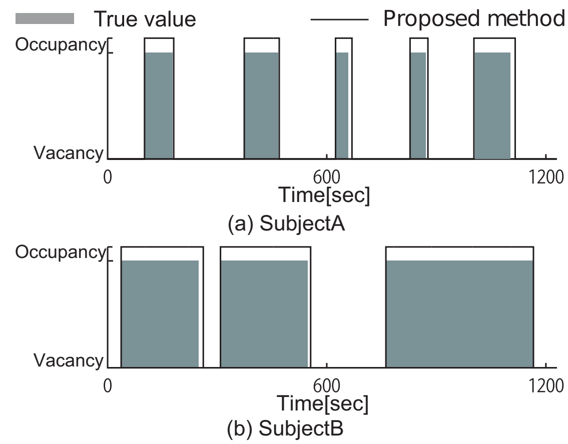

Figure 4: the history of occupancy (with PC)

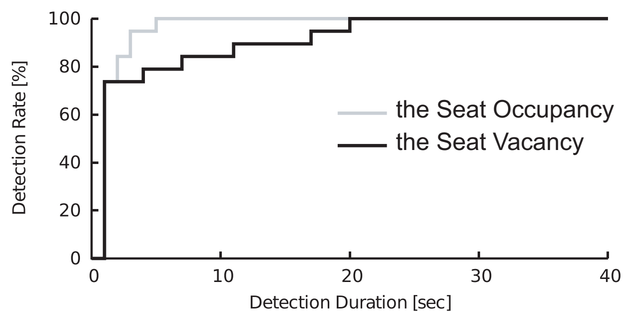

Figure 5: Relation between duration and detection rate (with PC)

4.2 Result of Verification in a PC Work Environment

This section examines the detection rates of occupancy and vacancy in a PC work environment by the proposed method and visual inspection as well as time required for detecting occupancy and vacancy. A PC was placed on the top of each desk at which each subject was to be seated. During 20 minutes, their seats were sometimes occupied and sometimes not.

Fig. 4 shows the transition of the occupied/ unoccupied status with Subjects A and B in accordance with the proposed method and visual inspection. Fig. 4 suggests that the method detects occupancy and vacancy well. Sometimes detecting vacancy took more time than detecting occupancy.

Next, we examine time required for detecting occupancy and vacancy respectively. Fig. 5 shows the relation between time required for detecting occupancy and vacancy and the corresponding detection rate. Fig. 5 indicates that the detection rate of occupancy reaches 100% 5 seconds after a seat is occupied by a subject. The detection rate of vacancy reaches 100% about 20 seconds after a seat becomes unoccupied by a subject.

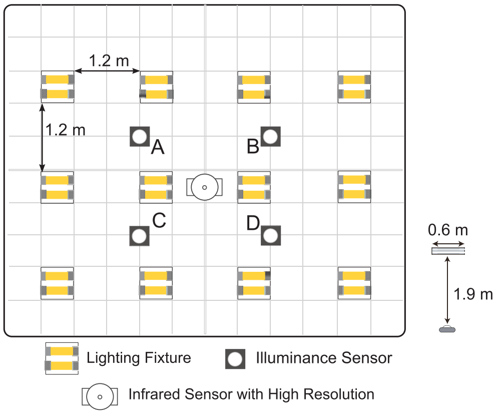

Figure 6: Experiment environment of the illuminance convergence experiment

4.3 Summary of Verification Result

The result of the verification experiment confirmed that the proposed method enables the detection of human occupancy and vacancy using high-resolution infrared sensor. In addition, it was found that detecting vacancy requires more time than detecting occupancy because the effect of a subject's body temperature on the desk and the chair lingers after the seat becomes unoccupied by the subject. It was confirmed that the detection rate of both occupancy and vacancy reaches 100% after 21 seconds.

In the Intelligent Lighting System, if the processing of occupancy and vacancy is delayed for 1 minute, assuming that the lighting luminance of the relevant lighting fixture changes from the maximum to 0 as a result of the processing, the corresponding difference in power consumption amounts to several Wh. Therefore, an impact of a 1-minute delay in the Intelligent Lighting System on power consumption is small, and the delay of 21 seconds is within the permissible range.

5. Intelligent Lighting Control Using High-resolution Infrared Sensors

5.1 Outline of Experiment

A verification experiment was conducted with the Intelligent Lighting System incorporating the occupancy/ vacancy detection method using high-resolution infrared sensors. Fig. 6 shows the environment of the verification experiment. As shown in Fig. 6, 12 lighting fixtures and one high-resolution infrared sensor were installed in the experiment environment. Four illuminance sensors were placed to simulate a real office. Assuming a typical office, pairs of desks placed opposite each other were placed apart from each other pairs.

In this experiment environment, an illuminance convergence experiment for the Intelligent Lighting System was conducted using the occupancy/ vacancy detection method with high-resolution infrared sensor. Table 2 shows target illuminance set for each illuminance sensor. In the illuminance convergence experiment, a target illuminance is set for a subject's illuminance sensor detecting occupancy and vacancy by the proposed method as shown in Table 2.

Table 2: Setup of the target value for experiment

Time [sec]	A [lx]	B [lx]	C [lx]	D [lx]
0	—	—	—	—
350	—	500	—	600
750	400	500	—	600
1050	400	500	350	600
2150	400	—	350	—
2500	—	—	—	—

We conducted an illuminance convergence experiment for the Intelligent Lighting System incorporating the occupancy/ vacancy detection by high-resolution infrared sensors and compared illuminance convergence results with each other.

The flow of control by the Intelligent Lighting System incorporating the proposed method is shown below.

1) Set the target illuminance of each illuminance sensor.
2) Turn on each lighting fixture at the initial luminance.
3) Obtain values measured by illuminance sensors and a power meter.
4) Determine whether a seat is occupied or unoccupied by the proposed method.
5) Calculate the values of the objective function.
6) Determine the next luminance in accordance with illuminance/ luminance influence and turn on each lighting fixture at the next luminance.
7) Obtain values measured by illuminance sensors and a power meter.
8) Determine whether a seat is occupied or unoccupied by the proposed method.
9) Calculate the values of the objective function referred to in step (5) under the new lighting condition.
10) Conduct a regression analysis with changes in luminance of each lighting fixtures and changes in the illuminance of each illuminance sensor to estimate illuminance/ luminance influence.
11) If the value of the objective function is improved, accept the next luminance. Otherwise, revert to the original luminance.
12) Go back to step (3).

5.2 Result

Let us state the result of the verification experiment performed in the experiment environment shown in Fig. 6. Fig. 7 shows the log of illuminance indicated by each illuminance sensor under the proposed method. In light of Fig. 7, it is confirmed that, by using the proposed method changes in the occupied/ unoccupied status for each worker were detected to change the luminance of the lighting fixture to meet the target illuminance. The illuminance value

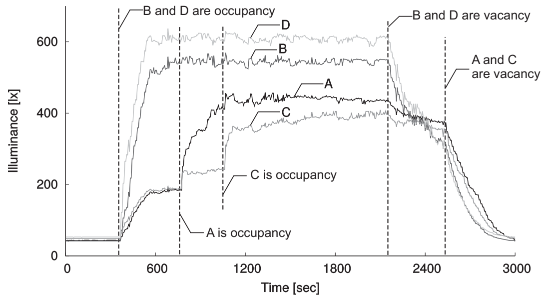

Figure 7: Illuminance history of lighting control based on the proposed detection approach

obtained by each illuminance sensor converged to the target illuminance 200 seconds after a change in the occupied/ unoccupied status. The system also subsequently worked to maintain the target illuminance. Illuminance again converged to the target illuminance demanded by Subjects A, B, and D 200 seconds after the presence of Subject A was detected at 750 seconds. After detecting the absence of Subjects B and D at 2150 seconds, illuminance converged to the target illuminance demanded by Subjects A and C, which confirmed that the target illuminance was maintained. As the result of the verification experiment shows that the occupied/ unoccupied status can be correctly managed by automatically changing the occupied/ unoccupied status using high-resolution infrared sensors, the Intelligent Lighting System using the proposed method can be said to be useful.

5.3 Verification of Power Consumption Reduction

The previous section confirmed that the Intelligent Lighting System incorporating the proposed method detects occupancy and vacancy to make illuminance converge to the target illuminance. We thus verify how power consumption changes by the occupancy rate to show the usefulness of the proposed method.

Fig. 8 shows the simulation environment. 30 lighting fixtures and 33 seats were placed, with an illuminance sensor installed on each seat. The minimum luminance of the lighting fixture was set to 0 cd, and the maximum luminance was set to 1,300 cd. The target illuminance of the illuminance sensor for each seat was set randomly from 300 lx to 700 lx at 50 lx interval. The occupancy rate of a worker's seat was set from 10% to 100% at 10% interval, and simulation was run 100 times for each rate set.

Fig. 9 shows the average power consumption for each occupancy rate. Since power consumption and luminance of lighting fixtures are in a linear relationship, on the basis of this linear relationship, power consumption for each occupancy rate was calculated by assuming power consumption to be 100% when the target illuminance is set to 750 lx for all illuminance sensors. Therefore, power consumption is about

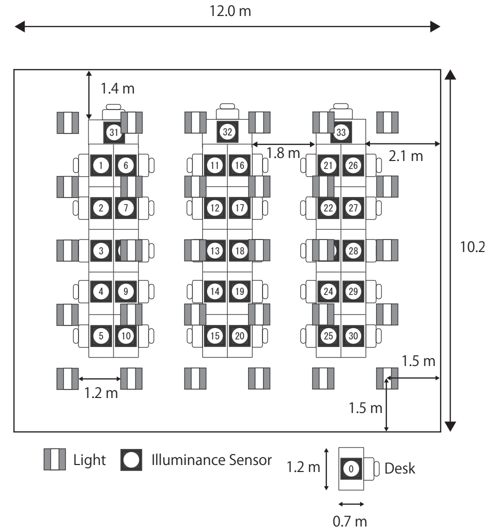

Figure 8: Simulation environment

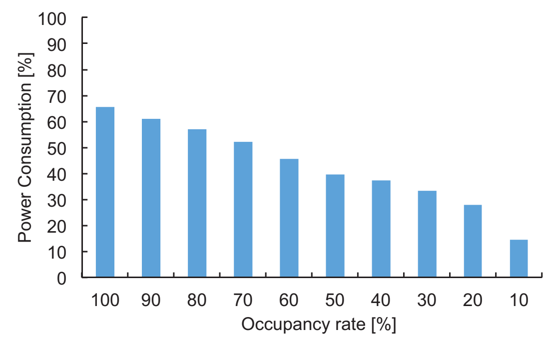

Figure 9: each occupancy rate and power consumption of the Intelligent Lighting Systems

118% when all lighting fixtures are turned on at uniform luminance with the minimum value of the illuminance on each worker's desk being set to 750 lx.

These results show that power consumption can be reduced by 35% even if the occupancy rate is 100% by introducing the Intelligent Lighting System. This reduction is made because, as noted above, the average illuminance in an office as a whole decreases by meeting the individual target illuminance for each worker. Fig. 9 also shows that power consumption decreases almost linearly as the occupancy rate decreases.

On the other hand, as shown in Fig. 2, power consumption increased during the periods when workers arrived at and left the office because the occupied/ unoccupied status was not changed appropriately. Simulation was thus run for the following three cases to compare power consumption.

1) The occupancy rate is 100%, and the Intelligent Lighting System is used. (The target illuminance for each

worker is uniform at 750 lx.)

2) The occupancy rate is 100%, and the Intelligent Lighting System is used. (The target illuminance for each worker is random and ranges from 300 lx to 750 lx.)
3) he occupancy rate is 70%. The number of workers is assumed to increase and decrease linearly, respectively, when they come to and leave the office. The Intelligent Lighting System is used. (The target illuminance of each worker is random and ranges from 300 lx to 700 lx.)

Cases 1 and 2 assume that workers do not change the occupied/ unoccupied status at all, come to the office at 8:00 at the earliest, and leave the office at 22:00 at the latest. The worker coming to the office first turns on lighting, and the one leaving the office last turns it off. Simulation is run using the Intelligent Lighting System when the occupancy rate is 100%.

Case 3 assumes that workers come to the office from 8:00 to 9:00 and leave the office from 18:00 to 22:00 and that the number of workers increases and decreases linearly during those periods of time. Since Fig. 2 indicates that the average seat occupancy by workers in office is considered to be 70% taking into account their attending meetings and going out, the occupancy rate is assumed to be 70%. By assuming power consumption to be 100% when the target illuminance is set to 750 lx for all illuminance sensors, power consumption was calculated for each case.

Fig. 10 gives the result of simulation for these cases. Fig. 10 shows that, in the Intelligent Lighting System, power consumption can be reduced by about 35% if the target illuminance for each worker (300 lx — 700 lx) is met individually compared with the case where, for all illuminance sensors, the target illuminance is set to 750 lx on the desk, which is generally recommended for an office. The reduction rate assumes that all workers are seated and never leave their seat. This is the basic energy saving performance of the Intelligent Lighting System.

It was found that power consumption reduced further by about 20% by introducing the Intelligent Lighting System incorporating the occupancy/ vacancy detection method using high-resolution infrared sensor proposed in this study. Thus it was found power consumption reduction amounted to about 55% if the Intelligent Lighting System was used, with each individual working with different preference for illuminance, and if occupancy and vacancy were detected correctly.

Note that power consumption is assumed to be 100% when the target illuminance on the desk is set to 750 lx using the Intelligent Lighting System. If uniform lighting were used without using the Intelligent Lighting System, power consumption would be 118% in Fig. 10. Therefore, the Intelligent Lighting System incorporating high-resolution infrared sensors proposed herein can reduce power consumption by about 73% compared to uniform lighting.

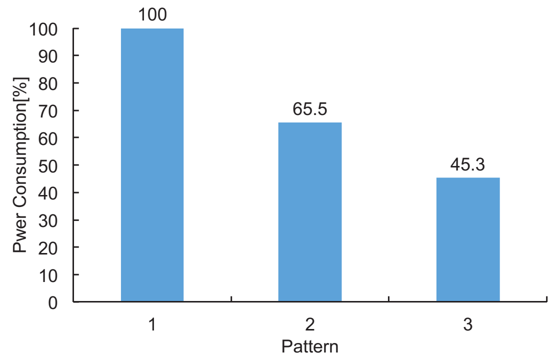

Figure 10: Simulation result

6. Conclusion

As a result of verification experiment in real office for practical realization, it is found that workers didn't change the occupied/ unoccupied status appropriately. Thus, there were lighting fixtures which provided brightness more than required even though there were no workers and energy saving deterioration the Intelligent Lighting System. Consequently, we propose a method for controlling changes using a high-resolution infrared sensor in the occupied/ unoccupied status of a worker's seat. We verified the effectiveness of proposed method. As a result we confirmed that the high-resolution infrared sensor can detect the occupied/ unoccupied status. We also confirmed that The Intelligent Lighting System incorporating the proposed method detects the occupied/ unoccupied status and realizes the illuminance demanded by a worker and reduces the power consumption. Moreover we confirmed that power consumption reduces by about 20% in simulation environment. Therefore the system detects the occupied/ unoccupied status automatically and improve the energy saving performance in the Intelligent Lighting System.

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