An Intelligent Lighting System using a Smartphone as an Illuminance Sensor

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Abstract— *The authors have engaged in research and development of Intelligent Lighting Systems which realize individual brightness (illuminance) levels required by workers with minimum power consumption. As Intelligent Lighting Systems use illuminance sensors for illuminance control, smartphones with a built-in illuminance sensor may be used for this purpose. This can reduce the initial cost for introducing an Intelligent Lighting System as well as realize easier maintenance. For that purpose, in this study, we examined the possibilities of an Intelligent Lighting System using built-in illuminance sensors in smartphones. Performance verification experiments concerning smartphone's built-in illuminance sensors showed that their resolutions are so low that their measurements differ from the true values. Based on this result, we propose methods to estimate the positions of built-in illuminance sensors and to estimate the level of influence by each lighting fixture, and a method to solve the gap between their illuminance measurements and the true values. A verification experiment to confirm the effectiveness of the constructed system demonstrated that it can realize the estimation of approximate smartphone positions and individual illuminance control.*

Keywords: Lighting Control, Illuminance, Optimization, Smartphone, Position Estimation, Energy Conservation

1. Introduction

In recent years, as the improvement of energy efficiency has become a topic of broad discussion, there has been a drive toward energy saving in office buildings. Since lighting accounts for about 20% of the total power consumption in office buildings, improving the lighting environment can bring about a significant power saving and thus a great contribution to energy conservation [1], [2], [3]. Meanwhile, there have been many researches concerning intellectual productivity, creativity and comfort [4], [5]. Improving office lighting environments leads to the improvement of worker productivity. Above all, it has been reported that realizing brightness (illuminance) optimal for the work individually for each worker is effective for improving office environments [6].

Against this backdrop, the authors focused on lighting environments and proposed an Intelligent Lighting System which individually realizes illuminance levels required by individual workers while saving power consumption [7], [8]. The effectiveness of Intelligent Lighting Systems has already been recognized and verification experiments have been conducted at real offices in Tokyo and Fukuoka. These experiments verified that the system can individually realize illuminance levels preferred by workers while cutting down on energy consumption.

In Intelligent Lighting Systems, an illuminance sensor is set on each worker's desktop; based on the illuminance measurements by these sensors, the brightness (luminance) of the office lighting fixtures are controlled by an optimization method. These systems currently use expensive illuminance sensors manufactured to order, but it may be possible to replace them with smartphones now widely owned by people. This is expected to reduce the initial cost for introducing an Intelligent Lighting System while realizing easier maintenance. Hence, this study examines the possibilities of an Intelligent Lighting System using smartphones as illuminance sensors.

2. Intelligent Lighting System

2.1 Configuration of Intelligent Lighting System

An Intelligent Lighting System is a system to realize required illuminance at the position where an illuminance sensor is installed with minimum power consumption [7], [8]. As shown in Fig.1, it consists of lighting fixtures, control devices, illuminance sensors, a power meter and a network to connect them.

The control device accompanying each lighting fixture varies the luminance to an extent unnoticed by workers using an optimization method based on illuminance and power consumption data. By repeating this, the system realizes the illuminance required by each worker with saving power consumption.

2.2 Illumination Control Algorithm

An Intelligent Lighting System solves an optimization problem using an Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC) based on Simulated Annealing (SA) [7], [9] in an autonomous distributed style, in

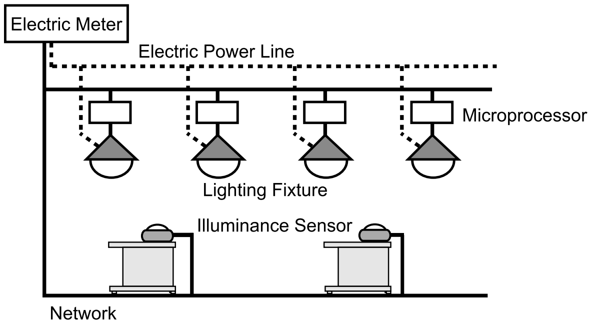

Fig. 1: The construction of an Intelligent Lighting System

which the luminance of each lighting fixture is the design parameter, the target illuminance of each lighting fixture is the constraint and the total power consumption of the lighting is the objective function. In short, it randomly varies the luminance of each lighting fixture in each search to an extent unnoticeable by workers [10] to search an optimum lighting pattern. The ANA/RC estimates the level of influence (referred to as “illuminance/luminance influence factor") on each illuminance sensor through regression analysis concerning the illuminance change and luminance change during search for a solution, and gives an orientation to the random change in luminance corresponding to the illuminance/luminance influence factor. In this way, the system operates those lighting fixtures yielding strong influence on each illuminance sensor to realize the illuminance required by each worker at minimum power consumption, while operating the other lightings to minimize power consumption.

2.3 Illuminance Sensor in the Intelligent Lighting System

Illuminance sensors used in Intelligent Lighting Systems are broadly divided into wired types and wireless types. Wired illuminance sensors can be powered via PoE, but necessitate power cables under the floor. This is not practical in an environment where illuminance sensor positions may change. On the other hand, wireless illuminance sensors, requiring such considerations as battery replacement or charge but not cables, are a practical solution for offices having frequent sensor relocations due to layout changes. Moreover, the illuminance sensors currently used by Intelligent Lighting Systems are expensive order-made products, which has hindered the popularization of Intelligent Lighting Systems.

Meanwhile, smartphones and tablets (hereinafter mentioned as “smartphones") have become ubiquitous in recent years, and the illuminance sensors built into these smartphones may be used as illuminance sensors in Intelligent Lighting Systems. Hence, this study proposes a method to control Intelligent Lighting Systems using smartphones as illuminance sensors.

3. Built-in illuminance sensors in smartphones

3.1 Advantages of using smartphones

In recent years, smartphones such as Android products or iPhones have prevailed as sophisticated multi-function mobile phones. Since smartphones have a built-in illuminance sensor for screen brightness control, they may be utilized as illuminance sensors for Intelligent Lighting Systems. Not only that they may function as illuminance sensors, the use of commercial general purpose products will also increase the ease of maintenance while reducing initial system construction cost; they may also provide a touch-panel user interface.

However, since illuminance sensors built into smartphones are intended primarily for screen brightness control, whether they function properly in an Intelligent Lighting System needs to be checked through performance verification.

3.2 Performance verification experiment for built-in illuminance sensors

To verify the performance of illuminance sensors built into smartphones (hereinafter referred to as “built-in illuminance sensors"), their measurements were compared with the actual measurement values of an external illuminance meter. In the experiment, only one lighting fixture right above point A shown in Fig.2 was turned on. Then illuminance meters and smartphones (including tablets) were placed on 70 cm high desktops at points A to E. For the experiment, lighting fixtures with a light control in 256 steps were used. At each of these steps, the brightness at each point was measured using a built-in illuminance sensor and an external illuminance meter. The illuminance meter used was ANA-F11 (Tokyo Koden: JIS C 1609-2 compliant), and the four smartphone models listed in the left column of Table 1.

Fig.3 compares the values from the built-in illuminance sensors of the four models and measurements by an external illuminance meter. Also, Table 1 shows the resolution of the built-in illuminance sensor as obtained from this experiment. In Fig.3, the horizontal axis shows the measurements from the external illuminance meter, while the vertical axis shows the values from each built-in illuminance sensor. Only at Point A, values up to 400lx were plotted both for the vertical and horizontal axes, while values up to 200lx were plotted for others. For the purpose of clarity, the figure shows the number of plots in summary. The data from point D is not shown because the result was similar to that at point B.

From Fig.3 and Table 1, the values from built-in illuminance sensors of ARROWS and XOOM are were relatively of high resolutions and a linearity was confirmed between them and the external illuminance meter measurements, but the values from the XOOM built-in illuminance sensor at position A (vertically and directly below the lighting fixture) were larger than those from the external illuminance

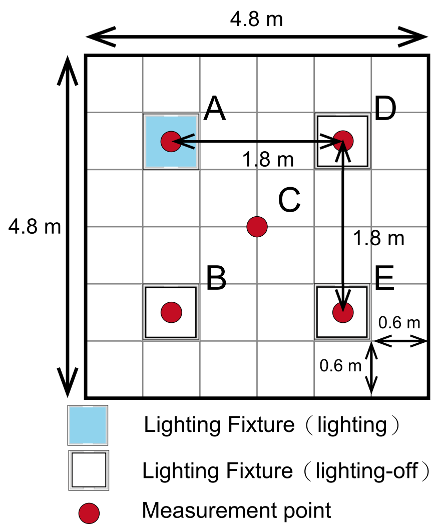

Fig. 2: Experimental environment for performance verification (top view)

meter. On the other hand, the values from AQUOS and INFOBAR showed greater gaps from external illuminance meter measurements, aside from low resolutions.

To sum up, the measurements from a built-in illuminance sensor of a smartphone significantly differ from the measurements from an external illuminance meter. For this reason, we will examine their effects on the control of an Intelligent Lighting System using built-in illuminance sensors of smartphones.

3.3 Considerations on the performance of built-in illuminance sensors

First, we will look at the resolutions of built-in illuminance sensors. It was demonstrated that the built-in illuminance sensors of the smartphones used in the experiment all had a resolution lower than that of the external illuminance meter. Meanwhile, as mentioned in section 2.2, an Intelligent Lighting System estimates the illuminance/luminance influence factor of each lighting fixture on an illuminance sensor from a regression analysis of the lighting's luminance change and the sensor's illuminance change, and use that estimate in an illuminance control algorithm. In the process, the luminance of the lighting fixture is varied by such a small extent unnoticeable to workers that illuminance sensors of a low resolution may not be able to show the change in illuminance

Table 1: The resolution of the illuminance sensor built in the smartphone

Smartphone's model	Resolution [lx]
ARROWS Z ISW 11F	7 - 8
XOOM	20 - 22
AQUOS PHONE ZETA SH-06E	50 - 500
INFORBAR C01	80 - 170

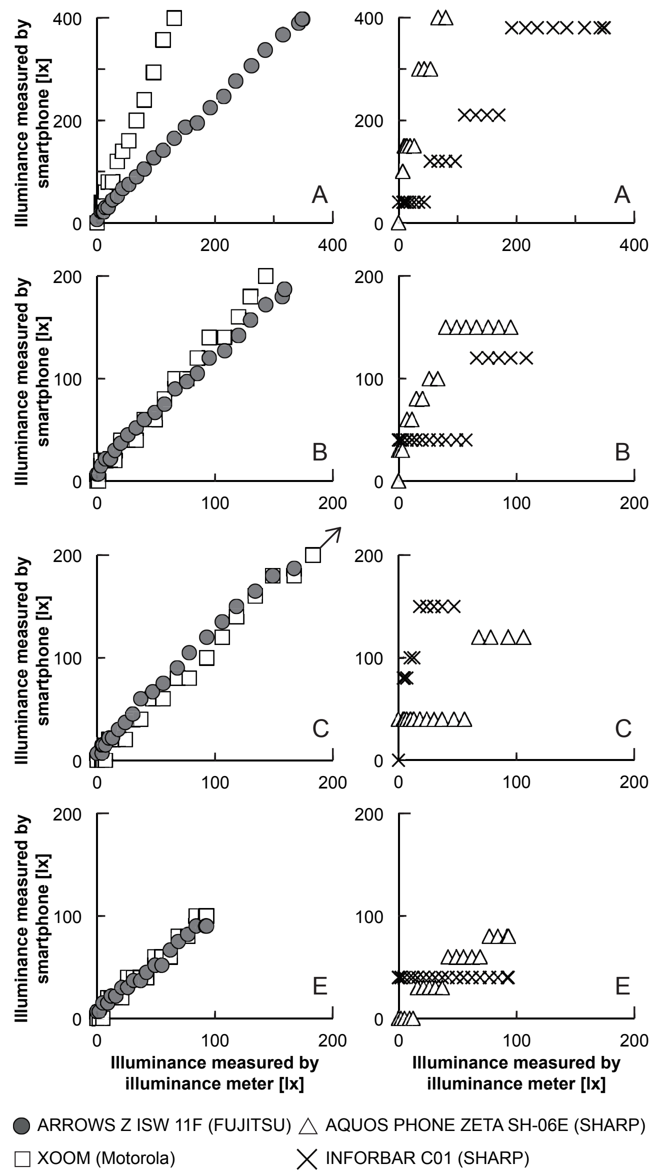

Fig. 3: The values from the illuminance sensor built in the smartphone

measurements in response to the microscopic change in luminance. Since the illuminance/luminance influence factor cannot be correctly estimated in such cases, convergence into an optimum lighting pattern is not easy. This gives rise to the need of a new method to estimate illuminance/luminance influence factor which can work properly with built-in illuminance sensors.

Next, let us think about the gap between built-in illuminance sensor measurements and the actual illuminance values. An Intelligent Lighting System sets the brightness required by each worker as a target illuminance value for each illuminance sensor, then controls the luminance of lighting fixtures so that the target will be met. However, when smartphone's built-in illuminance sensors are used, there occurs a gap between their measurements and the actual illuminance values, necessitating some idea to solve this gap.

These are considered to be the challenges for using smartphone's built-in illuminance sensors for an Intelligent Lighting System.

4. Individual illuminance control using built-in illuminance sensors of smartphones

4.1 Determining illuminance/luminance influence factors based on a position estimation method

Here we discuss a new method to estimate illuminance/luminance influence factors, which we mentioned as a challenge in section 3.3. This method determines an illuminance/luminance influence factor by estimating the approximate position of a smartphone. Note that the illuminance/luminance influence factor used in this method does not take into account the effects of light reflected by walls nor degradation of lighting fixtures. Since the system controls illuminance by varying the luminance of lighting fixtures, this study will utilize the change in the luminance of lighting fixtures for estimating smartphone positions.

From section 3.2, it is confirmed that, although smartphone's built-in illuminance sensors have low resolutions, the output values can be raised by intensifying light above a certain extent. Therefore, a binary search approach is applied to estimate a smartphone position. The concept is shown in Fig.4(1) to (4). The control flow for the position estimation is shown below.

1) From the initial status, divide all lighting fixtures in the room into two groups
2) For each of the divided groups, change the luminance of lighting fixtures uniformly by a degree unnoticeable to workers [10], to cause an illuminance change greater than the resolution of the built-in illuminance sensor
3) The built-in sensor on the smartphone measures the changes in illuminance values caused in step 2)
4) Choose the group showing a greater change in illuminance as measured in step 3), and divide it again into two groups
5) Return to step 2)

In case lighting fixtures are arranged in an odd number of rows as in the case of Fig.4(3), the central row is regarded as belonging to both groups for the purpose of control. In case a smartphone is positioned around the middle of the two groups, there may be only little difference between the values of change obtained from the built-in illuminance sensor. In that case, the adjacent ends of the two groups are combined

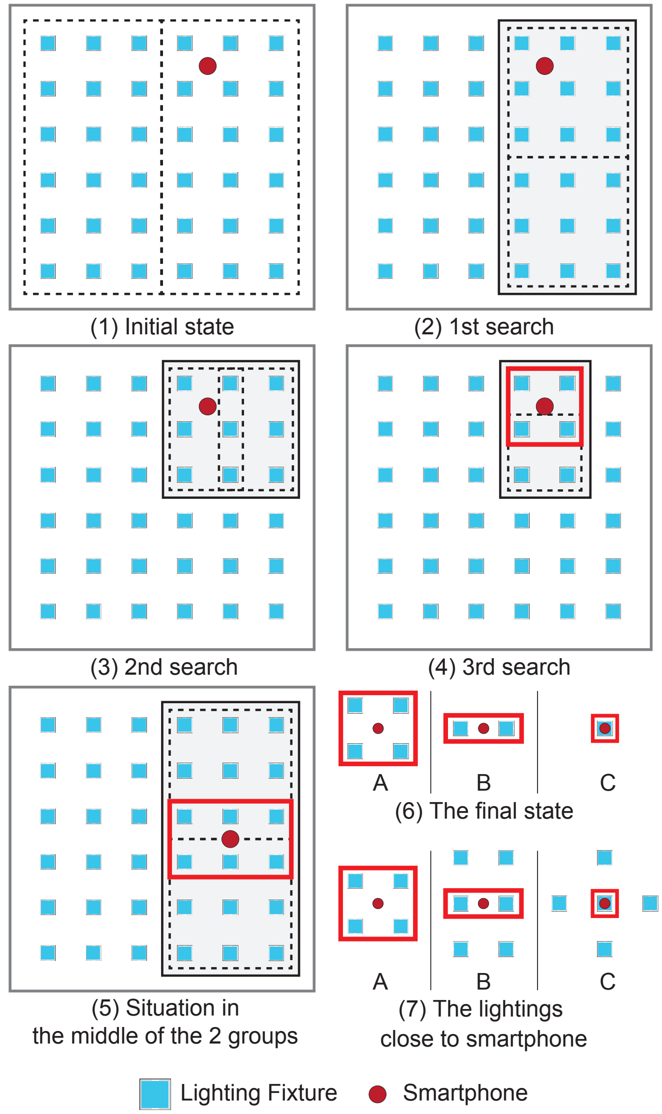

Fig. 4: The concept of proposal position estimation

into a group as shown in Fig.4(5) for the purpose of search.

Since the lighting fixtures significantly affecting the built-in illuminance sensor are basically the four around it, when the scope of search is reduced to the size of 2 lines $\times$ 2 rows, the search is deemed to reach an end. The search results are classified into patterns A to C shown in Fig.4(6). The smartphone is positioned around the center of four lighting fixtures in pattern A, around the middle of two lighting fixtures in pattern B and right below a lighting fixture in pattern C. Since pattern B and pattern C result in less than four lighting fixtures, also other nearby lighting fixtures are defined as "lighting fixtures close to the smartphone" as shown in Fig.4(7). A group resulting in 2 lines $\times$ 1 row is treated in the same way as pattern B.

Next, from the result of position estimation, the illuminance/luminance influence factor is determined. For this purpose, a preliminary experiment was conducted in which accurate illuminance/luminance influence factors were calculated for each of the patterns A to C shown in Fig.4(7) using an external illuminance meter, and the resulting values were associated with those lighting fixtures which were judged to be close to the smartphone according to the position estimation results. In this way, the lighting fixtures picked up through the position estimation process can be controlled by an algorithm described in section 2.2.

4.2 Solution to a difference between a built-in illuminance sensor measurement and the actual illuminance value

This section discusses how to solve the problem of a difference between built-in illuminance sensor measurements and the actual illuminance values. As a first step, for the purpose of this study, we propose an approach to solve the problems stemming from this difference without correcting the built-in illuminance sensor measurements, provided that a single type of smartphones of a relatively high resolution are used.

In an Intelligent Lighting System, a target illuminance is set by the user (worker) designating a preferred brightness level as an illuminance value. However, designating an illuminance value is just one of the ways for an individual to set a preferred illuminance level: what a worker essentially requires is not illuminance as an absolute value. For this, a target illuminance may be configured in a relative approach, in which the user chooses whether to raise or lower illuminance from the current level. In this approach, each time the worker raises or lowers the illuminance setting in relative terms, the target illuminance value held inside the system is changed, and each lighting fixture controls its luminance to bring the built-in illuminance sensor measurement as close as possible to the target value. If the built-in illuminance sensor measurement is in a linear relation with the actual illuminance value, it is not necessary to show the sensor measurement to the worker: the worker can realize a preferred illuminance simply by increasing or lowering the target illuminance relative to the current setting. A sample user interface on a smartphone in this approach is shown in Fig.5.

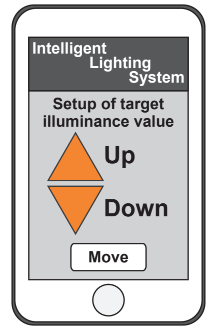

Fig. 5: The concept of operation screen for smartphones

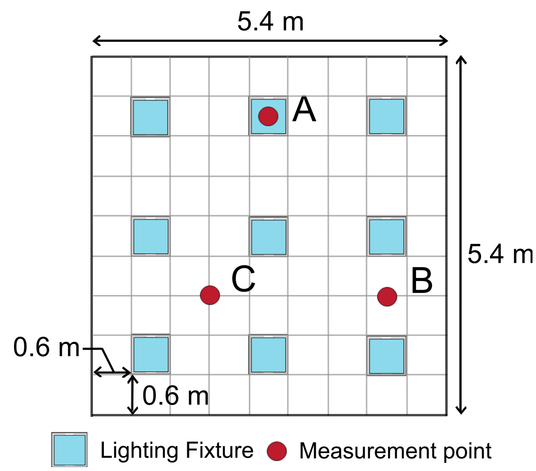

Fig. 6: Experimental environment

5. Verification experiment

5.1 Experiment summary and conditions

A verification experiment was conducted for an Intelligent Lighting System using smartphones based on the proposed method. In the experiment, 3 smartphones and 9 lighting fixtures were set up as shown in Fig.6 in a room without natural light. Based on section 3.2, ARROWS Z ISW 11F was selected as a smartphone model for this purpose, the type with the highest-performance built-in illuminance sensor. As lighting fixtures, white LED lamps manufactured by Panasonic Corporation (controllable between 20% and 100%, maximum lighting luminance is 1040 cd). The lighting fixtures were installed at 1.8 m intervals, which is a distance commonly used in typical office environments.

In this experimental environment, as shown in Table 2, the target illuminance value preset on each smartphone was changed at the point of 650 seconds after the start of the experiment. The initial luminance setting of each lighting fixture was 100%. Under these conditions, each smartphone estimates lighting positions, determines illuminance/luminance influence factors and starts a search for an optimum lighting pattern.

5.2 Experiment result

Fig.7(a) shows the history of values obtained from the built-in illuminance sensors of the each smartphone. The

Table 2: Setup of the target illuminance values

	A [lx]	B [lx]	C [lx]
First target illuminance	600	450	300
Second target illuminance	300	450	600

chart shows that the three smartphones completed estimating the lighting positions and illuminance/luminance influence factors in about 50 seconds, and the illuminance sensor measurements converged to the target value in about the next 50 seconds.

Fig.8(a) shows the status of lighting at the point of 500 seconds from Fig.7(a). This figure shows the percentage of luminance of each lighting fixture to its maximum luminance, with the size of the circle representing the luminance percentage. The figure shows that the lights with a large influence on the built-in illuminance sensors light up strongly, while those inessential for realizing the illuminance targets set on the smartphones light up at a minimum luminance level. The fact that convergence to the target illuminance was realized in this lighting status confirms that the position estimation by smartphones was effective for controlling each light. Next, Fig.7(b) shows the history of actual illuminance measured by an illuminance meter at the same points. This chart shows that the built-in illuminance sensor measurements and the actual illuminance values were controlled at equivalent levels, confirming that using built-in illuminance sensors can also maintain actual illuminance at a constant level.

Furthermore, the target illuminance settings on smartphones A and C were changed at the point of 650 seconds after the experiment start. Fig.7(a) shows that the measurements by smartphones converged to the target illuminance levels in about 70 seconds from the target change, which confirms that using smartphones can also cope with changes to the target luminance.

Fig.8(b) shows the status of lighting at the point of 1,100 seconds from Fig.7(a). This figure shows the percentage of illuminance of each lighting fixture. Just like the lighting status before change shown in Fig.8(a), it shows that lighting fixtures with strong influence on the built-in illuminance sensors are lighted strongly. Furthermore, the lights which had been lit strongly before the change to the target illuminance are now lowered after the luminance targets were changed on smartphones. These results demonstrate that an Intelligent Lighting System using smartphones as illuminance sensors can respond to changes to target illuminance and realize an appropriate individual lighting control.

6. Conclusion

By using the proposed method, smartphones of a single model can substitute for illuminance sensors used in an Intelligent Lighting System, provided that their built-in illuminance sensors have a high resolution. A verification experiment demonstrated that the actual illuminance can be maintained at a constant level even when smartphone's built-in illuminance sensors are used. Moreover, even though the built-in sensor measurements differ from actual illuminance values, the approach proposed in section 4.2 can realize illuminance levels preferred by the worker.

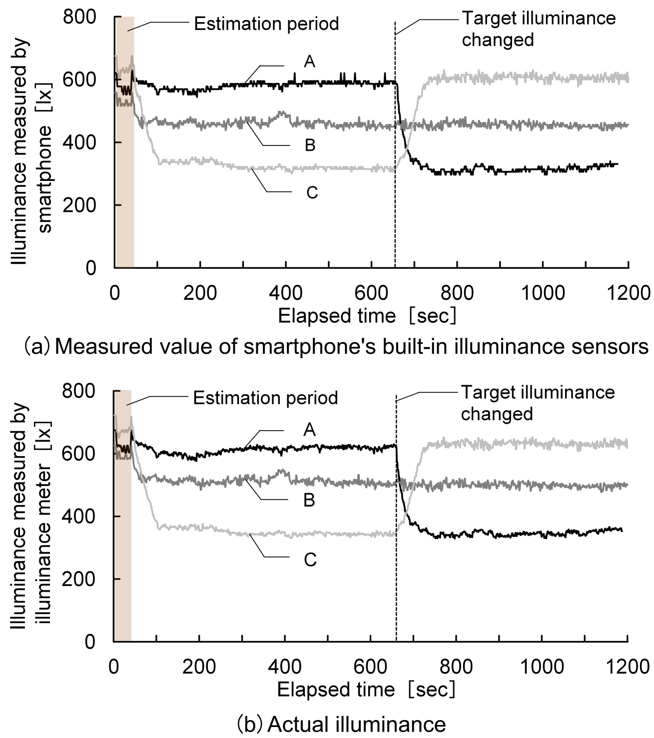

Fig. 7: The history of illuminance data

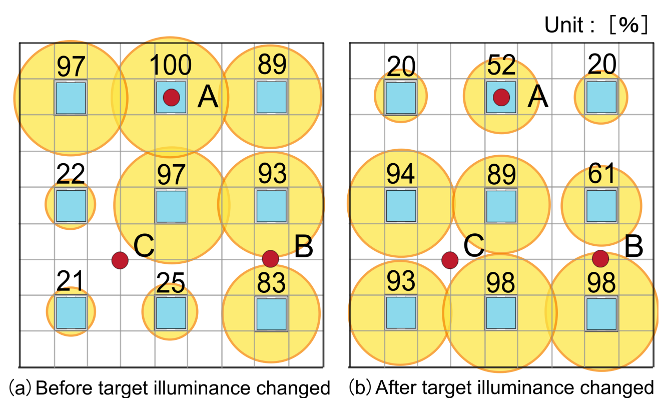

Fig. 8: The status of lightings

In future, we plan to study such topics as individual illuminance control in an environment with multiple smartphone models, or position estimation in a shorter time period.

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