Verification of the position estimation method of the smartphone by using visible light communication and its application to Intelligent Lighting System

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Abstract— *The Intelligent Lighting System controls individual lighting fixtures in accordance with illuminance information obtained from the illuminance sensor assigned to each worker and provides preferred illuminance to each worker. We established a method to realize the Intelligent Lighting System by using an illuminance sensor embedded in a smartphone instead of a standalone illuminance sensor. The Intelligent Lighting System turns on each lighting fixture in the optimal lighting pattern that minimizes power consumption by estimating the positional relationship between illuminance sensors and lighting fixtures. This study proposes a method for estimating the location of a smartphone by visible light communication. The proposed method enabled completing location estimation in 2 seconds regardless of the number of smartphones and obtaining the optimal lighting pattern in a shorter time than before.*

Keywords: Lighting Control, Illuminance, Smartphone, Position Estimation

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. Against this backdrop, the authors proposed an Intelligent Lighting System which individually realizes illuminance levels required by individual workers while saving power consumption[1].An Intelligent Lighting System is a system to realize required illuminance at the position where an illuminance sensor is installed with minimum power consumption. We established a method to realize the Intelligent Lighting System by using an illuminance sensor embedded in a smartphone instead of a standalone illuminance sensor[2]. Since smartphones have a built-in illuminance sensor for screen brightness control, they may be utilized as illuminance sensors for Intelligent Lighting System. 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.

When the Intelligent Lighting System controls individual lighting fixtures, it needs to determine the effect of each lighting fixture on each illuminance sensor (referred to as "illuminance/luminance influence factor") in order to realize an efficient lighting pattern. As a method to determine this illuminance/luminance influence factor, the Intelligent Lighting System using smartphones estimates the positional relationship between lighting fixtures and smartphones[2]. On the basis of the estimated positional relationship, the Intelligent Lighting System preferentially brightens lighting closer to smartphones, namely, those with a greater illuminance/luminance influence factor, in increasing lighting and preferentially dims lighting further from smartphones, namely, those with less illuminance/luminance influence factor in decreasing lighting. An efficient lighting pattern that curbs power consumption is realized by such lighting control. In our preceding study, we reported a method for estimating smartphone's position using binary search[2]. With the binary search method, however, the number of lighting control steps required for search increases as the number of smartphones searched increases. Therefore, it is considered that a large amount of time is required for search in an environment with many smartphones. Thus, this study proposes a position estimation method using visible light communication as one whereby search times do not depend on the number of smartphones and verifies the Intelligent Lighting System in which this method is implemented.

Many studies have reported on visible light communication[3][4]. Visible light communication refers to wireless data communication using light visible to human eyes (visible light) as transmission media. It is drawing attention not only as a conventional data communication method but also as a new position estimation method in an indoor environment where position estimation by GPS, etc. is difficult. On the other hand, since an illuminance sensor is built in a smartphone, visible light communication using a smartphone as a receiver is considered to be possible. The performance of smartphone built-in illuminance sensors differ, however, by smartphone models, which is considered to result in difference in the speed and range of visible

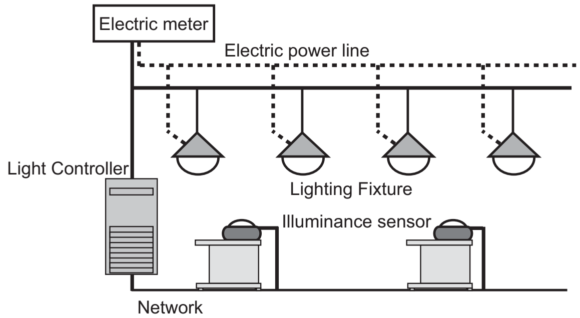

Figure 1: The construction of an Intelligent Lighting System

light communication by smartphones. This study thus examines, first of all, the response to luminance changes and communication range of the built-in illuminance sensor of different smartphone models. We then show the effectiveness of the proposed method by demonstrating that the convergence of illuminance to the illuminance preferred by a worker is possible by conducting position estimation by visible light communication.

2. Intelligent Lighting System

2.1 Configuration of Intelligent Lighting System

Figure 1 shows the construction of an 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[1]. 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 installed on each lighting fixture changes luminance within the range undetected by a worker using an optimization method on the basis of illuminance and power consumption information. By repeating this, illuminance required by a worker is realized with power saving.

Using an algorithm based on simulated annealing, the Intelligent Lighting System solves, for each lighting fixture, an optimization problem with the luminance of each lighting fixture as the design variable, the target illuminance of each illuminance sensor as the constraint, and the power consumption under the total illuminance as the objective function in an autonomously distributed manner. Namely, the luminance of each lighting fixture is randomly changed within the range undetected by a worker for each search to search for the optimal lighting pattern. An illuminance/luminance influence factor is set for each lighting fixture in accordance with its positional relationship with each illuminance sensor, and a random change in luminance is made to have directionality in accordance with the degree of the effect.

One time search constitute a single step, and lighting is controlled by repeating the step every 2 seconds. The objective function of each function is represented by Formula (1).

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

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

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

i: Number of lightings, j: Number of sensors
P: power consumption[W], ω: weight[W/lx]
Ic: current illuminance[lx], It:target illuminance[lx]
r: illuminance/luminance influence factor (regression coefficient), T:threshold value

The objective function represented by Formula (1) is composed of power consumption P and illuminance constraint g and calculated for each lighting fixture. Penalty g whose constraint is the target illuminance of each illuminance sensor changes by the illuminance/luminance influence factor. The system functions in such a manner that only a lighting fixture with a large illuminance/luminance influence factor is significantly affected by penalty. In addition, by setting the threshold T to illuminance/luminance influence factor r, lighting fixtures affecting a given illuminance sensor can be narrowed down to those in its neighborhood. This causes lighting fixtures far from the illuminance sensor to be controlled to minimize power consumption.

2.2 Intelligent Lighting System using smartphones

It is conceivable to substitute illuminance sensors of the Intelligent Lighting Systems with smartphones, which have widely spread in recent years. Using smartphones as illuminance sensors has advantages such as reducing cost for installing dedicated sensors, improving serviceability by using generic parts, etc. An illuminance sensor for adjusting screen brightness is embedded in a smartphone, and it is possible to obtain illuminance by using it. Our previous study reported the effectiveness of the Intelligent Lighting System using smartphones as illuminance sensors by obtaining illuminance by means of smartphone built-in illuminance sensors[2].

3. Performance verification of smartphones

3.1 Response performance

Smartphones have an illuminance sensor built in for adjusting screen brightness, whose performance is considered

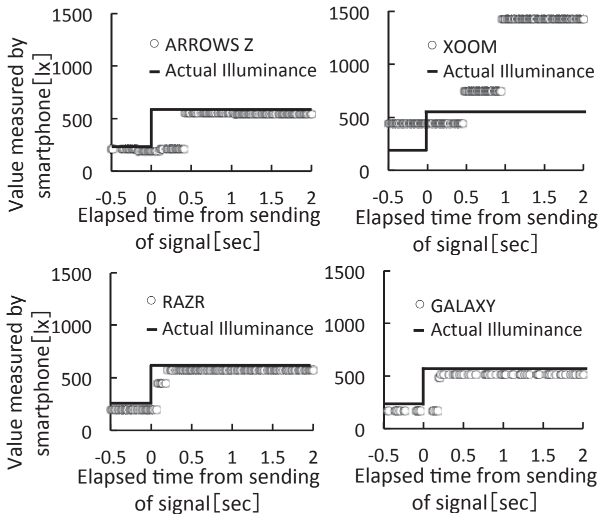

Figure 2: The history of illuminance given by smartphones

to vary by smartphone models.

We examined the response performance of smartphone built-in illuminance sensors in order to determine data communication speed in performing visible light communication using smartphones. Built-in illuminance sensors do not obtain a correct illuminance value immediately in response to a change in luminance of the lighting fixtures, and it takes some time for illuminance values to converge to the correct one. In visible light communication, time required for sending data of 1 bit is considered as time after a lighting fixture's luminance changes and by the time when a built-in illuminance sensor manages to measure the change correctly. Thus we conducted a verification experiment to measure time after a lighting fixture's luminance changes and by the time a built-in illuminance sensor measures the change correctly.

Smartphones ARROWS Z, made by Fujitsu, XOOM and RAZR, made by Company Motorola, and GALAXY, made by Company Samsung were used. The LED lighting system by Company Sharp was used, which can be controlled in 1,000 stages. The lighting fixture was turned on at constant luminance in advance, and the illuminance on the top of a desk directly under the lighting fixture which was 70 cm high above the floor was then measured with smartphones. The lighting luminance of the lighting fixture was subsequently increased by a certain amount. Then we measured time from the point when the lighting luminance rose to the time when illuminance values given by smartphones converged to a constant value. Luminance was set to 30% of the maximum lighting luminance before it was raised and 90% of the maximum after it was raised.

In order to measure a change in illuminance sensor precisely, an illuminance sensor NaPiCa made by Company Panasonic, capable of obtaining illuminance at an interval of about 1 ms, was placed adjacent to a smartphone to measure illuminance simultaneously.

Figure 2 shows the history of illuminance given by ARROWS Z, XOOM, RAZR, and GALAXY. The vertical axis of the graph indicates the illuminance value, and the horizontal axis, time from the transmission of a light control signal. The real change in illuminance measured by the illuminance sensor NaPiCa is shown in a solid black line. With every model in Figure 2, the illuminance value shown by the illuminance sensor NaPiCa rose almost simultaneously with signal transmission. It is thus found that the lighting fixture's luminance changed to a constant value immediately after signal transmission. It is also found from these graphs that with ARROWS Z, XOOM, RAZR, and GALAXY, it required 0.4 seconds, 1 second, 0.2 seconds, and 0.2 seconds respectively for the illuminance value to converge to a constant value after signal transmission. In this way, it was confirmed that time until convergence to a constant value differs by smartphones measuring illuminance.

Table 1 shows the result of measurement. The column Model in Table 1 shows models examined. The column Time shows the response time of built-in illuminance sensors. The longest response time recorded in 10 times of measurement is shown for each sensor. Values in this column can be regarded as transmission time per bit in visible light communication. Let RAZR, which yielded the shortest response time among smartphones shown in Table 1 shall be referred to as "Smartphone1," and GALAXY, which yielded the second shortest response time, as "Smartphone2."

Figure 3 shows the history of illuminance recorded when an information bit string (referred to as "Lighting ID") of "0101" is transmitted by actually changing a lighting fixture's lighting luminance, with the illuminance value obtained by Smartphone2 placed directly under the lighting fixture. The solid line shows the actual change in the lighting fixture's illuminance. The transmission speed in this instance was set to about 5 bps based on the result in Table 3. The lighting fixture's lighting luminance corresponding to a Lighting ID was set to 100% of the current luminance when a Lighting ID is 1 and 90% when a Lighting ID is 0. Figure 3 tells that Smartphone2 managed to obtain the change in illuminance corresponding to signal value transmitted.

3.2 Distance which can engage in visible light communication

When visible light communication is performed between a smartphone and a lighting fixture, it is necessary to change

Table 1: The response time

Model	Time [sec]
ARROWS Z	0.64
XOOM	1.22
RAZR(Smartphone1)	0.15
GALAXY(Smartphone2)	0.19

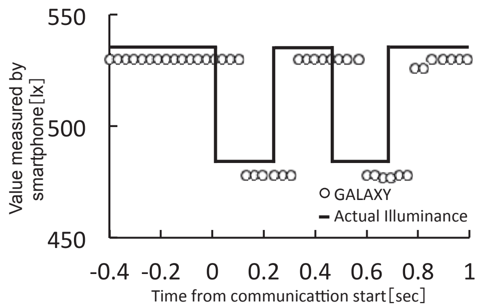

Figure 3: The history of illuminance when the Lighting ID of "0101" is transmitted

the lighting fixture's luminance within the extent that the change remains undetected by workers[5]. Since the range of an illuminance change which a VDT worker cannot detect is within 10% of the current illuminance, the luminance of a lighting fixture used in visible light communication in this study is changed by 10%. The distance between a lighting fixture and a smartphone that can detect the change in luminance of the lighting fixture is considered to differ by the smartphone's model. Thus, for each model, we measured the distance between a smartphone and a lighting fixture which can engage in visible light communication.

A lighting fixture was turned on at constant luminance and then the lighting luminance was raised by 10%. We measured the location of a smartphone which can detect the change in luminance was placed by measuring the horizontal distance from the point directly under the lighting fixture to the location of the smartphone. This distance can be regarded as the range within which visible light communication is possible. Table 2 shows the detection range of Smartphone1 and Smartphone2 when the lighting fixture was turned on at the maximum lighting luminance and minimum lighting luminance. The minimum lighting luminance was set to 30% of the maximum lighting luminance. Since lighting fixtures are generally placed at an interval of 1.8 m, based on Table 2, it is found that, even under minimum lighting luminance, where the possible range of visible light communication is the smallest, signals transmitted by multiple lighting fixtures interfere with each other.

Therefore, we conducted an experiment verifying the range in which a Lighting ID can be received in a case where multiple lighting fixtures transmit Lighting IDs which are different from one another. Different Lighting IDs were sent by two lighting fixtures A and B placed at an interval of 1.8 m, shown in Figure 4. "1010" was transmitted from the

Table 2: The detection range

Model	Distance(max luminance) [m]	Distance(min luminance) [m]
Smartphone1	1.3	1.1
Smartphone2	2.6	1.8

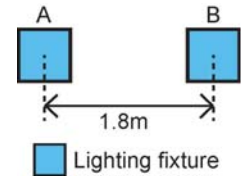

Figure 4: The preliminary experimental environment

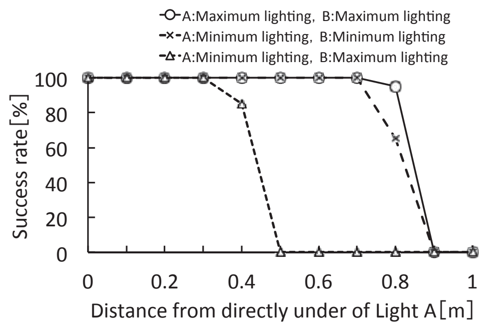

Figure 5: The rate of successful reception

lighting fixture A, and "0101," from the lighting fixture B. The lighting fixture's lighting luminance corresponding to a Lighting ID was set to 100% of the current luminance when a Lighting ID is 1 and 90% when a Lighting ID is 0. A smartphone was placed on the top of the desk along the line connecting the point directly under the lighting fixture A and the point directly under the lighting fixture B. The horizontal distance was measured between the point directly under the lighting fixture A and the point where the smartphone can detect the Lighting ID "1010." Figure 5 shows the rate of successful reception of the transmission of the Lighting ID in 20 attempts at each distance. The smartphone model used was Smartphone2, and the transmission speed was set to 5 bps. The result in Figure 5 tells that the distance at which the Lighting ID of the lighting fixture A can be received correctly at the probability of 100% is 0.7 m if both the lighting fixture A and the lighting fixture B are at the maximum or minimum lighting level and 0.3 m if the lighting fixture A is at the minimum lighting level with the lighting fixture B being at the maximum lighting level. Therefore, it was found that, even if the lighting luminance of a lighting fixture closest to a smartphone is minimal with the lighting luminance of other lighting fixtures being maximal, a correct Lighting ID can be received if a smartphone is placed within 0.3 m of the point directly under the nearest lighting fixture. The minimum lighting luminance was set to 30% of the maximum lighting luminance.

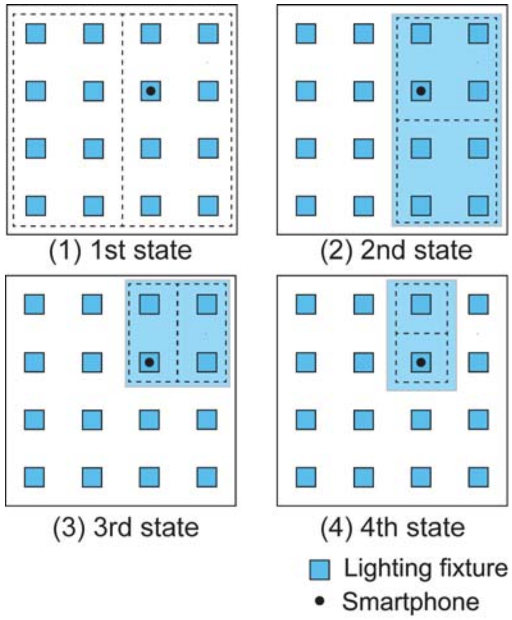

Figure 6: The concept of the binary seach method

4. A position estimation method of a smartphone using visible light communication

4.1 A conventional position estimation method

A position estimation method using binary search has conventionally been used in calculating an illuminance/luminance influence factor in the Intelligent Lighting System using smartphones. Conceptual diagrams for a binary search method are shown in Figure 6. Diagrams (1) through (4) in Figure 6 show an office environment in which 16 lighting fixtures were placed. First, lighting fixtures in the room are classified into 2 groups, as in (1) in Figure 6, and the luminance of lighting fixtures are changed uniformly in each group in such a range that workers do not perceive the change. Then, since a group closer to the smartphone causes a greater change in values obtained by a smartphone built-in illuminance sensor, it can be determined which group is closer to the smartphone by comparing the amount of change by groups. By recursively searching a group determined to be closer, as shown in (2), (3), and (4) in Figure 6, an approximate position of the smartphone can be narrowed down.

Next, an illuminance/luminance influence factor is determined based on the result of the position estimate. A preliminary experiment is conducted in advance using an illuminance meter for obtaining the precise illuminance/luminance influence factor at each location, and values thus obtained are assigned to lighting fixtures determined to be closer to the smartphone. An illuminance/luminance influence factor corresponding to the position of the smartphone can then be obtained.

In searching multiple smartphones, however, lighting fixtures need to be classified into groups for each smartphone under the binary search method. Consequently, as the number of smartphones to be searched increase, the required frequency of lighting control increases. Therefore, it is considered that a large amount of time is required for position estimation in an environment with many smartphones to be searched.

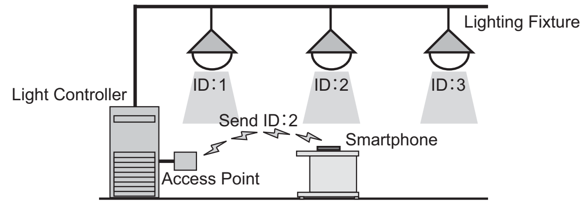

Figure 7: The position estimation method using visible light communication

4.2 A position estimation method using visible light communication

Figure 7 is a conceptual diagram for the position estimation method using visible light communication. In Figure 7, by changing luminance through repeated lighting in a pattern unique to each lighting fixture, a Lighting ID composed of 1 and 0 unique to each lighting fixture is transmitted. A built-in illuminance sensor of a smartphone measures changes in illuminance and receives a Lighting ID by analyzing illuminance values measured to determine it. The smartphone then transmits a Lighting ID received to a control device. The control device determines that the smartphone is located in the neighborhood of the point directly under the lighting fixture whose Lighting ID is transmitted to complete position estimation.

4.3 Proposal of the position estimation method using visible light communication

Visible light communication using smartphones can realize the communication speed of about 5 bps, if Smartphone1 or Smartphone2 is used, based on the result of performance verification in Section 3.1. As stated in Section 2.1, the lighting control algorithm of the Intelligent Lighting System repeats a control step every 2 seconds. Therefore, this study required completing position estimation in a single step of 2 seconds. In assigning a unique Lighting ID to each of about 100 lighting fixtures in a large office environment, the required length of a is 7 bits. In conducting visible light communication by using the algorithm shown below, 2 bits for a control signal are required in addition to the number of bits for a Lighting ID. Since the communication speed in

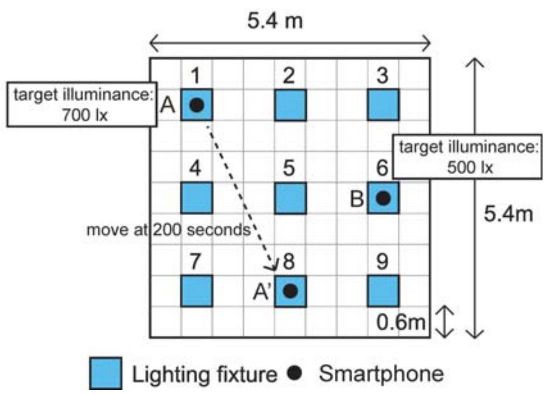

Figure 8: Experimental environment

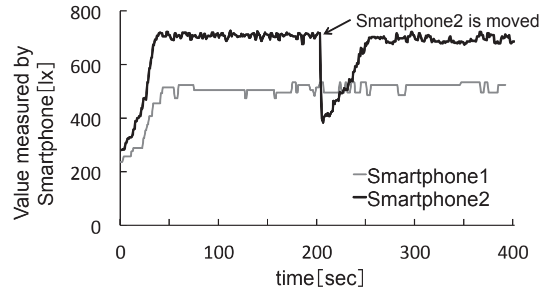

Figure 9: The history of illuminance data

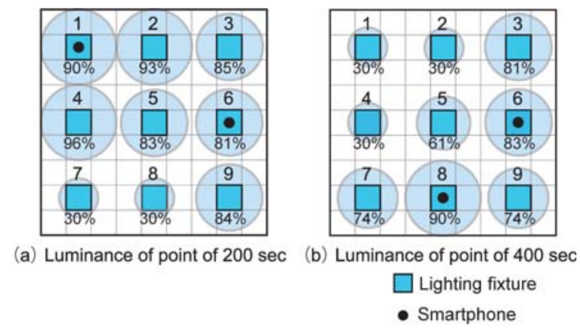

Figure 10: The status of lightings

transmitting the total of 9 bits in a single step of 2 seconds is 4 to 5 bps, position estimation can be completed in a single step by using Smartphone1 and Smartphone2, which can realize the speed of 5 bps.

The algorithm for position estimation by visible light communication is described below.

(1) Suspend luminance control for convergence to the target illuminance.
(2) Save the illuminance value of a smartphone under the current luminance as the standard value.
(3) Turn on all lighting fixtures at the lighting luminance of 90% of the current luminance and save the illuminance value of a smartphone as a standard value, as in (2).
(4) Turn on each lighting fixture at the lighting luminance of 100% or 90% of the luminance at the start of visible light communication in accordance with a Lighting ID uniquely assigned to each lighting fixture. Set lighting luminance to 100% if a Lighting ID is 1 and 90% if a Lighting ID is 0. At the same time, measure a change in illuminance by a smartphone. Set the median of standard values obtained in (2) and (3) as the threshold. Receive the Lighting ID "1" if an illuminance value is higher than the threshold and the Lighting ID "0" if it is lower than the threshold. Repeat this processing for the number of bits of a Lighting ID.
(5) Determine that the smartphone is placed directly under the lighting fixture corresponding to the Lighting ID received by it and finish position estimation.
(6) Determine the illuminance/luminance influence factor of each lighting fixture based on the result of position estimation by the method described in Section 4.1.
(7) After finishing position estimation, resume convergence to the target illuminance.

5. Verification experiment

5.1 Experiment summary and conditions

An experiment verifying the effectiveness of this method was conducted by actually running the Intelligent Lighting System incorporating the proposed method. Base on the result in Table 1, one Smartphone1 and one Smartphone2 were used in this verification experiment.

In an experiment environment shown in Figure 8, Smartphone2 and Smartphone1 were placed at locations A and B, respectively, to estimate the positions of those smartphones. During visible light communication, the signal communication speed was set to 5 bps and the number of communication bits was set to 9.Based on the result in Figure 4 in Section 3.2, the range of visible light communication was set to within the horizontal distance of 0.3 m of the point directly under a lighting fixture. After completing position estimation, the Intelligent Lighting System was run to start illuminance convergence to the target illuminance. The target illuminance was set to 700 lx for the smartphone Smartphone2 at location A and 500 lx for Smartphone1 at location B. At 200 seconds after starting illuminance control, S2 placed at location A was moved to location A' indicated in Figure 8. The movement was made in 10 seconds. After moving the smartphones, their positions were estimated again. After the position estimation was completed, convergence to the target illuminance was resumed.

5.2 Experiment result

Figure 9 shows the transition of illuminance values obtained from illuminance sensors built in the smartphones. The horizontal axis of the graph indicates elapsed time, and the vertical axis, illuminance values from smartphones. The result of the experiment shows that the estimation of the position of the smartphone at location A was completed in about 2 seconds from the start of control and that processing started subsequently for realizing the target illuminance. Figure 9 tells that illuminance converged to target illuminance in about 50 seconds after the start of control. As the movement of the smartphones started at 200 seconds after the start of control, the measured value sharply decreased then. Figure 9 tells that, after the movement, illuminance converged to the target illuminance of 700 lx and 500 lx.

Next, Figure 10 shows the lighting state of lighting fixtures at 200 seconds and 400 seconds in Figure 9. The value indicated under each lighting fixture represents the lighting luminance of the lighting fixture with the maximum value as 100%, and a circle centered at each lighting fixture is intended to visualize its lighting luminance. Based on Figure 10, it was confirmed that the luminance of lighting fixtures near smartphones increased both before and after the movement and that the luminance of distant lighting fixtures was 30% of the minimum lighting luminance. As convergence to the target illuminance was realized in this lighting state, it was confirmed that the position estimation of smartphones was effective in controlling lighting fixtures.

5.3 Experiment conclusion

The proposed method was successful in estimating the positions of smartphones. In addition, the Intelligent Lighting System managed to realize an optimal lighting pattern even when a smartphone was moved, by obtaining the illuminance/luminance influence factor from the location estimated by the proposed method and increasing the luminance of lighting fixtures near the smartphone. It was also shown that, in visible light communication, it was possible to realize communication speed of 5 bps and estimate the positions of smartphones in about 2 seconds even with 100 lighting fixtures if a smartphone model with a faster response speed to an illuminance change was used.

In the position estimation by the proposed method, however, it is difficult to receive a Lighting ID precisely if a smartphone is placed under a point between multiple lighting fixtures as Lighting IDs of those lighting fixtures interfere with each other. A visible light communication method using a camera built in a smartphone can be cited as a solution to this problem. If a smartphone is placed on the top of a desk, two or more lighting fixtures can always be in its camera's viewing angle if they are installed at a common interval of 1.8 m. By sending a unique Lighting ID from each lighting fixture, a smartphone can receive multiple Lighting IDs at the same time. It is considered possible to estimate even the position of the smartphone placed under a point between multiple lighting fixtures by having the smartphone distinguish lighting fixtures by Lighting IDs it receives and identify the positional relationship among lighting fixtures by image processing.

6. Conclusion

This study examined the response performance of illuminance sensors built in smartphones and managed to perform visible light communication at the speed of 5 bps by using smartphones with a built-in illuminance sensor with short response time to an illuminance change. It then verified the method for estimating the position of a smartphone using visible light communication in the Intelligent Lighting System using smartphones as illuminance sensors and showed that a smartphone can be used in the Intelligent Lighting System only if it was placed near the point directly under a lighting fixture.A position estimation method for cases where a smartphone is placed under the point between multiple lighting fixtures needs to be examined in the future by further working on visible light communication using a camera built in a smartphone.

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