Implementation of Light Quality Evaluation System using Smartphone

Yang-Soo Kim¹, Sook-Youn Kwon² and Jae-Hyun Lim^{1*}

^{1, 1*}Dept. of Compute Science Engineering, Kongju National University ²Smart Natural Space Research Center, Kongju National University ¹kmarine89@kongju.ac.kr, ²sookyoun@kongju.ac.kr, ^{1*}defacto@kongju.ac.kr

Abstract

According to recent research result that light not only offers psychological and emotional stability to an occupant, but affects human's health, efforts to improve the indoor lighting environment are increasingly made. Looking into existing studies, lighting's hardware performance has been evaluated using high-priced measuring equipment in order to identify the characteristics of suitable light according to space type and resident's activity, or user satisfaction has been assessed through a survey method. However, efficiency is low from the cost and reliability aspects, since these methods are dependent upon high-priced measuring equipment, the size of patent group and survey questions. This paper implements a smartphone-based light quality evaluation system through which light characteristics can be measured or quality can be evaluated anywhere, anytime using a mobile device that a user always possesses, and such a system that supports readjusting to the user-preferred lighting environment depending on situation. The proposed system's processing process is as follows: The smartphone located around a user measures the currently-serviced light characteristics from the embedded RGBW color sensor. The RGBW sensing data are converted into tristimulus values XYZ, and then color coordinate xy, color temperature CCT and illuminance Y are calculated. Lastly, this study proves the proposed system's performance by evaluating whether the lighting environment suitable for the current situation is serviced, based on KS Illuminance Standard, and Naoyuki Oi' graph.

Keywords: light equality evaluation system, Smartphone, Mobile application, LED

1. Introduction

Light has an important effect on human's mental and physical health and work efficiency, as well as decides human's visual perception [1-3]. Especially, the characteristics of light's luminance, color temperature and brightness have enormous influences on the work efficiency and life pattern of modern people staying in the office and residential space for a long time. Since the quality of lighting indoor space is closely associated with daily life and the retention of health, efforts to improve such a quality is necessary [4].

As relationship between light and human's emotional response is recently emphasized, studies to identify the suitable characteristics of light that change according to user's situation are carried out. Naoyuki Oi presented the combination of moderate illuminance and color temperature according to residential space, based on Kruithof's Curve. The researchers including Lee Jin-Sook, Kim Jong-Gurl and Jee Soon-Duk in Korea are undertaking studies on the lighting environment targeting various spaces such as office, lounge and classroom, as well as residential space [5-8]. The characteristics of light has been measured using high-priced measuring equipment to identify the light suitable for space type or occupant's work type, and user satisfaction has been evaluated through a survey method by composing a parent group [9-11]. Such a method has limitations in

drawing reliable and objective results according to the parent group size and evaluation method, and its efficiency is low from the cost aspect [10].

This study proposes a smartphone-based light quality evaluation system through which the characteristics of light serviced anywhere, anytime using a smartphone can be identified quantitatively, and the light quality can be evaluated. A smartphone that a user always possesses senses surrounding light characteristics with a certain cycle through the embedded RGBW color sensor, after the application is executed. After the smartphone converts RGBW sensor data into tristimulus values XYZ by a conversion process (RGBW->XYZ), the smartphone calculates optical attribute value of color coordinates, based on the tristimulus values XYZ. This study utilizes Naoyuki Oi's graph that presented the suitable combination of color temperature and illuminance according to user's four acts (gathering, studying, relaxing and retiring) as the standard for light quality evaluation depending on situation [5] [12]. A user can easily measure the surrounding light including lighting in indoor space through the proposed system, and identify detailed information or evaluate whether light suitable for the current situation is serviced. In addition, a user can readjust his/her preferred light through user interface, or the light can be automatically changed by the system. Lastly, an experiment is carried out by presenting standard indicators of illuminance and color temperature according to KS Illuminance Standard, after the characteristics of space and occupant's act type for system's performance evaluation are classified.

2. Experimental Environment and Method

2.1. Experimental Environment

This Chapter is about the calculation of RGBW->XYZ conversion equation targeting wWcW LED lighting, and about a basic experiment to build DB on the characteristics of light changing according to 0~255 range of illuminance level. To calculate the RGBW XYZ conversion equation, the characteristics change of experiment-targeted lighting should be measured by using the RGBW color sensor and colorimeter embedded in the smartphone. The smartphone and colorimeter used for the experiment is Galaxy S4 and CL-200A that embedded a RGBW color sensor of CM3323 model, respectively. The color sensor of CM3323 model senses the red, green, blue and white values, which are the color data. Colorimeter CL-200A outputs tristimulus values XYZ, color coordinate xy, color temperature CCT and illuminance Y value through conversion algorithm included in the measuring equipment.



Figure 1. Image of Experimental Space and Profile

Figure 1 shows a test bed for the measurement of light characteristics shaped as the dark room environment with the size of $1.2m \times 1.2m \times 2m$. In the experimental space, height-adjustable wWcW LED lighting is attached at the location 30cm apart vertically from the ceiling, and measuring equipment such as a smartphone and colorimeter is located. The distance from the floor to the lighting is 1.7m, and the design was made by referring to the ceiling height of general residential space (2.4m~2.5m), and the height of study and kitchen (0.7m~0.8m).

2.2. Experiment Method

The experiment consists of three-phase process: Lighting control, measurement of light characteristics and measured data storage. As shown in Figure 2, measure lighting and its characteristics with each measuring equipment (smartphone, colorimeter) and store the measurements in the DB through diming control of warm white LED and white LED sources of light in $0\sim255$ levels with a certain cycle, after an illuminance control application is developed using the Java language.

```
void mainProcess( ) {
    int w,c;
    for(w=0; w<=256; w+=4) {
        for(c=0; w<=256; c+=4) {
            if(w==256) w = 255;
            if(c==256) c = 255;
            controlLED(w,c);
            sleep(10000);
            storeLightFeatures();
        }
    }
}</pre>
```

Figure 2. Application Source for Lighting Control and Storage (Sample)

The controlLED(w, c) method in Figure 2 controls LED lighting by delivering the control rate values of warm white and cool white, which are parameters, as a parameter, respectively. After ten seconds, the data measured from the smartphone's RGBW color sensor and colorimeter are stored in the DB through storeData(). The stored data means RGBW color data, tristimulus values XYZ, color coordinate xy, color temperature and illuminance value.

2.2.1. DB of Light Characteristics: Table 1 shows MYSQL-based database structure designed for measured data storage, and the composition of each field in the table is as follows:

Field Name	Туре	Explanation	
warm	int	Control rate of warm white	
cool	int Control rate of cool white		
cl200a_lux	float	Illuminance of CL-200A	
cl200a_CCT	float	Color temperature of CL-200A	
cl200a_x	float	Color coordinate x of CL-200A	
cl200a_y	float	Color coordinate y of CL-200A	
cl200a-X	float	Tristimulus value X of CL-200A	
cl200a-Y	float	Tristimulus value Yof CL-200A	

Table 1. Table	Composition
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cl200a-Z	float	Tristimulus value Z of CL-200A
colorsensor-r	int	Red of CM3323
colorsensor-g	int	Green of CM3323
colorsensor-b	int	Blue of CM3323
colorsensor-w	int	White of CM3323

In the warm and cool fields in the table structure, LED lighting's control rate is stored, and cl200a_lux and cl200a_CCT fields mean the illuminance and color temperature values measured from a colorimeter. Also, in the cl200a_x, cl200a_y and cl200a_X, cl200a_Y and cl200a_Z fields, the color coordinate x, y and tristimulus values XYZ are stored. In the colorsensor_r/g/b/w fields, each digital signal value of red, green, blue and white sensed from the CM3323 color sensor embedded in the smarthphone is stored. By calculating a relational expression through the multiple regression analysis using tristimulus values XYZ measured from the colorimeter and RGBW data of the color sensor, the RGBW raw data collected through the smartphone-embedded color sensor can be converted as various lights' optical attributes. Tristimulus values XYZ on the converted RGBW through the RGBW->XYZ relational expression is used in calculating color coordinate xy, illuminance Y and color temperature CCT.

2.2.2. RGBW->XYZ Conversion: 4,096 light characteristics are stored in the DB table collected through the basic experiment. Among them, effective data are identified as 2,809, when only effective data are extracted. As a result of applying the multiple regression analysis targeting them, the conversion equation of Equation 1 was generated. The R-squared was demonstrated as 0.9996 on X, as 0.9995 on Y and 0.9992 on Z.

$$X = 0.0444R - 0.0263G + 0.0693B + 0.7264W - 0.075$$

$$Y = -0.0049R + 0.266G + 0.0771B + 0.360W - 0.319$$

$$Z = -0.236R + 1.388G + 0.1918B - 1.2026W - 4.243$$
(1)

Figure 3 shows the comparison of error rate among the converted XYZ data measured from the smartphone color sensor through Equation 1 and the XYZ data measured through the colorimeter. The mean and standard deviation of error rate were 0.954% and 1.222% on tristimulus value X, 1.0% and 1.305% on Y, and 4.047% and 5.988% on Z, respectively. In consideration of illuminance change that a person can recognize, the allowable limit of error is judged to be within 10%. Based on this, as a result of identifying the generation rate of tristimulus values XYZ exceeding the allowable limit of error, it was over 2.71% [13].



Figure 3. Error Rate of Tristimulus Values XYZ

2.2.3. Color Temperature Conversion: Equation 2 shows the relational expression of McCamy to calculate color temperature CCT from the color coordinate xy [14]. Because the conversion equation of McCamy uses only the color coordinate xy of the target lighting, the color temperature calculation method is known to be very easy, and suitable for LED lighting [15].

$$x = \frac{X}{X + Y + Z}, y = \frac{Y}{X + Y + Z}$$
$$n = \frac{x - 0.332}{y - 0.1858}$$
CCT = -437n³ + 3607n² - 6861n + 5514.31 (2)

As for the RGBW sensing data collected through smartphone's color sensor, the color temperature value is calculated by the following Equation 2, which was converted into tristimulus values XYZ through the RGBW XYZ relational expression. Figure 4 shows the error with the color temperature collected through converted color temperature and colorimeter, and the mean and standard deviation were 58.651K and 92.0K, respectively. Most data were less than the mean value. Therefore, they are at the level that an occupant cannot recognize visually [16].



Figure 4. Error Rate of Tristimulus Values XYZ

3. Light Quality Evaluation System

3.1. System Configuration

Figure 5 shows the entire configuration of the proposed system, and the system is divided into two areas: Smartphone application area for measurement and conversion of light characteristics and an area of application for server for lighting control. The entire hardware consists of smartphone, server, LED lighting, lighting controller and gateway.



Figure 5. System Configuration

The proposed processing process of the proposed system is as follows: The smartphone application measures the digital values of red, green, blue and white lights currently serviced through the RGBW color sensor. And then, RGBW color data are converted into tristimulus values XYZ data through RGBW \Box XYZ conversion algorithm. The converted tristimulus values XYZ data are utilized to calculate color coordinate xy, color temperature CCT and illuminance Y. Using the information, the currently serviced light's suitability is evaluated using the KS Illuminance Standard and Kruithof's Comfort Curve. The result is outputted through the user interface screen. In doing so, when a user wants to convert to the user-preferred light, the user inputs the control rate of each light source of lighting through the interface screen, and sends the information concerned to the server. In this way, the light can be readjusted.

3.2. System Implementation

3.2.1. Measurement and Conversion Algorithm: The following Figure 6 shows some source codes implemented to calculate color coordinate xy, color temperature CCT, and illuminance Y, after converting the smartphone-embedded RGBW data into tristimulus values XYZ.

```
void handleRedceiveMessage(float * arrayOfFloat)
ł
  double mc;
 if(rab == NULL) return;
  sensorR = arrayOfFloat[0];
  sensorG = arrayOfFloat[1];
  sensorB = arrayOfFloat[2];
  sensorW = arrayOfFloat[3];
  tristimulusX = 0.04445*sensorR-0.02633*sensorG
                +0.06931*sensorB+0.72644*sensorW-0.07577;
  tristimulusY = -0.004924*sensorR+0.266874*sensorG
                +0.077151*sensorB+0.360532*sensorW-0.319959;
  tristimulusZ = -0.2362*sensorR+1.38801*sensorG
                +0.19189*sensorB-1.20266*sensorW-4.24325;
  chromaticityX = tristimulusX / (tristimulusX+tristimulusY+tristimulusZ);
  chromaticityY = tristimulusY / (tristimulusX+tristimulusY+tristimulusZ);
  illuminance = tristimulusY;
  mc = (chromaticityX-0.3320) / (chromaticityY-0.1858);
  colortemp = -437*pow(mc, 3)+3607*pow(mc, 2)-6861*mc+5514.31
```

Figure 6. Conversion Module Source Codes

The sensor R, sensor G, sensor B and sensor W are the variables, where RGBW color data sensed from the RGBW color sensor embedded in the smartphone are stored, and tristimulus X, tristimulus Y and tristimulus Z mean the tristimulus values XYZ data converted by the RGBW \Box XYZ conversion equation. The chromaticity X and chromaticity, and brightness and colortemp are utilized as the variables to store color coordinate xy, illuminance and color temperature data, respectively. In the local variable mc declared inside of the method concerned, the values necessary for McCamy's color temperature calculation equation are stored, which are induced by the color coordinate values. The 15 constants used to calculate tristimulus X, tristimulus Y and tristimulus Z are the values mathematically induced through the multiple regression analysis, and they indicate the values optimized to wWcW LED lighting overall.

3.2.2. Mobile App UI: This Chapter implemented mobile application UI as shown in Figures 7 and 8 to evaluate whether light suitable for user's current situation is serviced. User interface consists of three representative functions: Monitoring, control and setting. Monitoring is to evaluate whether the detailed information (color coordinate, color temperature and lighting) of the currently serviced light surrounding a user is suitable for the current situation, based on Oi's improved Kruithof's Curve graph, and is to output the result on the screen. In the Control menu, the characteristics of light can be readjusted by receiving the input of detailed information on the preferred light characteristics according to various situations including the characteristics of space and acts (work type) from the user. In the Setting menu, IP address for communication with the server can be inputted, and ID information of the control target lighting can be set.



Figure 7. Mobile App UI (Monitoring)



Figure 8. Mobile App UI (Control & Setting)

The mobile application developed through this study can be installed at Android 2.3.3 and higher specifications, and can be normally operated on the RGBW color sensorembedded smartphone. User interface was configured for a user to easily move on the screen by using the Tab button at the bottom of the screen, and also was implemented to support a swipe function through ViewPager class supported by android-support-v4. For Kruithof's Curve and CIE1931 graphs, the achartengine-1.1.0, which is graph library for android, was used.

4. System Performance Evaluation

4.1. Design of Light Evaluation Indicators

This Chapter designed light evaluation indicators according to the characteristics of space and occupant's acts as shown in Table 2. To analyze the performance of the system proposed in this study, KS Lighting Standard (KS A 3011) and indoor occupant's act type (gathering, studying, relaxing and retiring) presented by Oi's improved Kruithof's Comfort Curve were referred to in this study.

Space		Act	KS Illuminance Standard [lx]	Color Temperature [K]
	Living room (Overall)	Gathering	300-400-600	3000~6000
Home	Study (Reading)	Studying	600-1000-1500	5000~6500
	Living room (Entertainment)	Relaxing	150-200-300	3000~4000
	Bedroom (Overall)	Retiring	15-20-30	3000
School	Classroom (Overall)	Gathering	300-400-600	3000~6000
	Lab	Studying	300-400-600	5000~6500
	Lounge	Relaxing	150-200-300	3000~4000
	Night-duty room	Retiring	60-100-150	3000~4000

 Table 2. Evaluation Indicator Design

4.2. Performance Evaluation Result

To evaluate the performance of the proposed system, control the experiment-targeted lighting through the mobile application based on the Light Evaluation Indicators in Table 2. After measuring the serviced light with a smartphone and colorimeter, respectively, compare the error. Table 3 shows the lighting control result according to evaluation indicators by applying the developed system, and shows the following: Illuminance and color temperature control indicators according to target space and occupant's act, and the measurement and evaluation result of serviced light, based on those indicators.

 Table 3. Evaluation Result of Light Quality

Space		Target value setting and lighting image	Occupant's act type	
Home	Living room (Overall)	Illuminance: 500 lx color temperature: 4500 K	4546, 490) 400 400 400 400 400 400 400 4	
	Study (Reading)	Illuminance: 600 lx color temperature: 5000 K	100 100 100 100 100 100 100 100	



As shown in Table 3, the evaluation result met all the illuminance and evaluation indicators (Table 2) according to the measured data of the serviced light characteristics. However, the means of illuminance and color temperature showed 19.831x error and 57.98K error, respectively.

5. Conclusion and Future Study Direction

This paper implemented a mobile system for a user to easily measure and evaluate whether light suitable for the current situation is serviced by using a smartphone. The proposed system's processing process is as follows: After the mobile application measures the characteristics of the currently serviced light from the smartphone-embedded RGBW sensor, the application calculates the optical attribute values of light such as tristimulus values XYZ, color coordinate xy, color temperature CCT and illuminance Y through the RGBW->XYZ conversion equation calculated by targeting the wWcW LED lighting. And then, whether the light suitable for the current situation is serviced is evaluated, based on the detailed information of the serviced light through user interface, KS Illumination Standard and Naoyuki Oi's graph, and the result is outputted. Home and school are targeted, detailed spaces are divided into four areas, and user acts are classified into four types. In this manner, this study designed the evaluation indicators

of illuminance and color temperature. As a result of applying the developed system based on the evaluation indicators, all the characteristics of light met the evaluation indicators, and the mean error rate according to RGBW->XYZ conversion was less than 5%. The generation rate of XYZ exceeding 10% allowable limit of error, which is the illuminance change rate that a person can recognize, was identified as 2.71%. In the future, the developed system needs to expand space and act type to apply the system to actual environment, and more accurate evaluation indicators should be designed. Not only the targeted lighting used in this study, but the performance of the lighting system having generally usable measurement and evaluation functions need to be improved in consideration of the hardware characteristics of various types of lighting and the surrounding environment.

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Authors



Yang-Soo Kim, he is studying toward M.S in Computer Science and Engineering at Kongju National University, Republic of Korea. He received a B.S degree from the Kongju National University, Republic of Korea in 2015. His interest is in the research areas of Light Analysis System, Green Energy, Plant Factory, LED Lighting and Ubiquitous Sensor Network.



Sook-Youn Kwon, she is a research professor with Smart Natural Space Research Center in Kongju National University, Republic of Korea. She Received a B.S. degree from the Korea National Open University in 2000, an M.S. degree from Kongju National University, in 2002, and a Ph.D. degree from Kongju National University in 2013. Her interest is in the research areas of Context-Aware, Green Energy, Plant Factory, LED Lighting and Ubiquitous Sensor Network.



Jae-Hyun Lim, he is a professor in Computer Science and Engineering at Kongju National University in Chun-an si, Republic of Korea, leading the Wireless Internet Technology (WIT) Laboratory. He received BS and MS degrees in Computer Science and Engineering from the ChungAng University, in 1982 and in 1988, respectively, and a Ph.D. in Computer Science and Engineering from the ChungAng University, Republic of Korea, in 1998. His interests are in the research areas of Context-Awareness, Energy Management, LED Lighting, Plant Factory, USN Services and implementation of real sensor platforms. International Journal of Bio-Science and Bio-Technology Vol. 8, No.3 (2016)