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Tunnel lane-positioning system for autonomous driving cars using LED chromaticity and fuzzy logic system

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Currently, studies on autonomous driving are being actively conducted. Vehicle positioning techniques are very important in the autonomous driving area. Currently, the global positioning system (GPS) is the most widely used technology for vehicle positioning. Although technologies such as the inertial navigation system and vision are used in combination with GPS to enhance precision, there is a limitation in measuring the lane and position in shaded areas of GPS, like tunnels. To solve such problems, this paper presents the use of LED lighting for position estimation in GPS shadow areas. This paper presents simulations in the environment of three-lane tunnels with LEDs of different color temperatures, and the results show that position estimation is possible by the analyzing chromaticity of LED lights. To improve the precision of positioning, a fuzzy logic system is added to the location function in the literature [1]. The experimental results showed that the average error was 0.0619 cm, and verify that the performance of developed position estimation system is viable compared with previous works.

KEYWORDS
autonomous driving car, chromaticity, LED, LED communication, positioning system

1 | INTRODUCTION

Many studies have been conducted on autonomous driving vehicles. Technologies such as the Advanced Driver Assistant System (ADAS), Vehicle to Everything (V2X), Connected Car, and Intelligent Transport System (ITS) should be implemented for autonomous driving. The positioning system is very important in such autonomous driving vehicles. However, the inertial navigation system (INS), currently under study, has a problem in which an error rapidly diffuses over time in the inertial measurement unit (IMU). Because GPS and differential GPS (DGPS) are highly dependent on satellites, positioning in GPS shadow areas is difficult. Although a combination of Wi-Fi, geomagnetic sensor, radar, and vision was attempted to solve this problem, it has a limitation in terms of the effectiveness compared to cost, and is difficult to implement. For example, although Wi-Fi finds the location using a triangulation method, it requires the installation of a terminal. In addition, the accuracy may decrease due to distortion of surrounding magnetic fields and deviation of sensors in the case of geomagnetic fields [1–11].

The authors of [14–16] studied a visible-light communication (VLC) system. However, the position measurement error is approximately 22 cm. The error is reduced to several centimeters using the angle of arrival and received signal strength (AOA-RSS) and an optical filter [17]. However, in visible-light (VL) positioning based on AOA estimation for location positioning, the AOA parameters obtained at the receiver sometimes have a random and distributed angular form instead of a point angle form due to the multipath transfer of the actual visible light and short positioning distance [18]. The AOA estimation of a VL signal with a random and parametric distributed

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angular form may yield incorrect AOA parameter estimates, which may result in poor VL positioning performance [18].

To solve the problems of current lane-positioning systems, this study developed a fuzzy logic algorithm to estimate the lane position of vehicles by using chromaticity variations, that is, the change in color temperature of LED light from each lane. The fuzzy logic algorithm was added to the position-estimation system studied in previous works [1,2]. Fuzzy logic has advantages to solve nonlinear problems, such as lane-position detection via chromaticity analysis [19].

The experiment was conducted in an experimental environment mimicking a GPS shadow area, such as a tunnel. Three LED illuminators, expressing color temperatures of 3,000K, 4,000K, and 6,000K, respectively, were installed under the ceiling of the tunnel model over the lanes. The color temperatures measured at different locations on the lane are different because the effect of each color temperature varies corresponding to the variations in measurement locations. The change of the color temperatures is converted into the chromaticity values, and the position is estimated by using a fuzzy logic system designed in this study. The current positioning methods using LEDs are based on assigning an ID, whereas this study conducts position estimation using chromaticity [12–18]. The average error of the conventional positioning system is approximately 2 cm–22 cm [12–18]. In the proposed system, the average error is less than 1 cm.

2 | CHROMATICITY COORDINATE THEORY OF LED

It shows that the chromaticity theory is presented in literature [1,2]. Color is distinguished based on wavelength and can be represented by red, green, and blue values (*R*, *G*, *B*). The cone cells and rods in the retina eyes are the visual cells of the eyes. The cone cell operates in light and identifies color; there are three types of these visual cells that react to red, green, and blue lights. Reactions of such visual cells for light are combined to give the sense of brightness and color [1,2].

The color coordinates for three stimulus values of objects (*X*, *Y*, *Z*) are the three color coordinates adopted by the Commission Internationale de l'Eclairage (CIE). From an RGB sensor with the same function as that of the cone cells, *R*, *G*, *B* stimulus values corresponding to changes in color temperature of LED light yield three stimulus values, *X*, *Y*, *Z*, through the conversion process of (1) [1,2,20].

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.7689 & 1.7517 & 1.1302 \\ 1.0000 & 4.5907 & 0.0601 \\ 0.0000 & 0.0565 & 5.5943 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{1}$$

However, a three-dimensional color space is required to express the vector elements geometrically. However, this has the shortcomings of a delay factor and system complexity in implementation. Therefore, it produces chromaticity coordinates of the chromaticity diagram using the *x*, *y* points of intersection of the color vector (*X*, *Y*, *Z*) and unit plane of $X + Y + Z = 1$ in *X*, *Y*, *Z* color coordinates, as described in (2) and (3). It is convenient to use, as chromaticity can express color on a two-dimensional plane [1,2,20].

$$x = \frac{X}{X+Y+Z} \tag{2}$$

and

$$y = \frac{Y}{X+Y+Z}. \tag{3}$$

In particular, the chromaticity coordinate of monochromatic light can be connected on the order of the wavelength, and the spectrum locus can be drawn as shown in Figure 1.

The amount of black-body radiation can be expressed according to the color temperature of a black body. Accordingly, the chromaticity point according to the color temperature of an LED can be expressed as a color coordinate *x*, *y* on the chromaticity diagram [1,2,20].

3 | LED ILLUMINATION AND CHROMATICITY MEASUREMENT

The LED illumination and chromaticity-measurement method are shown according to the lane position suggested in the literature [1].

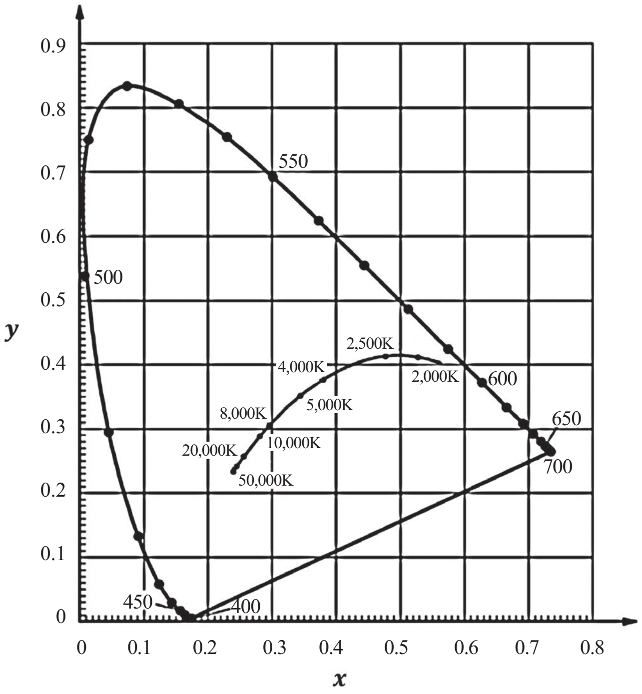

FIGURE 1 Chromaticity diagram

3.1 | Tunnel three-lane LED illuminator

This paper configured simulation environment of three-lane LED tunnel lighting as shown in literature [1] indoor is shown in Figure 2. This paper configured the lane positioning experiment environment by vertically installing LED with color temperatures of 3,000K, 4,500K, and 6,000K on 80-cm-wide lanes. In the experimental environment, the 3,000K, 4,500K, and 6,000K lights illuminated the first, second, and third lanes, respectively, as shown in Figure 3, and then each LED light was overlapped. For example, the color between the first lane and the second lane could have different colors as 3,000K and 4,500K are blended, resulting in a change in chromaticity. This paper measures the location of the lane using the change in chromaticity corresponding to mixing the color temperatures [1].

While lane positioning is conducted, the RGB sensor in Figure 5, placed on the lane, reacts to the car headlights and/or light from the surrounding road environment as well as the LED light from the lane positioning system. That is, the RGB sensor does not distinguish headlamp lights and LEDs of the road lighting [1].

However, because the incidence angle of the LED lighting for the lane positioning and the angle of the car headlamp are different, disturbances due to car headlamps may be avoided to some degree if receiving angle of the RGB sensor is adjusted. To remove the fundamental elements of the disturbance, however, this study separates LED light for lane positioning from environmental noise. That is, the pulse-operating LED illuminator at 1.75 kHz is illuminated by the LED switching driver, as shown in Figure 4, for lane positioning, and the *R*, *G*, *B* stimulus other than the wavelength at 1.75 kHz was eliminated by filtering.

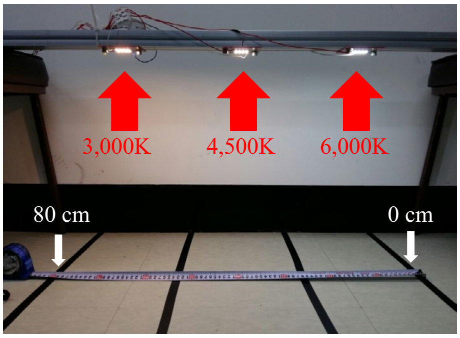

FIGURE 2 Experimental environment to measure lane positioning

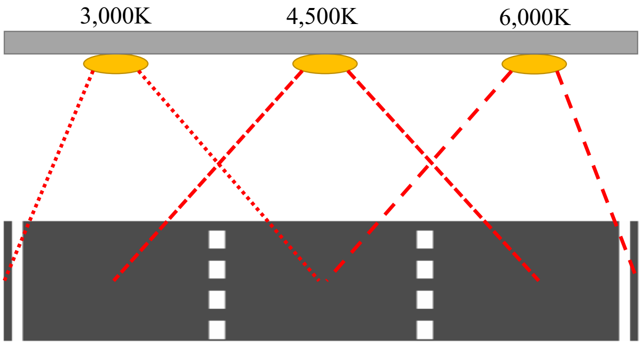

FIGURE 3 Light from each fixture on the illuminated road

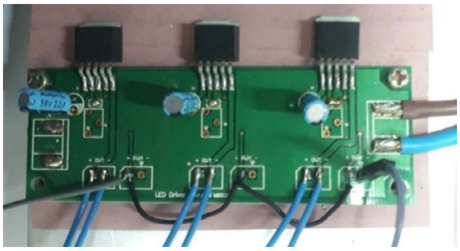

FIGURE 4 Image of the LED-switching driver

FIGURE 5 Image of RGB sensor

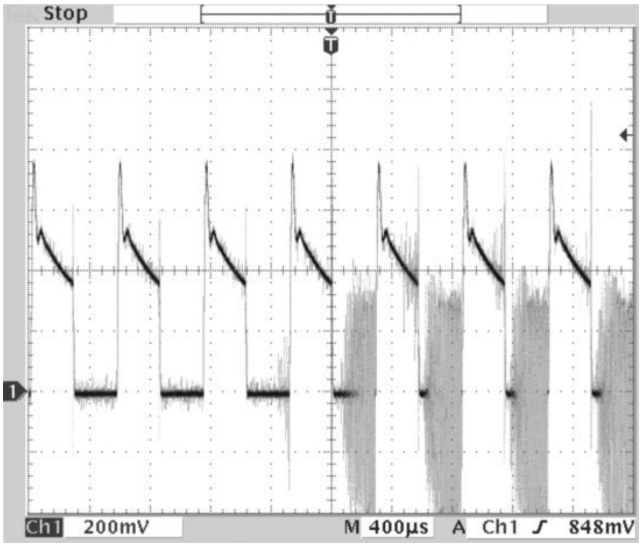

FIGURE 6 Output waveform of *R* stimulus value

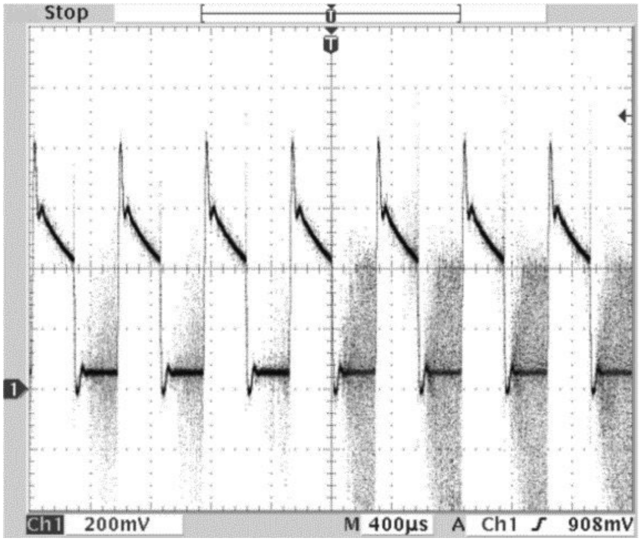

FIGURE 7 Output waveform of *R* stimulus value with low frequency disturbance light

3.2 | Measurement of three-lane LED chromaticity

This study obtains the vector elements of XYZ color coordinate from RGB sensor in Figure 5, and obtains the chromaticity diagram by applying this value to (2) and (3). The stimulus values of *R*, *G*, *B* are displayed as analogue sensitivity values of *R*, *G*, *B* [1]. Figure 6 shows the output waveform of the *R* stimulus value.

RGB stimulus values measured on the road environment have disturbances including car headlights. Figure 7 shows the R stimulus values measured when the pulses of LED light for lane positioning are disturbed by pulses of LED light with different frequencies [1].

In this study, two types of lights disturbing lane positioning were considered. The first type is that the frequency of disturbing light is very low. In that case, the disturbing light causes floating offsets in the output waveform, as shown in Figure 7.

To remove floating offsets and amplify the signals, the prefilter circuit as shown in Figure 8 was designed. The second is that the frequency of disturbing light is a high pulse type. In this case, the disturbing light causes significant distortion of the output waveform, as shown in Figure 9.

To prevent the output signal from the distortion by high-frequency lights, an infinite impulse response (IIR) band pass filter was designed by using MATLAB & Simulink controlling Micro Autobox with a sampling frequency of 30 kHz to exclude frequency components in the output signal other than the frequency component of 1.75 kHz. Figure 10 shows the output waveform after the IIR band pass filter [1].

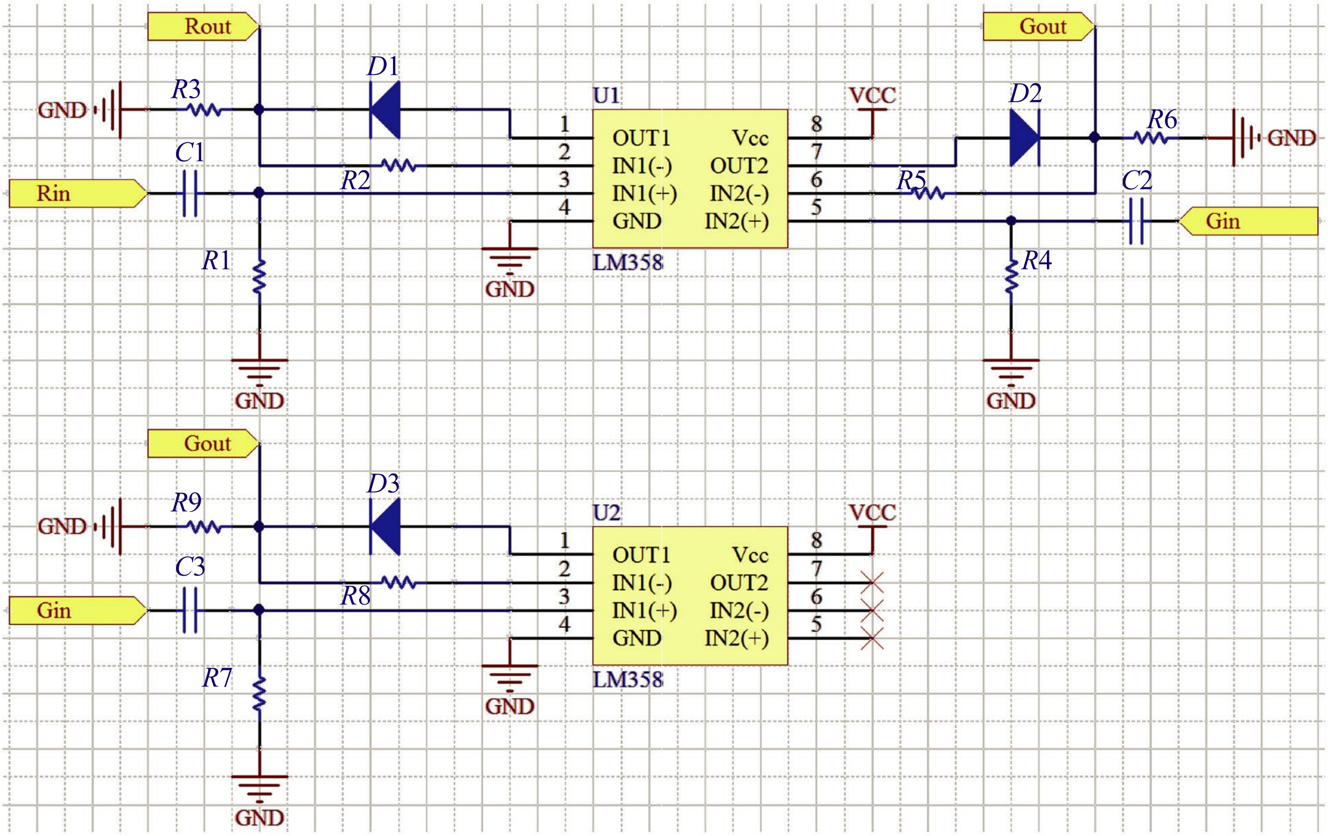

FIGURE 8 Circuit schematic diagram of prefilter circuit

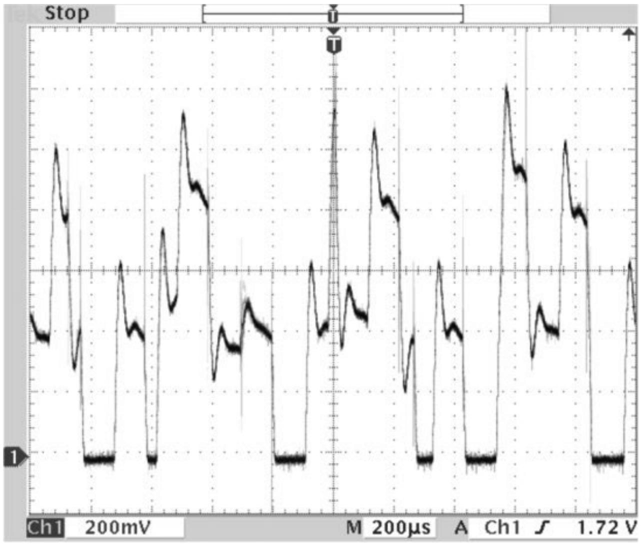

FIGURE 9 Output waveform of *R* stimulus value with high frequency disturbance light

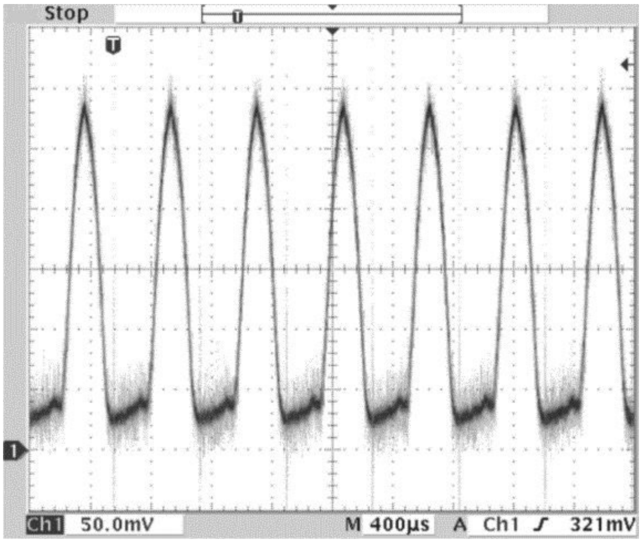

FIGURE 10 Output waveform of *R* stimulus value after bandpass filter

Figure 11 shows the entire experimental procedure. After filtering, the signal is transferred to arduino2580, controlled by MATLAB & Simulink, to measure *x* and *y* chromaticity.

Because the variation in the x chromaticity value is greater than that in the y value, as shown in Figure 1, this study used *x*-chromaticity variation values to detect the position on the road. Table 1 shows the *x* chromaticity measured by 8 RGB sensors placed on the lane in a broad direction in the interval of 10 cm [1].

As shown in Table 1, *x* chromaticity increased due to light of low color temperature as it moved gradually from 0 cm in the interval of 10 cm [1].

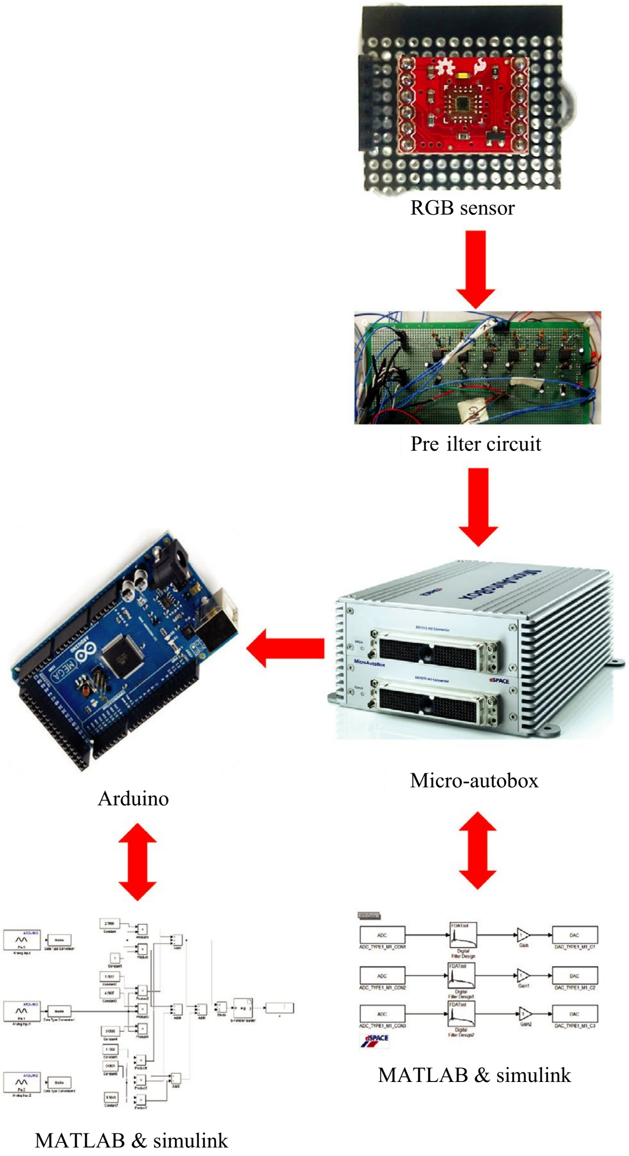

FIGURE 11 Experimental setup to measure LED chromaticity

4 | DESIGN OF LANE POSITIONING FUZZY LOGIC SYSTEM

In this paper, the *x*, *y* chromaticity values are measured by using the RGB stimulus values from the RGB sensors, and the fuzzy logic system estimates the position on the lane by using *x* chromaticity values as input variables. The estimated positions on the lane are compared with the experimental data in Table 1.

4.1 | Fuzzification procedure

In the fuzzification procedure, *x* chromaticity values are classified by using an input membership function, as shown in

TABLE 1 Measured *x* chromaticity value depending on road location

Position (cm)	*x* chromaticity
0	0.3591
10	0.3610
20	0.3635
30	0.3658
40	0.3685
50	0.3709
60	0.3739
70	0.3766
80	0.3793

Figure 12. During the procedure, the *x* chromaticity values have their own weights between 0 and 1 through the triangle functions from $f_{\text{in}1}$ to $f_{\text{in}9}$. For instance, if the input *x* chromaticity value is 0.3739, the functions, $f_{\text{in}6}$, $f_{\text{in}7}$, and $f_{\text{in}8}$ are activated, and the chromaticity values have weights of 0, 1, and 0 as the outputs of the fuzzification procedure, as shown in Figure 12.

4.2 | Fuzzy rule-evaluation procedure

The rule-evaluation procedure consists of "*if–then*" rule statements. In this research, nine fuzzy rules are used, as shown in Figure 13. In the procedure, the rules with output position values, which only have non-zero weights, are activated. In the example used in the fuzzification procedure, only $f_{\text{in}7}$ has non-zero weight; therefore, *Rule* 7, with an output value of 60 in Figure 13, is activated.

4.3 | Defuzzification procedure

In the defuzzification process, the lane's width is calculated from the outputs generated during the rule-evaluation process. This process is performed by the defuzzification technique. In this study, the weighted average technique, defined by (4), is used, where y is the estimated position on the lane, m is the weight generated in the fuzzification procedure, and w is the center value (0, 10, 20, …, 80) of the triangle functions, in the output membership functions, which is selected in the rule-evaluation procedure. In the same example used in the previous fuzzy procedures, *Rule 7* is selected because $f_{\text{in}7}$ only has non-zero weights; therefore, the number of activated rules (*i* in (4)) is 1 and the weight (*m* in (4)) is 1. The center value (*w* in (4)) is 60 because only is *Rule 7* activated. Hence, the output *y* is calculated as (1 × 60)/1 = 60, meaning the estimated position in the lane is 60 cm in a broad direction, as shown in Figure 14.

Rule 1: *if* (input is $\mathrm{f}_{\mathrm{in}1}$) *then* (output is 0)
Rule 2: *if* (input is $\mathrm{f}_{\mathrm{in}2}$) *then* (output is 10)
Rule 3: *if* (input is $\mathrm{f}_{\mathrm{in}3}$) *then* (output is 20)
Rule 4: *if* (input is $\mathrm{f}_{\mathrm{in}4}$) *then* (output is 30)
Rule 5: *if* (input is $\mathrm{f}_{\mathrm{in}5}$) *then* (output is 40)
Rule 6: *if* (input is $\mathrm{f}_{\mathrm{in}6}$) *then* (output is 50)
Rule 7: *if* (input is $\mathrm{f}_{\mathrm{in}7}$) *then* (output is 60)
Rule 8: *if* (input is $\mathrm{f}_{\mathrm{in}8}$) *then* (output is 70)
Rule 9: *if* (input is $\mathrm{f}_{\mathrm{in}9}$) *then* (output is 80)

FIGURE 13 Fuzzy rules for the reasoning of positions

$$y=\frac{\sum_{i=1}^{\text{Number of activated rules}}\left(m^i\times w^i\right)}{\sum_{i=1}^{\text{Number of activated rules}} m^i}. \tag{4}$$

The Simulink model shown in Figure 15 was developed by combining (1), (2), and the fuzzy system for the estimation of the position in the lane.

5 | RESULTS AND DISCUSSION

To verify the position estimation ability of the designed fuzzy logic system, we measured real-time chromaticity data using the system in Figure 11 and the MATLAB & Simulink algorithm (Figure 15) in a three-lane LED lighting environment. The results are shown in Figure 16.

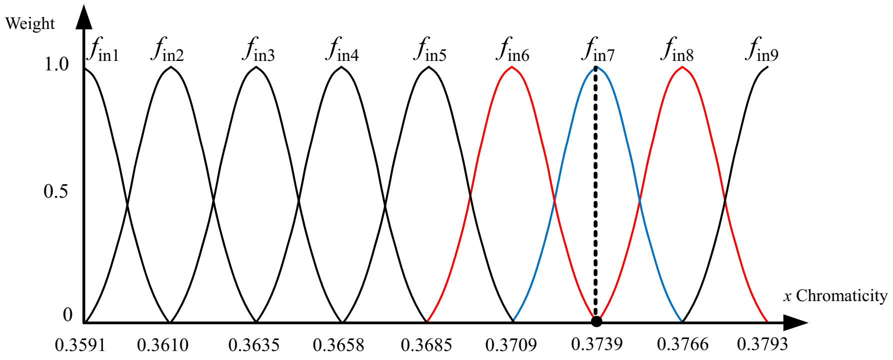

FIGURE 12 Input membership function for the fuzzification of *x* chromaticity value

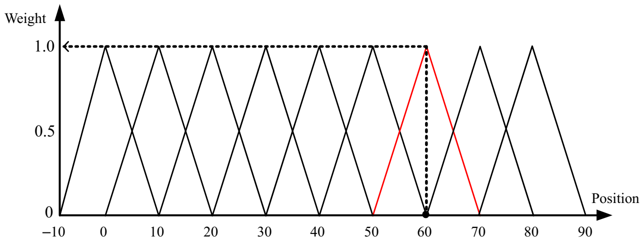

FIGURE 14 Output membership function for position estimation

There are also many problems with the VLC positioning system. For example, each LED illuminator must have an ID, and additional devices are required. In addition, multiple LED illuminators are required for position estimation, and it is impossible to measure the entire space where the light spreads [13–17].

In this paper, however, we proved a new positioning method using an LED illuminator through experiments. The maximum error between the measured and estimated positions in this experiment is approximately 1.82 cm (0.008, 1.82 ± 0.1267, mean, max ± SEM). The mean error of the first measurement in Figure 16 is 0.0619 cm, the mean of the second measurement error is 0.1585 cm, and the mean of the third measurement error is 0.3771 cm. The average error of the result of Reference [1] is 0.1732 cm. However, when the fuzzy logic system of this paper is used, the average error is 0.0619 cm. From these results, it can be confirmed that the measurement is more accurate in the fuzzy logic system. These experiments and studies have proven the efficiency of lane positioning with LED chromaticity values.

In this experiment, the position was measured by setting a sampling frequency of Arduino2580 of 20 Hz. Because the sampling frequency of commercial GPS is approximately 1 Hz, it is expected that the position of the high-speed vehicle can be detected by using the proposed technique.

In this study, when the congestion of the RGB sensor occurs in the tunnel, a positional change occurs. Because of the characteristics of the LED illuminator, the measured position data changes depending on the heat. This error is approximately 2%–5%. However, optimizing the heat-dissipation structure of LED illuminator will reduce these errors.

Furthermore, the disturbance caused by the ambient light causes the measurement error depending on the intensity of the light. The influence of such illumination disturbance can be removed by using a prefiltering circuit, as shown in Figure 9. In the experimental environment, when other illumination disturbances exist, the error is less than 5%. However, the position cannot be measured if strong illumination occurs near the sensor. This problem can be prevented depending on the location of the actual RGB sensor [13–17].

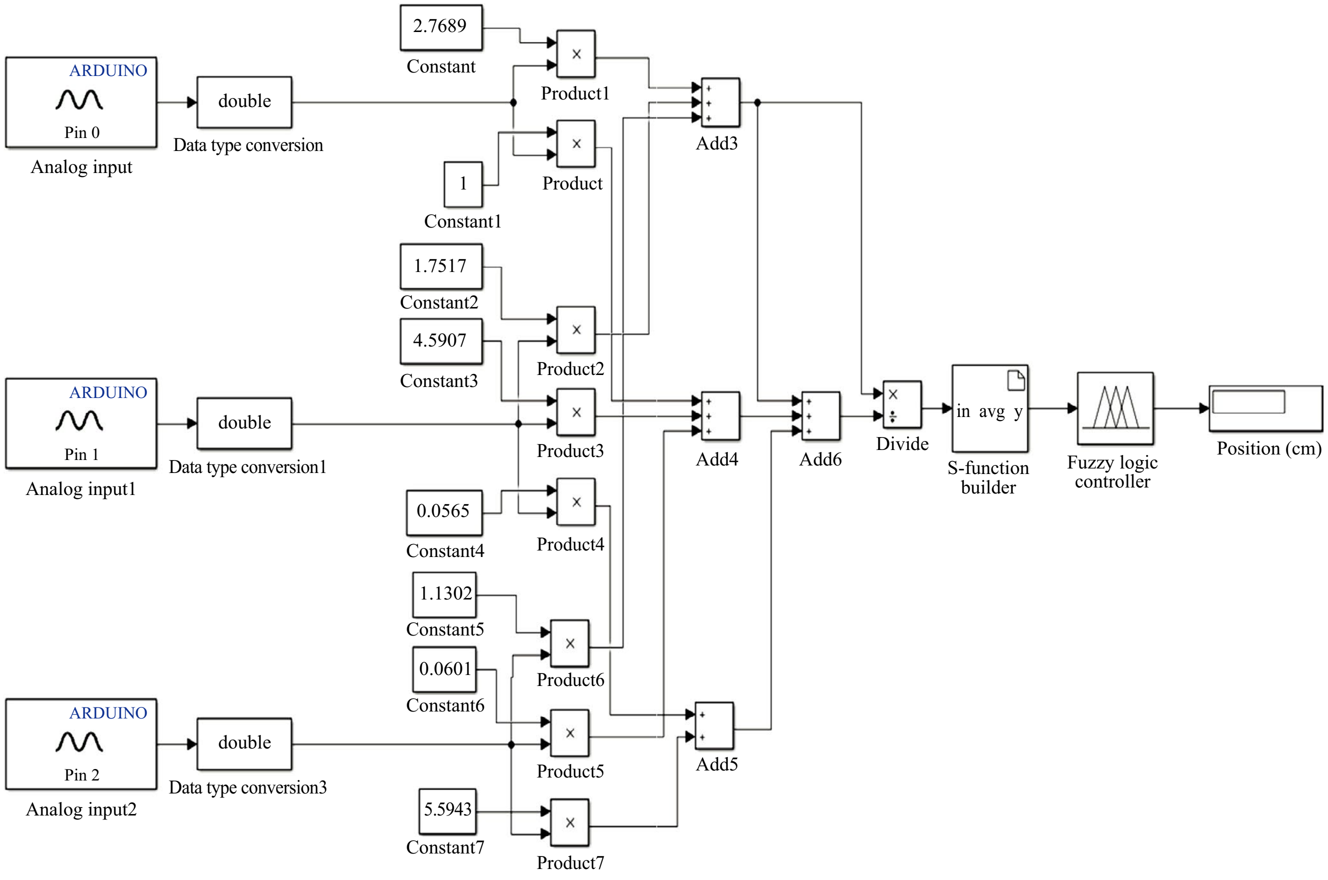

FIGURE 15 MATLAB & Simulink design for position estimation

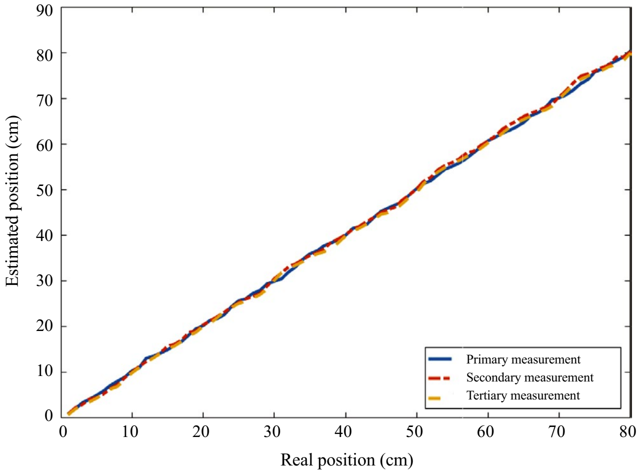

FIGURE 16 Comparison between real and estimated positions

6 | CONCLUSION

This paper confirms that our system has accurate performance through the addition of a fuzzy logic system to the existing lane-positioning system. In addition, this study investigated the position-estimation system in GPS shadow areas, such as tunnels. This study configured LED lighting at 3,000K, 4,500K, and 6,000K and conducted position estimation within the lane by using the change in chromaticity corresponding to the location of each sensor. The chromaticity intensity signal from the sensors was filtered by a pre-filtering circuit and IIR band-pass filter to minimize the disturbance from other light sources. The fuzzy logic system improved the precision of position estimation on the lane. The experimental results showed that the average error was 0.0619 cm, which verifies the performance of the lane-positioning compared with previous works.

This paper showed the potential of the position estimation technology. If the technology using LED chromaticity, as suggested in this paper, is used in connection with existing technology, the limitations of current lane-positioning technology, which is highly dependent on GPS, could be overcome. In addition, more studies should be conducted to increase the precision of the lane-positioning technology by applying other methods, such as deep learning. It is also necessary to minimize disturbance in the actual environment. It is planned to carry out follow-up studies to estimate the location in x, y spaces using the lane-positioning system proposed in this paper.

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