Received November 30, 2017, accepted January 9, 2018, date of publication January 15, 2018, date of current version February 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2793306

Vehicle-to-Vehicle Distance Estimation Using a Low-Resolution Camera Based on Visible Light Communications

VO THI BICH TRAM[1] AND MYUNGSIK YOO[2]
[1]Department of ICMC Convergence Technology, Soongsil University, Seoul 06978, South Korea
[2]School of Electronic Engineering, Soongsil University, Seoul 06978, South Korea

Corresponding author: Myungsik Yoo (myoo@ssu.ac.kr)

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea, Ministry of Education, Science and Technology, under Grant 2015R1A2A2A01006431.

ABSTRACT This paper proposes an intelligent transport system positioning technique that determines the distance between vehicles via image sensor-based visible light communication. The proposed algorithm uses two image sensors and requires only one LED to estimate the distance. Furthermore, the cameras installed in vehicles are often of an inferior resolution that is insufficient to accurately determine the coordinates of the pixels on the image sensor. This paper addresses this problem by proposing a method that accurately determines the distance between two vehicles when the camera resolution is low. Simulations are conducted to verify the performance of the proposed algorithm.

INDEX TERMS Distance estimation, vehicle, visible light communication, image sensor, resolution.

I. INTRODUCTION

Visible light communication (VLC) is an emerging technology that alleviates wireless spectrum saturation, and this new and promising wireless communication technology will receive a considerable amount of attention in the coming decades. VLC has become popular due to its low cost, environmental friendliness, ease of maintenance, high security, controllability, etc. [1]–[3]. Light Emitting Diode (LED)-based VLC systems are suitable for vehicular use, and there are numerous road safety applications and services for such use [4]. These systems help drivers to remain safe and comply with traffic regulations. VLC systems can deliver road traffic safety information, minimize possible accidents and increase the flow of traffic on the road [5].

The VLC technology is being developed for commercialization in many research institutes around the world, and some products have already been released, including underwater VLC equipment by MRC, Picapicamera by Casio, etc [6], [7].

Recently, researchers have used image sensor based VLC for vehicle-to-vehicle positioning. This comprises the basic structure for an Intelligent Transportation Systems (ITS) that improves driving safety [8]. ITS coordinates people, roads, and vehicles through a modern information technology system that resolves problems regarding road traffic and traffic circulation efficiency while also reducing the environmental load.

This article uses camera-based VLC to determine the distance between two vehicles. The camera is mounted on the estimating vehicle to capture the LED of the target vehicle in front, and the distance between the two vehicles is determined using the picture that has been taken. The high illumination and compact shape of LED make it easy to detect the LED in the captured image. Also, with the communication capability, information which is useful for positioning can be transmitted between vehicles. Also, the light from vehicle LED can have modulational blinking patterns which make the vehicle LED distinguishable from other lighting objects in the background.

Although this problem has been addressed in prior studies, two basic problems still remain. Existing algorithms require the camera to capture at least three or four LEDs [9]. But in reality, the camera may capture only one LED because the remaining LEDs are hidden due to traffic on the road. The second problem is that the resolutions of the cameras attached in vehicles are usually insufficient since high-resolution cameras are expensive. When a camera has a low resolution, it is very difficult to accurately determine the image coordinates of the LEDs. Therefore, the distance error is high.

This article will solves these two issues. When the LEDs are obscured, the camera can capture only one LED, so this problem is solved using two cameras. Two cameras are set on the vehicle, and the proposed algorithm determines the distance between the two vehicles by using just one LED. Regarding the low resolution, this paper implements a compensation method in which a pixel in the image is subdivided into many possible regions. Then, more accurate distances between the two cars will be calculated by assuming that the LEDs are located within the possible regions. After that, Kalman filter and the median selection method are used to determine the most accurate distance between the two vehicles.

A simulation is conducted in Matlab to evaluate the performance of this solution. The results show that by using the compensation method, the distance between the two vehicles can be precisely determined even when the resolution of the camera is low.

This paper is organized as follows. Part II presents the system architecture, Part III presents the proposed system, and the simulations are presented in Section IV.

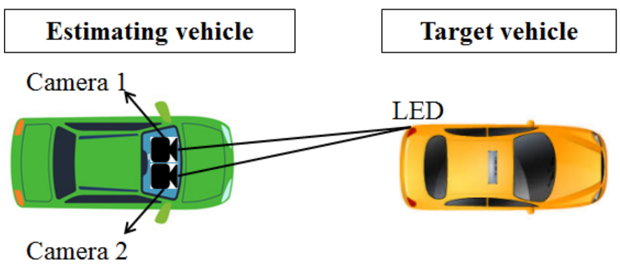

FIGURE 1. System architecture.

II. SYSTEM ARCHITECTURE

The system architecture is described in Figure 1. Two cameras are attached to the estimating vehicle to take the pictures of the LEDs of the target vehicle. After capturing the images containing the LEDs, the data extraction process is conducted to determine the LED coordinates of the image [10]. The coordinates of the images will then be used to determine the distance between the two vehicles.

The process to extract data from the image is shown in Figure 2. It is assumed that the luminance of LEDs is much higher than that of non-lighting objects in the background. Therefore, the values of pixels corresponding to LEDs in the captured image are much higher than that corresponding to the background. Consequently, the pixel coordinates of the LEDs in the image can be detected easily. For lighting objects such as street lights, the LEDs of vehicles still can be distinguished easily thanks to modulational blinking pattern of vehicle LEDs.

Note that the contrast between the LED and the image background in daytime environment is lower than that in nighttime environment. However, the luminance of LEDs is still much higher than that of other objects such as the body of vehicle or the road surface and thus the LEDs are still detectable. Currently, most commercial cars are produced with daytime running lights (DRL) which have luminance sufficiently high to be seen in daylight environment. In previous studies related to vehicle communication using LEDs [11], [12], the detection of LED in daytime environment has been experimentally shown to be feasible.

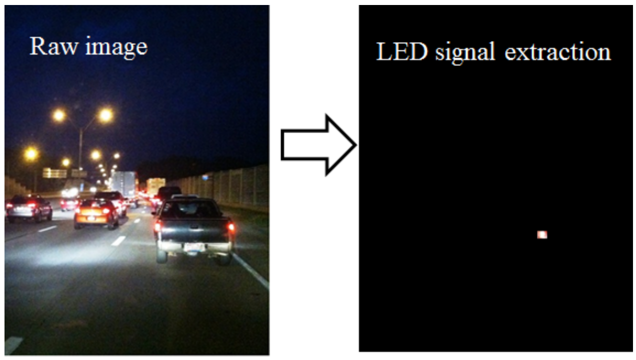

FIGURE 2. Extracting the LED signal from the image.

This paper assumes that the captured images do not suffer from distortion effect. Distortion is an unavoidable effect due to flaws of lens. However, this effect can be compensated using various kinds of calibration software, which are embedded in most commercial cameras nowadays. For those cameras that are not equipped with any calibration software, it is assumed that some kinds of calibration algorithms [13], [14] are applied to the captured images to eliminate the distortion effect before performing the data extraction process.

It is also assumed the air medium is reasonably clear so that the decrease of brightness of LED due to dust or fog at long distance is negligible. When the distance between vehicles increases, the size of the LED in the captured image would decrease. When the distance becomes too long, the LED image becomes too small to be detectable. However, this is not a problem since the threats to any vehicle are the ones reasonably close to them. Therefore, the distance estimation of the vehicle at very long distance would be unnecessary.

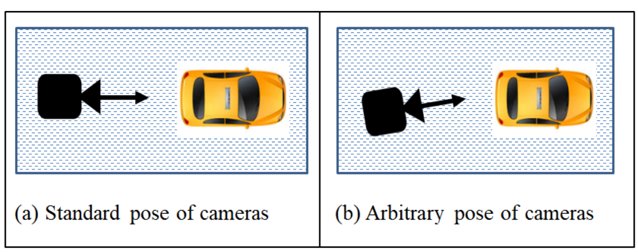

FIGURE 3. Camera angle.

III. PROPOSED SYSTEM

A. DISTANCE ESTIMATION USING TWO CAMERAS AND ONE LED

The distance estimated using two cameras and a single LED can be determined in both cases of the pose of the camera: standard and arbitrary poses, which are shown in Figure 3.

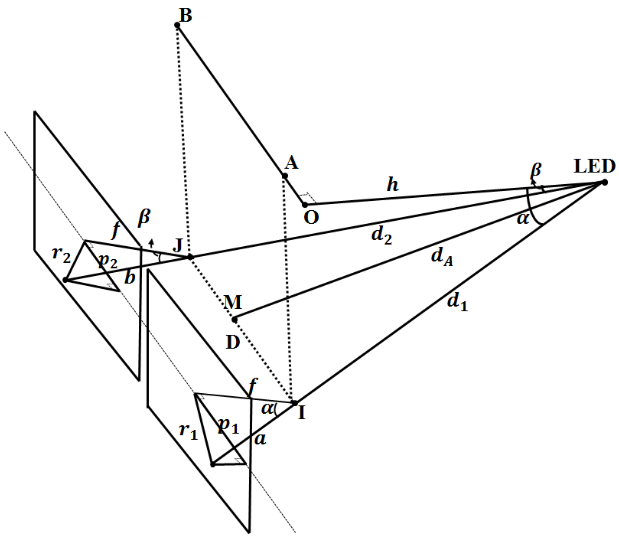

FIGURE 4. Proposed distance estimation algorithm.

1) DISTANCE ESTIMATION WITH A STANDARD CAMERA ANGLE

The distance from the vehicle to a street light is determined according to the geometric relationship between street lights in the real world and that observed in the image. The physical arrangement of the system is presented in Figure 4. Two cameras are placed next to each other and capture the image of a single LED. Each camera has its sensor plane perpendicular to the axis of the street and the wide edge of the sensor parallel to the surface of the street. This case is considered as the standard orientation of the camera. It is assumed that the two cameras are installed in the same plane at a known lateral distance with their major axis in the same line. The focal length of the lens in two cameras is equal.

In Figure 4, let f denote the focal length of the lens and D denote the distance between the two cameras. It is assumed that f and D are known.

The distance from the LEDs to each camera can be calculated with precision. The procedure to calculate the distance uses the camera specifications, including the focal length of the camera and the image sensor resolution, as follows.

First, set r_1, r_2 as the respective distance between the center of the image sensor and the pixel on IS. Then, the projection of r_1, r_2 on the major axis of IS are p_1 and p_2, respectively. Basic calculations then produce the following system of equations:

$$\begin{cases} a = \sqrt{f^2 + r_1^2} \\ b = \sqrt{f^2 + r_2^2} \end{cases} \tag{1}$$

Use similar triangle properties:

$$\begin{cases} \dfrac{h}{f} = \dfrac{d_1}{a} = \dfrac{OA}{p_1} \\ \dfrac{h}{f} = \dfrac{d_2}{b} = \dfrac{OB}{p_2} \end{cases} \tag{2}$$

$$\frac{h}{f} = \frac{OA}{p_1} = \frac{OB}{p_2} = \frac{OB - OA}{p_2 - p_1} = \frac{IJ}{p_2 - p_1} = \frac{D}{p_2 - p_1} \tag{3}$$

where h is the vertical distance between the LED and the image sensor.

Then, h can be calculated using Equation (4):

$$h = \frac{D \cdot f}{p_2 - p_1} \tag{4}$$

Then, according to the law of tangents, we will determine the value of angle α, β from

$$\begin{cases} \tan\alpha = \dfrac{r_1}{f} \\ \tan\beta = \dfrac{r_2}{f} \end{cases} \tag{5}$$

where α and β are the angles formed from the LED light and the IS space through the pinhole camera model.

From the real-world coordinates, the focal length is assumed to be known, and then two angles α and β can be calculated. The distances d_1 and d_2 can be calculated using the Equation:

$$\begin{cases} d_1 = \dfrac{h}{cos\alpha} \\ d_2 = \dfrac{h}{cos\beta} \end{cases} \tag{6}$$

Because M is the mid-point of the IJ, the distance d_A can be computed based on the following formula:

$$d_A = \sqrt{\frac{2\left({d_1}^2 + {d_2}^2\right) - D^2}{4}} \tag{7}$$

2) DISTANCE ESTIMATION IN CASE OF AN ARBITRARY ORIENTATION OF THE CAMERA

In practice, the camera might have arbitrary orientations which are different to the standard one. In these cases, the images captured by the two camera need to be transformed into images as if they are captured by these camera in the standard orientation. This transformation can be performed given that the information related to the orientations of the two cameras is obtained through inertial sensors installed with the cameras. After that, the algorithm presented in the previous section is applied to these transformed images to estimate the distance between the two vehicles.

The transformation is performed using the pinhole camera model. This model includes a 3D world coordinate system and a 2D image coordinate system. Assuming, the coordinates of the measured LED have world coordinates of $X = (X, Y, Z)^T$, its 2D image coordinate $x = (x, y, 1)^T$ are defined as

$$X' = K \times R \times T \times X \tag{8}$$

where K is the camera intrinsic matrix, R is the 3×3 rotation matrix, and T is the 3×3 translation matrix.

$$T = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

The camera intrinsic matrix K can be obtained given that the intrinsic parameters of the camera, such as focal length and sensor size, are known.

$$K = \begin{bmatrix} f & 0 & x \\ 0 & f & y \\ 0 & 0 & 1 \end{bmatrix} \tag{10}$$

In the coordinates of the world, the rotation matrix is determined to represent the rotation of the IS from the current position to the position of the standard position of the camera. In particular, the inertial sensors extract information regarding the tilt of the x, y and z axis to form the rotating matrices. The inertial sensors are very sensitive, so any small changes in motion are immediately collected and processed without affecting the response time of the entire system. To form a rotating matrix, consider angles φ, ψ, θ as the deviation measured in the inertial sensors corresponding to the x, y, z axes. The rotation matrix obtained from the three matrix components rotated by matrix multiplication is as follows:

$$R = R_x(\varphi) R_y(\psi) R_z(\theta)$$

$$R_x(\varphi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi) & -\sin(\varphi) \\ 0 & \sin(\varphi) & \cos(\varphi) \end{bmatrix},$$

$$R_y(\psi) = \begin{bmatrix} \cos(\psi) & 0 & \sin(\psi) \\ 0 & 1 & 0 \\ -\sin(\psi) & 0 & \cos(\psi) \end{bmatrix},$$

$$R_z(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Then, the image can be transformed into the standard captured image by applying the following transformation to every point in the image:

$$x' = K \times T^{-1} \times R^{-1} \times K^{-1} \times x \tag{11}$$

where x' is the image coordinate corresponding to x in the standard captured image.

Once obtaining the transformed image, the distance between the two vehicles can be determined using Equation (6) to calculate d_1 and d_2 in the same process.

B. RESOLUTION COMPENSATION

1) PROBLEM CAUSED BY THE LOW-RESOLUTION IMAGE SENSOR

The low resolution of the image sensor is a problem for any positioning and distance estimation techniques that use camera. When the camera captures an LED, its image will appear on the image sensor with the row and column coordinates shown in Figure 5. In Figure 5 (a), when the coordinates of the LEDs are the left or right edge, then they are considered the same as the coordinates at the center of the pixel. In Figure 5 (b), when the IS has a higher resolution, two LEDs as in Figure 5 (a) result in image coordinates that are different. Therefore, when the IS resolution is low, the pixel coordinate of the LED detected in the image would not give the accurate information for the positioning and distance estimation algorithm. Consequently, the distance error obtained with low-resolution image sensor would be high. In this section, a technique will be proposed to compensate for the error caused by the low resolution of the image sensor to allow high distance estimation accuracy achievable even with low-resolution image sensor.

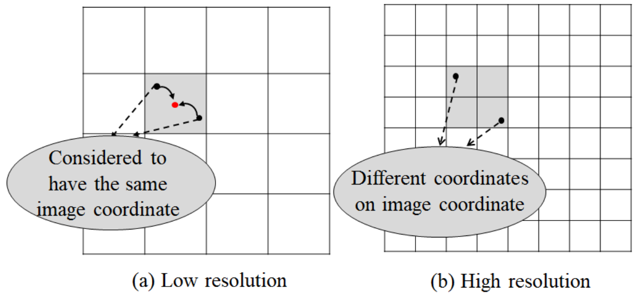

FIGURE 5. Difference between low and high resolution images.

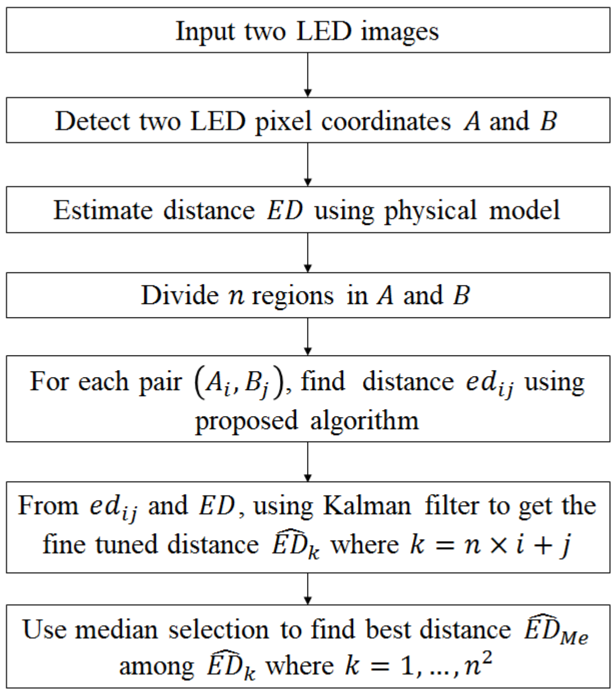

FIGURE 6. Proposed resolution compensation.

2) PROPOSED RESOLUTION COMPENSATION METHOD

a: OVERVIEW OF THE PROPOSED RESOLUTION COMPENSATION

The overview of the proposed resolution compensation is shown in Figure 6. An LED in the target vehicle will be captured by two cameras mounted in the vehicle. The two images from the two cameras are processed to obtained the LED pixel coordinates A and B in the two images. Before using the proposed algorithm presented in the previous section, the distance between the two vehicle ED will be estimated using physical model of the system. After that, each of these two pixels will be divided in to n possible regions. For each pair of possible regions A_i and B_j, the LED is assumed to appear in these two region in the two image and the vehicle distance ed_{ij} is estimated using the algorithm proposed in section III.A. Then from ed_{ij} and ED, Kalman filter is used to get the more accurate distance ED_k. Finally, the median selection method is used to find the best distance ED_{Me} among n^2 distance ED_k.

b: ESTIMATE DISTANCE USING PHYSICAL MODEL

Given the speeds of the estimating and the target vehicles can be obtained through speedometers and VLC transmissions and the time interval between two estimations is assumed to be known, the distance between two vehicles can be estimated through physical model of the system. More specifically, let v_1 denote the speed of the estimating vehicle, v_2 denote the speed of the target vehicle, ED_{pre} denote the distance obtained in the previous estimation, and Δt denote the time interval between the two estimation, the current distance ED between the two vehicle is estimated using the following formula:

$$ED = ED_{pre} + (v_2 - v_1)\Delta t. \tag{12}$$

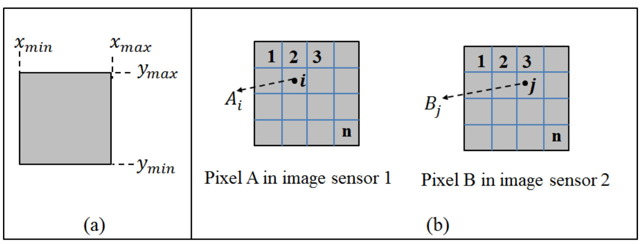

FIGURE 7. Possible region of the image coordinates.

c: DIVIDE PIXEL TO POSSIBLE REGIONS

The algorithm presented in the previous section is used to determine the distance between two vehicles. After taking a picture containing the LEDs, the pixel coordinates of the LED are determined, as shown in Figure 7 (a). With high-resolution cameras, the vehicle distance can be determined accurately using the detected LED pixel coordinates. However, when the resolution of the camera is low, the error of the distance estimation would be high using the detected LED pixel coordinate. Therefore, the detected LED pixels in the two images will be divided in to n possible regions $A_1, A_2, \ldots, A_n$ and $B_1, B_2, \ldots, B_n$ as shown in Figure 7(b). The true position of the LED in the two images is assumed to be one of pairs possible regions A_i, B_j.

d: ESTIMATED DISTANCE FROM EACH PAIR OF POSSIBLE REGIONS

Assuming that the true position of the LED is A_i, B_j, the algorithm presented in previous section is used to estimate the distance between the two vehicles. This estimated distance is denoted as ed_{ij}. The estimated vehicle distance is supposed to be more accurate given the pair A_i, B_j is selected. To this end, firstly Kalman filter will be used to improve the accuracy of the distance ed_{ij} estimated using the proposed algorithm.

e: IMPROVING THE ESTIMATED DISTANCE USING kALMAN FILTER

Given a pair of distances ed_{ij} and ED, where the former is estimated using the proposed algorithm and the later is estimated using physical model, Kalman filter [15] is used to fine tune the estimated distance to get the more accurate distance.

The Kalman filter includes two phases. In the first phase, called "predict" phase, the physical model of the system is used to find the vehicle distance ED and the distribution of the error is obtained.

Physical model for the prediction:

$$ED_k = F \cdot ED_{k-1} + w_k, \quad w_k \sim \mathcal{N}(0, Q_k) \tag{13}$$

where

$$F = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

and w_k is the process noise, which is assumed to be drawn from a zero mean multivariate normal distribution $\mathcal{N}$, with covariance Q_k.

In the second phase, called "update" phase, the vehicle distance ed_{ij} is estimated using proposed algorithm and the distribution of the error is obtained. Then the optimal Kalman gain is calculated from the distribution of the errors obtained using physical model and proposed algorithm. From the two distance ED and ed_{ij}, the optimal Kalman gain is applied to obtained the optimal distance $\widehat{ED}_k$, where $k = i \times n + j$. The optimal distance $\widehat{ED}_k$ is supposed to be more accurate than both ED and ed_{ij}.

The distribution of the error of the distance estimated using the proposed algorithm is given as follows:

$$ed_k = ed_{k-1} + v_k, \quad v_k \sim \mathcal{N}(0, R_k) \tag{14}$$

where $v_k$is the observation noise assumed to be the zero mean Gaussian white noise with covariance R_k.

From the distribution of the errors in estimating ED and ed_{ij}, the optimal Kalman gain is calculated as:

$$K_k = P_{k|k-1} S_k^{-1} \tag{15}$$

Using the optimal Kalman gain, the optimal distance can be obtained as:

$$\widehat{ED}_{k|k} = \widehat{ED}_{k|k-1} + K_k \cdot \left(ed_k - \widehat{ED}_{k|k-1}\right) \tag{16}$$

f: FIND THE BEST DISTANCE USING MEDIAN SELECTION

After applying the Kalman filter, the optimal distance $\widehat{ED}_k$ is obtained from each pair of possible regions A_i, B_j. There are n^2 such optimal distances in total. To find the most accurate distance, the median selection method is used:

$$\widehat{ED}_{Me} = \frac{\widehat{ED}_{n/2} + \widehat{ED}_{(n+2)/2}}{2} \tag{17}$$

where $\widehat{ED}_{Me}$ is the optimal distance after using median, $\widehat{ED}_{n/2}$ and $\widehat{ED}_{(n+2)/2}$ are the distance at the $(n/2)^{th}$ and $((n+2)/2)^{th}$, respectively, after the data has been sorted in ascending direction.

TABLE 1. Simulation parameters.

Parameter	Value
Sensor size	2.4 x 3.6 mm^2
Resolution	240 x 360 pixels
Focal length of camera	35 mm
Distance between center of two cameras	10 cm
LED size	$10 \times 20cm^2$
LED luminance	16000 cd/cm^2
Distance between two vehicles	10 m to 100 m
Average speed of estimating vehicle	45 km/h
Average speed of target vehicle	50 km/h

IV. SIMULATION

A. SIMULATION SETUP

The system performance is evaluated using Matlab. In the simulation, the LED images are simulated with system parameters including sensor size, sensor resolution, lens focal length, camera orientation, real distance between 2 cameras, LED size, LED luminance, and distance between 2 vehicles given in Table I. After that, the simulated LED images are processed to obtain the LED pixel coordinates. These LED pixel coordinates are then given to the proposed algorithm to estimate the distance between the two vehicles. After that, the distance errors are calculated to evaluate the performance of the proposed algorithm. The distance errors are calculated by subtracting the real distance and the distance estimated using the proposed algorithm.

B. ESTIMATION RESULT

The overall performance of the proposed system is shown in Figure 8. In this simulation, the initial distance between the two vehicles is 50 m. The average speeds of the estimating and target vehicle are 45 and 50 km/h, respectively. The speeds of two vehicle might increase or decrease randomly within 10% over time. It is also assumed that the target vehicle has only 1 LED visible to the estimating vehicle. The two vehicles are assumed to travel in 100s. During this time, the estimating vehicle keeps estimating the distance between the two vehicles. It can be seen through the figure that the estimation accuracy significantly increases after applying the proposed compensation method.

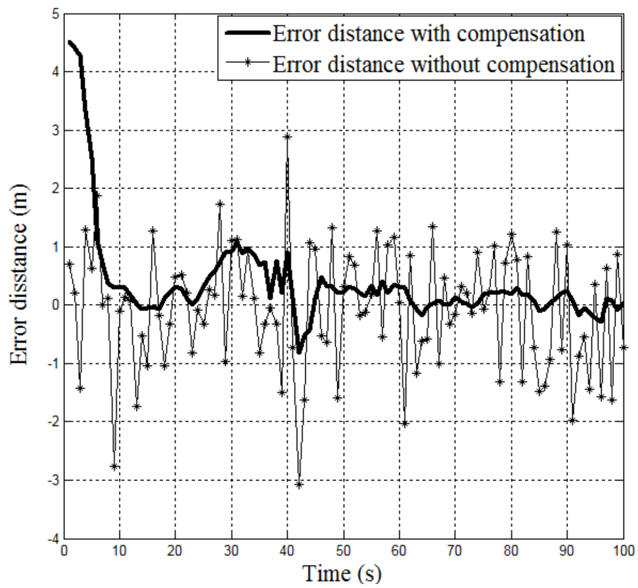

FIGURE 8. Distance error with and without low resolution compensation.

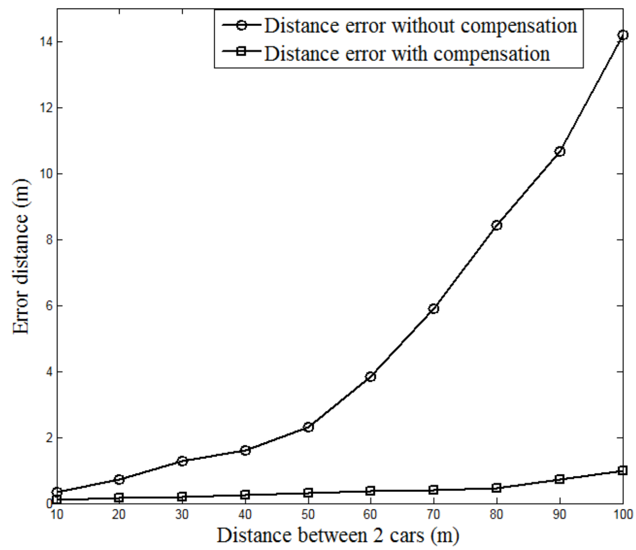

FIGURE 9. Distance error with and without low resolution compensation corresponding to different distance between vehicles.

The worst problem of the low resolution of the image sensor is that the estimation error caused by the low resolution would increases much higher when the distance between the two vehicles get longer. In the simulation shown in Figure 9, the distances between two vehicles are assume to range from 10 to 100 m. Other system parameters are assumed to have default values as in Table I. The simulation result shows that without the low resolution compensation, the distance error drastically increases as the distance between the two vehicles increases. However, after applying the proposed compensation method, the estimation errors do not change much regardless of the increase of the distance between the two vehicles.

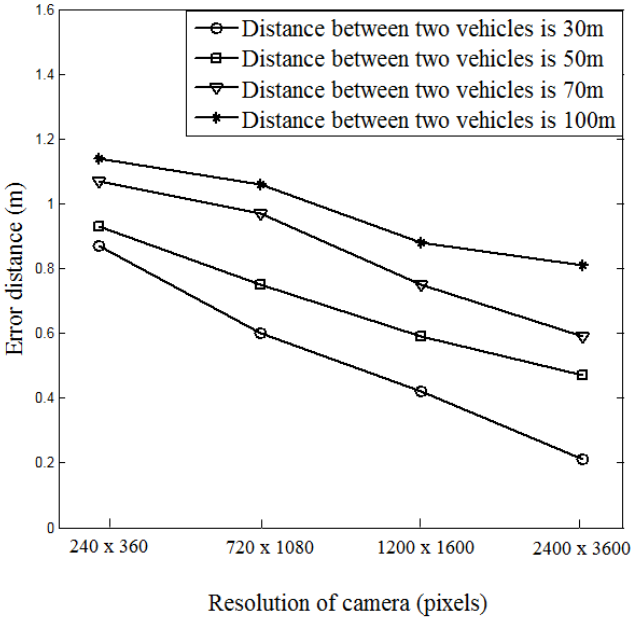

FIGURE 10. Distance error with resolution compensation corresponding to different resolution of image sensor.

The proposed resolution compensation method can be used with cameras having higher resolution. The performance of the proposed compensation corresponding to different resolution of the camera is shown in Figure 10. It can be seen that the proposed compensation method can further improves the estimation accuracy achieved with high resolution cameras.

V. CONCLUSION

This paper proposed a new positioning system for an outdoor environment using only one LED and two image sensors to determine the distance between two vehicles while traveling on a road. The contribution of the paper is two-fold. First, the paper proposes a new algorithm that uses two cameras to estimate the distance between the two vehicles given only one LED from the target vehicle is captured. This is important since in high traffic situation, only one of the two LED lamps in a vehicle can be seen from the behind vehicle and the proposed algorithm allows the behind vehicle to estimate the distance in this difficult situation. Second, the paper proposes a compensation method to reduce the estimation error caused by the low resolution of the camera. At close distance between two vehicles, the low resolution of the camera might not be a big problem. However, when the distance gets longer, the low resolution of the camera would drastically reduce the estimation accuracy as shown in the simulation. By using the proposed compensation method, the distance between vehicles can be estimated at higher accuracy and more importantly, the accuracy of the distance estimation remains almost the same as the distance increases.

REFERENCES

[1] L. Zeng *et al.*, "High data rate multiple input multiple output (MIMO) optical wireless communications using white LED lighting," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1654–1662, Dec. 2009.

[2] H. Elgala, R. Mesleh, and H. Haas, "Indoor optical wireless communication: Potential and state-of-the-art," *IEEE Commun. Mag.*, vol. 49, no. 9, pp. 56–62, Sep. 2011.

[3] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: Opportunities, challenges and the path to market," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 26–32, Dec. 2013.

[4] T.-H. Do and M. Yoo, "An in-depth survey of visible light communication based positioning systems," *Sensors*, vol. 16, no. 5, p. 678, 2016.

[5] N. Kumar, "Visible light communication based traffic information broadcasting systems," *Int. J. Future Comput. Commun.*, vol. 3, no. 1, p. 26, 2014.

[6] D. C. O'Brien, L. Zeng, H. Le-Minh, G. Faulkner, J. W. Walewski, and S. Randel, "Visible light communications: Challenges and possibilities," in *Proc. IEEE 19th Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2008, pp. 1–5.

[7] L. U. Khan, "Visible light communication: Applications, architecture, standardization and research challenges," *Digit. Commun. Netw.*, vol. 3, no. 2, pp. 78–88, 2017.

[8] B. Wook and S.-Y. Jung, "Vehicle positioning scheme using V2V and V2I visible light communications," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, May 2016, pp. 1–5.

[9] R. Roberts, P. Gopalakrishnan, and S. Rathi, "Visible light positioning: Automotive use case," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2010, pp. 309–314.

[10] G. Y. Song, K. Y. Lee, and J. W. Lee, "Vehicle detection by edge-based candidate generation and appearance-based classification," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2008, pp. 428–433.

[11] S. Iwasaki, C. Premachandra, T. Endo, T. Fujii, M. Tanimoto, and Y. Kimura, "Visible light road-to-vehicle communication using high-speed camera," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2008, pp. 13–18.

[12] S. Nishimoto, T. Yamazato, H. Okada, T. Fujii, T. Yendo, and S. Arai, "High-speed transmission of overlay coding for road-to-vehicle visible light communication using LED array and high-speed camera," in *Proc. Globecom Workshops (GC Wkshps)*, Dec. 2012, pp. 1234–1238.

[13] G. P. Stein, "Lens distortion calibration using point correspondences," in *Proc. IEEE Soc. Conf. Comput. Vis. Pattern Recognit.*, Jun. 1997, pp. 602–608.

[14] Y. Nakazawa, H. Makino, K. Nishimori, D. Wakatsuki, and H. Komagata, "Indoor positioning using a high-speed, fish-eye lens-equipped camera in visible light communication," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat. (IPIN)*, Oct. 2013, pp. 1–8.

[15] G. Bishop and G. Welch, "An introduction to the Kalman filter," *SIGGRAPH Course*, vol. 41, no. 8, pp. 27599–23175, 2001.

VO THI BICH TRAM received the B.S. degree in mathematics and computer science from the University of Science, VNU-HCM, Ho Chi Minh City, Vietnam, in 2015. She is currently pursuing the M.S. degree in information and telecommunication with Soongsil University, South Korea. Her research interest is visible light communication.

MYUNGSIK YOO received the B.S. and M.S. degrees in electrical engineering from Korea University, Seoul, South Korea, in 1989 and 1991, respectively, and the Ph.D. degree in electrical engineering from The State University of New York at Buffalo, Buffalo, NY, USA, in 2000. He was a Senior Research Engineer with the Nokia Research Center, Burlington, MA, USA. He is currently a Full Professor with the School of Electronic Engineering, Soongsil University, Seoul. His research interests include visible light communications, optical networks, sensor networks, and Internet protocols.