Tracking of LED headlights considering NLOS for an image sensor based V2I-VLC

Yuta KAWAI[1], Takaya YAMAZATO[1], Hiraku OKADA[1], Toshiaki FUJII[1], Tomohiro YENDO[2], Shintaro ARAI[3], and Koji KAMAKURA[4]

[1] Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, JAPAN

[2] Nagaoka Univeresity of Technology 1603-1 Kamitomioka, Nagaoka, Niigata, 940-2188, JAPAN

[3] National Institute of Technology, Kagawa College 551 Kohda, Takuma-cho, Mitoyo, 7691192 JAPAN

[4] Chiba Institute of Technology, 2-17-1, Tsudanuma, Narashino, 275-0016, JAPAN

Email:kawai@katayama.nuee.nagoya-u.ac.jp

***Abstract*—This paper focuses on image sensor based vehicle-to-infrastructure visible light communication (V2I-VLC) for Intelligent Transport Systems (ITSs). Because the image sensor can spatially separate multiple or noise sources, its receiver can simultaneously demodulate multiple sources. Thus, we consider multiple source reception from multiple vehicles. In image sensor based VLC, the transmitted data are received by extracting the luminance corresponding to the VLC transmitter from the captured image. Transmitter detection and tracking are an important requirement of these systems but are degraded by occlusion, which causes non-line of sight (NLOS). We focus on tracking of transmitters that may be occluded by moving vehicles in V2I-VLC. Our proposed method detects multiple LED headlights by combining a background difference method with an LED detection method based on time and space gradients. We also propose a tracking method based on optical flow-based tracking, which handles occlusion by linear or second-curve interpolation. The proposed methods were evaluated by a high-speed camera placed by the roadside. The false-positive and false-negative tracking rates were 6.25% and 3.32%, respectively, at $\kappa = 60$ (where κ defines the permissible error in the optical flow).**

***Keywords*—Visible Light Communication (VLC), Intelligent Transport System (ITS), Image sensor, Occlusion, NLOS, LOS**

I. Introduction

This paper focuses on image sensor based vehicle-to-infrastructure visible light communication (V2I-VLC) for Intelligent Transport Systems (ITSs). VLC is a wireless communication system that transmits information by a blinking pattern of the LED [1], [2], [3]. Because LEDs are solid-state lighting devices, they can be modulated at high speeds undetectable to the human eye.

VLCs using image sensors are called image sensor based VLCs [4]. The photodiode array of an image sensor can spatially separate multiple or noise sources. Therefore, the image sensor receiver can simultaneously demodulate multiple sources. In addition, by removing noise sources such as sunlight, it can detect visible light signals even in daytime or outdoor environments. Meanwhile, the image sensor of the VLC performs roles such as distance estimation [5], traffic surveillance [6], and drive recording. The use of image sensor based VLCs in ITSs has been already reported [7], [8], [9]. Here we focus on multiple source reception from multiple vehicles.

Detection and tracking of the transmitters is an important requirement of image sensor based VLC because the transmitted data are received by extracting the luminance corresponding to the VLC transmitter from the captured image. There are many studies on vehicle detection and tracking for traffic surveillance [6], driving assistance systems [10], and safe driving in ITS. The detection of LED array for infrastructure-to-vehicle (I2V-VLC) communication has also been reported [11].

Occlusion is a critical issue for detection and tracking in image sensor based VLC systems because it causes non-line of sight (NLOS) obstruction, which reduces the detection and tracking performance. Occlusion occurs when an object passes between the target object and the camera, hiding the target. The detection of partially occluded objects has been investigated in several studies [12]; however, tracking in the event of total occlusion has not been reported to date. Because it is important to track the LED headlights (assumed as the transmitters in our case), we focus on tracking these headlights even when

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they become occluded by moving vehicles in V2I-VLC.

We propose a detection method for detecting multiple LED headlights and a tracking method considering the NLOS. Combining a background difference method [13] with a LED detection method, our detection method considers the time and space gradients [11]. The proposed tracking method is based on optical flow [14] and handles occlusion by linear or second-curve interpolation.

This paper is organized as follows. Section II presents an overview of the system, and Section III describes the detection and tracking transmitters. Section IV presents the detection and tracking results of our proposed methods. Conclusions are presented in Section V.

II. SYSTEM OVERVIEW

A. Target Scenario

A conceptual diagram of an image sensor based V2I-VLC is shown in Fig. 1. As the transmitter and receiver, we employ a vehicle LED headlight and a high-speed camera set on the road, respectively. As shown in Fig. 1, the receiver can receive data from vehicle1 and vehicle2; however, the visible light signals of vehicle3 are blocked by vehicle2. We assume that multiple vehicles occupy a road with multiple lanes per side and that each vehicle has multiple (usually two) headlights.

In image sensor based V2I-VLC, the data are received by extracting the luminance of the LED headlight from the captured image. The photodiode array of the image sensor can spatially separate and demodulate multiple sources. By removing strong noises such as sunlight, the image sensor can receive visible light signals even in daytime or outdoor environments. This paper exploits these advantages of image sensors to develop multiple source reception from multiple vehicles occupying multi-lane roads.

The detection and subsequent tracking of LED headlights is important in image sensor based V2I-VLC. Detection of the LED headlights is defined as identifying the headlights in the captured image. Regarding the captured image as a 2D plane of (u, v), let us define $I(u_f, v_f)$ as the intensity of a pixel at position (u, v) in frame f. Detection of LED headlights refers to obtaining the position (u_{f_s}, v_{f_s}) of the LED headlights on the captured image, as shown in Fig. 2. The circle in this figure is assumed as the LED headlight. Tracking of LED headlights is defined as identifying the detected LED headlight in each frame. For this purpose, we adopt optical flow-based tracking [15]. The optical flow is a vector expressing the movement on the image, which is caused by a relative motion between the camera and object. We assume (u_{f_s}, v_{f_s}) and $(u_{f_{s+1}}, v_{f_{s+1}})$ as the LED headlight positions in the image coordinate systems of frame f_s and next frame f_{s+1}, respectively. The optical flow concept is presented in Fig. 3. The optical flow $(\Delta u_1, \Delta v_1)$ is then derived follows:

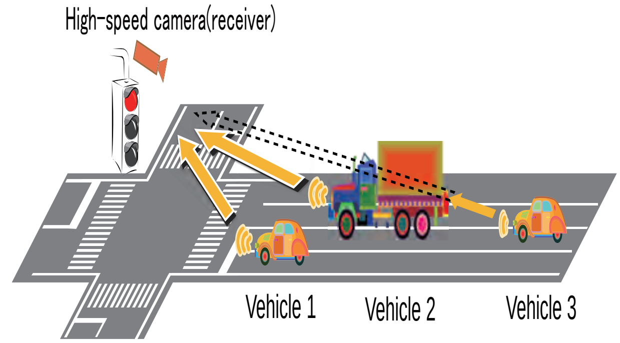


Fig. 1. V2I-VLC: transmitters and receivers are the vehicle LED headlights and a fixed high-speed camera, respectively.

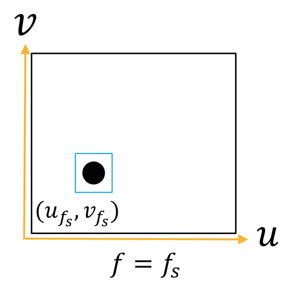


Fig. 2. Conceptual diagram of LED headlight detection in frame f_s, difined as identifying (u_{f_s}, v_{f_s})

$$\begin{aligned} \Delta u_1 &= u_{f_{s+1}} - u_{f_s} \\ \Delta v_1 &= v_{f_{s+1}} - v_{f_s} \end{aligned} \tag{1}$$

NLOS means that the transmitter of the image sensor based VLC cannot be detected from the captured image. In this study, NLOS is sourced from occlusion by vehicle movement. LOS and NLOS in image sensor based V2I-VLC are conceptualized in Fig. 4 . In Fig. 4 (a), vehicle1 and vehicle2 are in LOS because the receiver can detect their transmitters from the captured image. In Fig. 4 (b), while vehicle1 and vehicle2 are in LOS, vehicle3 is in NLOS because its transmitter is occluded, and cannot be detected in the captured image. We focus on cases in which a transmitter in NLOS shifts to LOS by further movement of the vehicle carrying the transmitter.

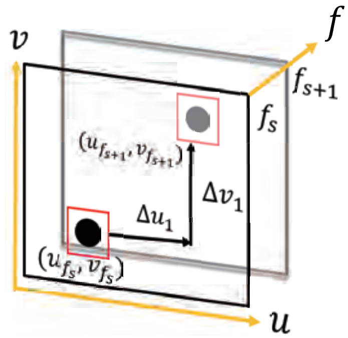
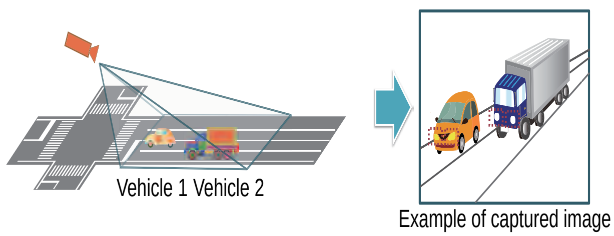
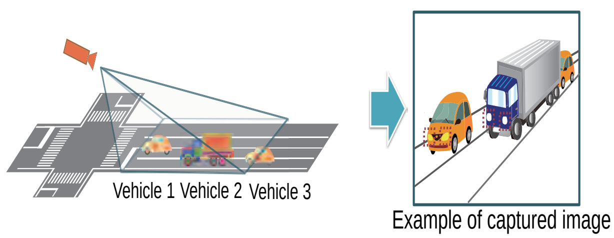


Fig. 3. Conceptual diagram of optical flow. (u_{f_s}, v_{f_s}) and $(u_{f_{s+1}}, v_{f_{s+1}})$ are the image coordinate positions of the LED headlight in frame f_s and the next frame,respectively.



(a) Example of LOS environment



(b) Example of NLOS environment

Fig. 4. (a):Vehicle1 and vehicle2 are in LOS because the receiver can detect both transmitters from the captured image. (b): Vehicle1 and vehicle2 are in LOS; however, vehicle3 is in NLOS because the receiver cannot detect its occluded transmitter from the captured image.

B. Purpose of This Paper

Here we aim to detect multiple LED headlights and track even when occlusion occurs. We propose optical flow-based tracking, which is easily achieved between consecutive frames because the receiver is a high-speed camera; consequently, the time interval between consecutive frames is very short. However, occlusion increases the difficulty of optical flow-based tracking because it lengthens the frame interval. To solve this problem, we calculate occluded optical flows by linear or second curve interpolation.

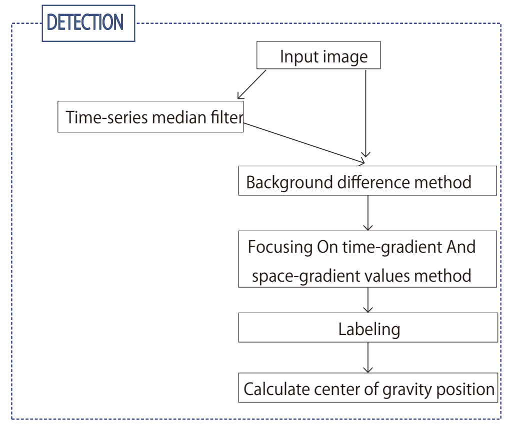


Fig. 5. Flowchart of the detection procedure.

III. SYSTEM MODEL

Our proposed detection method uses the background difference method and a detection method based on temporal and spatial gradients [11], as shown in Fig. 5 .These methods identify the LED headlights at the detection stage . The background image used in the background difference method is constructed by a time-series median filter [16]. Temporal and spatial gradients are suitable for LED headlight detection because LED headlights (such as LED arrays) have characteristically high time-gradient values and low space-gradient values in the captured images. The detection method is detailed in subsection. III-A.

We propose optical flow based tracking method. Optical flow is already used for tracking [15]. Optical flow is very small because time interval is very short when we use high-speed camera [17]. Therefore, our proposed method can easily track transmitter between consecutive frames by using optical flow. On the other hand, when LED headlight cannot be detected by occlusion, time interval increases. Therefore, in the event of occlusion, we should predict the positions of the transmitters in the image coordinate system. Our proposed method predicts these position using linear and second- curve interpolation.

A. LED Headlight Detection

First, our proposed method removes the background by the background difference method. The background difference method removes the moving objects from the background image. Here, we construct the background image by a time-series median filter [16], which effectively removes instantaneous noises. A moving object can be interpreted as an instantaneous noise by increasing the frame interval. Having removed the background, we use an LED detection method based on the temporal and spatial gradients [11]. As mentioned above, LED headlights and arrays are distinguished by high temporal gradients and low spatial gradients in the captured images. The detection image is then binarized. The third step of our proposed method is labeling of the binary image. Fourth, our method calculates the center of gravity position of each headlight.

First, our proposed method remove background by using background difference method.

B. LED Headlight Tracking

1) Judgement of NLOS: Our proposed method calculates the optical flow of occluded headlights by linear or second-curve interpolation. Therefore, the method must judge when the headlight environment changes from LOS to NLOS. A headlight is judged to become NLOS when it was previously detected, but cannot be detected in N consecutive frames. In this paper, because blinking speed of the LED was more than 100 Hz, LED should turn on at least 1 frame among 10 consecutive frames. Therefore, $N = 15$ was sufficient.

2) Tracking Method considering Occlusion: A conceptual diagram of optical flow computed by linear or second-curve interpolation is shown in Fig. 6.

- linear interpolation

optical flow is linearly interpolated to give $(\Delta u_\alpha, \Delta v_\alpha)$, as shown in Eqs (2) and (3). Here, α is the number of the frames in which the headlight was in NLOS.

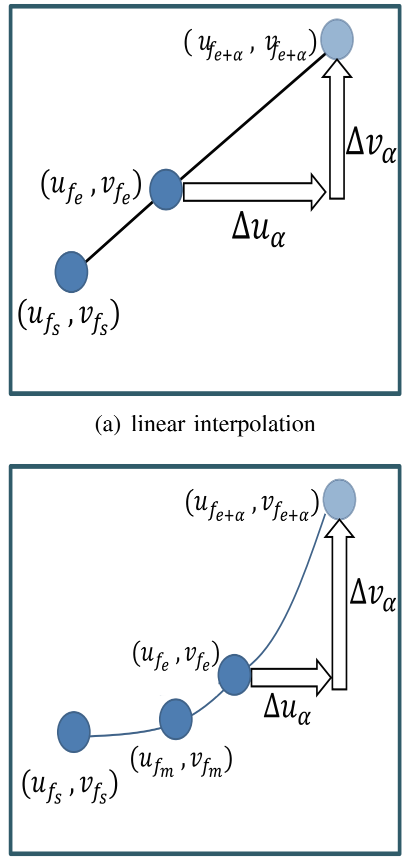
$$\Delta u_\alpha = (f_e + \alpha - f_s)\frac{u_s - u_e}{f_s - f_e} + u_{f_s} - u_{f_e} \quad (2)$$

$$\Delta v_\alpha = (f_e + \alpha - f_s)\frac{v_s - v_e}{f_s - f_e} + v_{f_s} - v_{f_e} \quad (3)$$

f_s is the frame in which the headlight was first detected; f_e is the frame in which the headlight was last detected before entering NLOS. (u_{f_s}, v_{f_s}) and (u_{f_e}, v_{f_e}) are the image coordinate positions of the headlight in f_s and f_e, respectively.

- second-curve interpolation

In second-curve interpolation, the optical flow $(\Delta u_\alpha, \Delta v_\alpha)$ is calculated by Eqs. (4) and (5).



(a) linear interpolation

(b) second-curve interpolation

Fig. 6. Optical flow calculated by (a) linear interpolation and (b) second curve interpolation. In frame f_s, the headlight is detected for the first time; in frame f_e, it is detected immediately before entering NLOS. $(u_{f_s}, v_{f_s}), (u_{f_e}, v_{f_e})$ are the image coordinate positions in f_s and f_e, respectively. $f_m = \frac{f_s+f_e}{2}$, (u_{f_m}, v_{f_m}) is the image coordinate position in f_m.

$$\begin{aligned}\Delta u_\alpha = {} & u_{f_s} \times \frac{(\alpha)(f_e+\alpha-f_m)}{(f_s-f_e)(f_s-f_m)} + u_{f_e} \times \frac{(f_e+\alpha-f_s)(f_e+\alpha-f_m)}{(f_e-f_s)(f_e-f_m)} \\ & + u_{f_m} \times \frac{(f_e+\alpha-f_s)(\alpha)}{(f_m-f_s)(f_m-f_e)} - u_{f_e} \quad (4)\end{aligned}$$

$$\begin{aligned}\Delta v_\alpha = {} & v_{f_s} \times \frac{(\alpha)(f_e+\alpha-f_m)}{(f_s-f_e)(f_s-f_m)} + v_{f_e} \times \frac{(f_e+\alpha-f_s)(f_e+\alpha-f_m)}{(f_e-f_s)(f_e-f_m)} \\ & + v_{f_m} \times \frac{(f_e+\alpha-f_s)(\alpha)}{(f_m-f_s)(f_m-f_e)} - v_{f_e} \quad (5)\end{aligned}$$

Here $f_m = \frac{f_s+f_e}{2}$, (u_{f_m}, v_{f_m}) is the position in the image coordinate system of frame f_m.

IV. EXPERIMENTAL MEASUREMENTS

A. Measurement Equipment and Setup

The experimental movies were acquired by a high-speed camera placed on a road with 3 lanes per side. The

TABLE I. THE NUMBER OF THE FRAMES α THAT EACH HEADLIGHT WAS NLOS

scene	Headlight	α (frame)	scene	Headlights	α (frame)
1	1	883	3	9	3021
	2	894		10	1602
	3	1202	4	11	1054
2	4	3234		12	1127
	5	2967		13	2532
	6	546		14	2003
	7	613	5	15	3597
	8	597		16	2784

width and height of the images was 512 (horizontal) and 512 pixels (vertical), respectively. Images were captured at 1000 fps (capture interval = 1 ms), and the lens diaphragm was 16. We recorded 9600 frames in each of 5 measurements. Table I lists the number of frames α in which the headlights were in NLOS. For NLOS environments caused by motorcycles or small vehicles, α was less than 700. The parameter N used for NLOS judgement was selected as 15.

B. Performance of LED Headlight Detection

To evaluate the performance of the LED headlight detection discussed in III-A, we calculated the false-positive and false-negative rates. The parameter used by the LED detection method was decided from a scatter diagram of the temporal gradients versus the spatial gradients (see Fig. 7). As shown in the figure, LED headlights have high temporal gradients, but sometimes also exhibit high spatial gradients. The high spatial gradients are thought to arise because we substituted the headlights with smaller fog lights. The false-positive and false-negative rates are defined as the ratios of the false detected and misdirected frames to the total number of frames including vehicles, respectively. The false-positive and negative rates were computed as 0.4% and 0%, respectively. Our proposed method use spatial gradients and temporal gradients not a characteristic point or an edge. Therefore, it is hard to be affected by fog and the train. Approximately 10000 frames were used in the LED headlight detection. The calculation time for detection was 67 ms per 1 frame. Therefore, it does not yet touch real-time processing.

C. Performance of LED Headlight Tracking considering NLOS

We next evaluated the performance of LED headlight tracking considering NLOS (see III-B). The tracking was considered successful if Eq. (6) was satisfied.

$$\sqrt{\Delta u_{\alpha}{}^2 + \Delta v_{\alpha}{}^2} \leq \kappa \tag{6}$$

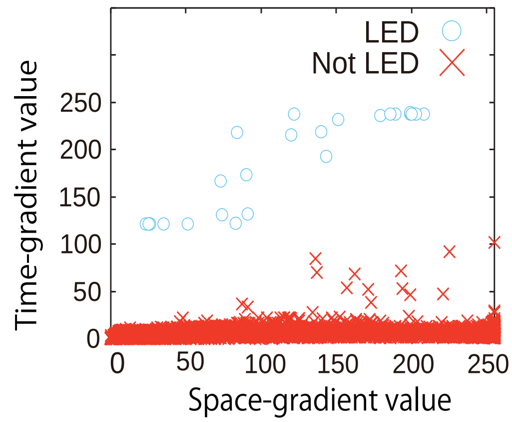


Fig. 7. Scatter diagram of temporal gradients versus spatial gradients.

The optical flow calculation between NLOS environments was evaluated by tracking the false-positive and false-negative rates. False-positive tracking occurred when our proposed method tracked a different headlight between frames, and false-negative tracking was a violation of Eq. (6). When κ is small (large), false-positive tracking is small (large) and false-negative tracking is large (small). The parameter κ defines the permissible error in the optical flow . Fig 8 shows the tracking result for $\kappa = 10, 20, 30, 40, 50, 60, \text{and} 70$. When $\kappa = 60$, the false positive and false negative tracking rates were 6.25% and 3.32%, respectively. Regardless of κ, interpolating the NLOS events by second-curve rather than by linear interpolation improved the tracking performance. Because of the geometrical relationship between the camera and its targets, the optical flow reduces at locations far from the camera and vice versa. For this reason, linear interpolation is inappropriate, and a second- or higher-order interpolation is required for optical flow based tracking. The occlusion hardly occurs from anyone other than the obstacle with other cars. Even if occlusion occurs, it is short time. Therefore, it is occlusion caused by othe cars to affect the performance of tracking most. The calculation time for tracking was 24 ms per 1 frame. Therefore, it does not yet touch real-time processing.

V. CONCLUSIONS

In this paper, we proposed LED headlight detection method and LED headlight tracking method considering NLOS. In NLOS environments, LED headlight tracking was performed by linear or second-curve interpolation of the optical flow. The validity of the proposed method was confirmed by experiment. The proposed tracking method

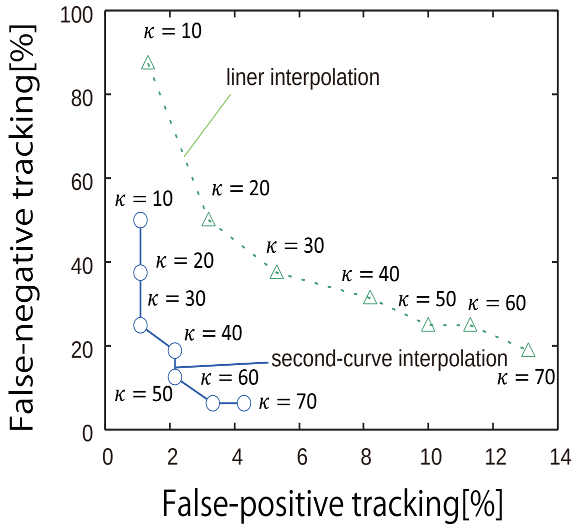


Fig. 8. Tracking result of optical flow-based tracking method using linear or second-curve interpolation with $\kappa = 10, 20, 30, 40, 50, 60, 70$.

achieved false-positive and false-negative tracking rates of 6.25% and 3.32%, respectively, at $\kappa = 60$.

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