Channel Fluctuation Measurement for Image Sensor Based I2V-VLC, V2I-VLC, and V2V-VLC

Masayuki KINOSHITA1, Takaya YAMAZATO1, Hiraku OKADA1, Toshiaki FUJII1, Shintaro ARAI2, Tomohiro YENDO3, and Koji KAMAKURA4

1 Nagoya University, Furo - cho, Chikusa - ku, Nagoya, 464 - 8603, JAPAN
2 National Institute of Technology, Kagawa College 551 Kohda, Takuma-cho, Mitoyo, 7691192 JAPAN
3 Nagaoka Univeresity of Technology 1603 - 1 Kamitomioka, Nagaoka, Niigata, 940 - 2188, JAPAN
4 Chiba Institute of Technology, 2-17-1, Tsudanuma, Narashino, 275-0016, JAPAN

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

Abstract—In image sensor based VLC, transmitter acquisition and tracking are critical issue. However, the fluctuation of the VLC transmitter in the image plane caused by vehicle movement, complicates correct data reception. Therefore, in this paper, we present results of channel fluctuation measurements for infrastructure-to-vehicle VLC (I2V-VLC), vehicle-to-infrastructure VLC (V2I-VLC), and vehicle-to-vehicle VLC (V2V-VLC). We analyze channel fluctuation in terms of optical flow from measured data.

Keywords—Visible Light Communication, ITS, Image sensor, Channel Fluctuation, Optical flow

I. INTRODUCTION

Light-emitting diodes (LEDs) offer a new and revolutionary light source that save energy. Since LEDs are solid-state lighting devices, we can control LED’s intensity at high speeds that are undetectable to the human eye. Thus, LED enable to transmit data with providing light [1]. For this advantage, Visible light communication (VLC) using LED have a great deal of attention as novel communication systems [2]-[4].

Since LED lights are widely used in road traffic such as traffic light, signage board, street and area lights, automotive headlights, and taillights, these LEDs attract VLC applications in field of intelligent transport systems (ITS) [3]-[6]. Among VLC in the field of ITS, this paper focuses on following automotive applications: 1) infrastructure to vehicle VLC (I2V-VLC); 2) vehicle to infrastructure VLC (V2I-VLC); 3) vehicle to vehicle VLC (V2V-VLC). For I2V-VLC, we assumed LED traffic light as a transmitter and in-vehicle high-speed camera (image sensor) as a receiver. Conversely, for V2I-VLC, we assumed vehicle headlight as a transmitter and high-speed camera set on the road as a receiver. For V2V-VLC, we assumed vehicle taillight as a transmitter and in-vehicle high-speed camera as a receiver.

In image sensor based VLC, the data reception is performed by extracting luminance corresponding to the transmitter from captured images. Hence, the VLC transmitter acquisition and tracking are critical. However, the fluctuation of the VLC transmitter in the image plane caused by vehicle movement, confuses the VLC receiver to select the correct pixels for data reception.

Therefore, we performed channel measurements for image sensor based VLC for automotive application and provided results. Especially, we examined the channel fluctuation based on mobile movements in the image plane detected by phase only correlation (POC) in the subpixel accuracy.

This paper is organized as follow; Section II presents optical flow of target transmitter as image sensor based VLC channel parameter. Section III presents our measurement campaign and post-processing method. Section IV shows experimental result. Finally, conclusions are presented in Section V.

II. IMAGE SENSOR BASED VLC CHANNEL

In image sensor based VLC, a transmitted optical signal is first captured by the image sensor as relative position in image coordinate \((u, v)\) in the image sensor plane and luminance value. Because movement in image coordinate \((u, v)\) of the target transmitter is important in image sensor based VLC, we treat such movement as a parameter to evaluating for VLC channel. Such movement is called optical flow [7] and denoted by vector \((\Delta u, \Delta v)\), where \(\Delta u\) and \(\Delta v\) are the distance the LED moved between frames.

For the mobile environment, image coordinate \((u, v)\) of the transmitter moves due to the movement of the transmitter itself, receiver, or both. We consider the following three cases: 1) V2I-VLC, 2) I2V-VLC, and 3) V2V-VLC.

1) V2I-VLC: In V2I-VLC case, a transmitter moves with vehicle and image sensor receiver is fixed on a road. Thus, the relative position of the transmitter also shift in the image sensor plane according to vehicle movement. Such movement must be considered to accurately receive the optical signal. Note that in this case, only the position of mobile transmitter changes, whereas the background scene does not.
2) I2V-VLC: Conversely, in I2V-VLC case, a transmitter is fixed on a road and image sensor receiver moves with vehicle. Therefore, pixel positions of captured images also move according to vehicle movement.

3) V2V-VLC: In the V2V-VLC case, both the image sensor receiver and the transmitter move. Due to such vehicle movements, pixel positions of captured images move in a manner very similar to that in the I2V-VLC case; in addition, the position of the LED transmitters move in a manner similar to that in the V2I-VLC case.

III. CHANNEL MEASUREMENT CAMPAIGN

A. Setup and Measurement Scenarios

We performed measurements with following equipment. The high-speed camera (Photoron IDP-Express R2000) was used as a receiver. The parameter of high-speed camera is shown in Table I. We recorded for 5 s (i.e., 5,000 frames) for every experiments. Since we are only interested in the movement of VLC transmitter position in the captured image, the lens diaphragm was set to 16 (which is relatively large F-number) to avoid saturation of the VLC transmitter. Large F-number also facilitate the segmentation of VLC transmitter area from captured image. The measured data was post-processed using PC.

For I2V-VLC channel measurement, 32 × 32 LED array was used as the transmitter. Note that the LEDs were the same as those actually used in LED traffic lights in Japan. During measurements, all LEDs were continually on. For V2I-VLC and V2V-VLC channel measurements, headlight of a vehicle was used for the transmitter. Since we focused only on the movement of the transmitter in the captured images, no blinking was performed in all cases. The parameters of VLC transmitters are shown in Table I.

We performed measurements at Nagoya University, Japan. All measurements were conducted during daytime (10 a.m. to 14 p.m.). Figure 1 shows the measurement scenarios. For I2V-VLC channel measurements, we set the high-speed camera on the dashboard of vehicle and recorded images of an LED array set on the ground. The vehicle moved toward the LED array at constant speeds (20 km/h and 30 km/h). For V2I channel measurements, we set the high-speed camera on the ground and recorded images of a vehicle with headlights on, moving toward the high-speed camera at speeds of 20 km/h and 30 km/h. For V2V channel measurements, we set high-speed camera on the back of the vehicle and recorded images of the headlight of the vehicle behind. The both vehicles moved at same speeds (20 km/h and 30 km/h) with a spacing of approximately 30 m.

B. Post-process

For post-processing, the first step was generating binary images from captured images. Since we set threshold value to 200 for maximum luminance 255, most of the background noise were eliminated. Further, we performed closing to binary images to remove morphological noise. Then, we applied POC [9], [10] to detect movement of LED optical flow in the subpixel accuracy.

<table>
<thead>
<tr>
<th>LED array</th>
<th>High-speed camera (receiver)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of LEDs</td>
<td>1,024</td>
</tr>
<tr>
<td>LED spacing</td>
<td>15 mm</td>
</tr>
<tr>
<td>Half value angle</td>
<td>26 degrees</td>
</tr>
<tr>
<td>Color of LEDs</td>
<td>Red</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Headlight</th>
<th>Type of vehicle</th>
<th>Color of headlight</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-speed camera (receiver) LED headlight (transmitter)</td>
<td>ESTIMAA</td>
<td>White</td>
</tr>
</tbody>
</table>

Fig. 1. VLC channel measurement scenario

POC is a strong method for estimating motion between two images. Let us consider two captured images at time $t$ and $t + 1$ (i.e., the next frame) as $f(u, v, t)$ and $f(u, v, t + 1)$, respectively. We assume that shift between two images as $\Delta u$ and $\Delta v$, then $f(u, v, t + 1) = f(u + \Delta u, v + \Delta v, t)$. If we denote the corresponding Fourier Transforms by $F(u, v, t)$ and $F(u, v, t + 1)$, we obtain

$$F(u, v, t + 1) = F(u, v, t)\exp\{-i(\Delta u \cdot u + \Delta v \cdot v)\}. \quad (1)$$

POC estimates subpixel accuracy by replacing the amplitude components of $F(u, v, t)$ and $F(u, v, t + 1)$ with unity

$$F'(u, v, t) = 1$$
$$F'(u, v, t + 1) = \exp\{-i(\Delta u \cdot u + \Delta v \cdot v)\}. \quad (3)$$

Then, takes the inverse Fourier transform of synthetic image as

$$H(u, v) = F'(u, v, t)(F'(u, v, t + 1))^*, \quad (4)$$
where $F'(u, v, t)$ and $F'(u, v, t+1)$ are the phase components of $F(u, v, t)$ and $F(u, v, t+1)$, respectively. Introducing small values $\delta u$ and $\delta v$, we obtain the inverse Fourier transform of $H(u, v)$ as

$$h(u - \Delta u, v - \Delta v) = \begin{cases} 
\frac{1}{\epsilon} \xi(\frac{\Delta v}{\epsilon}) & (u = \Delta, v = \Delta v) \\
\xi(\frac{\Delta u}{\epsilon}) & (u = [\Delta u], v = [\Delta v]) \\
0 & \text{otherwise}
\end{cases}$$  \hspace{1cm} (5)

where $\Delta u = [\Delta u] + \delta u$, $\Delta v = [\Delta v] + \delta v$, $[x]$ is nearest integer function of real number $x$, and $\epsilon$ is the noise term. Note that since $u$ and $v$ are integers, the peak value $\xi$ is less than 1. The phase differences in subpixel accuracy can be obtained by finding the best two-dimensional fit of phase difference, $\delta u$ and $\delta v$ in $\Delta$ such that the peak reaches 1 [8], [9].

Further, POC image $h(u - \Delta u, v - \Delta v)$ can be approximate by sinc function as

$$h(u - \Delta u, v - \Delta v) \approx \text{sinc}(u - \Delta u) \text{sinc}(v - \Delta v)$$  \hspace{1cm} (6)

Figures 2 and 3 show an example of the POC image and the sinc function approximation in cross-section of the POC, respectively.

IV. EXPERIMENTAL RESULT

Figures. 4, 5, and 6 show experimental results for the case of vehicle speed at 30 km/h. These results describe the probability density of optical flow, $\delta u$ and $\delta v$. For the case of I2V, we observe that the mean value of both $\delta u$ and $\delta v$ are -0.1 pixel. These shifts are caused by that the LED array was located away from the center on the images. Therefore the LED array moved toward the outside on the image every frames as vehicle approached. The variances are $\sigma_{\delta u}^2 = 1.52 \times 10^{-2}$ and $\sigma_{\delta v}^2 = 3.95 \times 10^{-2}$, respectively for $\delta u$ and $\delta v$. As the vehicle vibration mainly induced by road surface irregularities, we observe that $\sigma_{\delta v} \geq \sigma_{\delta u}$. Note that maximum flows are 1.5 pixel horizontally and 1.4 pixel vertically.

Similar tendency was observed for the case of V2I shown in Fig. 5. The means are shifted 0.1 pixel and variances are $\sigma_{\delta u}^2 = 6.11 \times 10^{-4}$ and $\sigma_{\delta v}^2 = 1.14 \times 10^{-3}$, respectively for $\delta u$ and $\delta v$. Although their means are shifted, optical flow characteristics of V2I and I2V have similar properties i.e., distributed mainly on average and vertical flow is greater than horizontal flow. However their variances, especially vertical direction, are different. Besides, the maximum flows are only 0.2 pixel in both horizontally and vertically. These result show I2V has more complex characteristic than V2I. We consider these differences are due to the posture of the camera. While the camera is completely static for the V2I, the posture of the camera is fluctuated by vehicle vibration for I2V.

For the case of V2V, similar tendency was also observed. The means are shifted 0.1 pixel horizontally and variances are $\sigma_{\delta u}^2 = 3.64 \times 10^{-3}$ and $\sigma_{\delta v}^2 = 6.40 \times 10^{-2}$, respectively for $\delta u$ and $\delta v$. For this case, the maximum flows are 0.7 pixel in horizontally and 1.8 pixel in vertically. Note that the variance of $\delta u$ is largest in three cases, however the variance of $\delta v$ is not. For vertical direction, since both transmitter and receiver moved, the effect of vibration was larger than other cases. On the other hand, we considered the effect of vehicle movement on horizontal direction was reduced, since transmitter vehicle chased receiver vehicle in our measurement.

Moreover, Figures 7, 8, and 9 show the results for the case of vehicle speed at 20 km/h. Each optical flow characteristics indicated similar results (i.e., mean shift, form and tendency of distributions, and $\sigma_{\delta v}^2 \geq \sigma_{\delta u}^2$), but their variances were smaller. From this reason, we considered that channel fluctuation related to the vehicle speed.

V. CONCLUSION

In this paper, we provided results of channel measurements for image sensor based VLC for automotive application. Especially, we examined channel fluctuation based on mobile movements in the image plane.

We measured the vehicle vibration described by optical flow with subpixel accuracy using POC. We evaluated optical flow characteristics in terms of probability density of flows and their variances. For the three cases of VLCs, such as I2V-VLC, V2I-VLC, and V2V-VLC, optical flow characteristics indicated similar properties, i.e., primarily distributed on average and vertical flows were greater than horizontal flow. However their variances were different. The variance of I2V and V2I were greater than that of V2I. We considered these differences were caused by fluctuation of camera posture. These results show that I2V and V2V have more complex characteristics of channel fluctuation than V2I.

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