Multiple LED Arrays Acquisition for Image-Sensor-Based I2V-VLC Using Block Matching

Shintaro Arai*, Yasutaka Shiraki†, Takaya Yamazato†,
Hiraku Okada†, Toshiaki Fujii† and Tomohiro Yendo‡
*Kagawa National College of Technology
551 Kohda, Takuma-cho, Mitoyo, 769–1192 JAPAN
arai@cn.kagawa-nct.ac.jp
†Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464–8063 JAPAN
‡Nagaoka University of Technology
1603–1 Kamitomioka, Nagaoka, 464–8063 JAPAN

***Abstract*—The present paper proposes a novel multiple-LED-arrays acquisition for an infrastructure-to-vehicle visible light communication (I2V-VLC) using LED arrays (transmitter) and an in-vehicle high-speed image sensor (receiver). In order to achieve a robust detection of LED arrays, we employ the block matching algorithm, which is a way of finding a corresponding position between two successive frames. The proposed method divides a captured image into a number of small domains (blocks) and determines if the LED array is present or absent using the block matching. We perform I2V-VLC experiments with multiple-LED arrays and evaluate the acquisition capability of the proposed method.**

I. Introduction

Light-emitting diode (LED) offers a new and revolutionary light source since it has several superior advantages, such as an energy-saving, long life and good visibility. Moreover, the intensity of LED (i.e. luminance) can be controlled at high speeds that are undetectable to the human eye because LED is a solid-state lighting device. Many researchers in the field of communication systems focus on these advantages and interest for visible light communications (VLC) using LED [1]–[3]. VLC, which is a novel optical wireless communication technology, can not only provide light but also broadcast data. Widespread use of LEDs in traffic applications and growing interest in intelligent transport systems (ITS) present an opportunity for the application of VLC [4]– [10]. Infrastructure-to-vehicle visible light communication (I2V-VLC) and vehicle-to-vehicle visible light communication (V2V-VLC) are typical applications for ITS. These systems contribute to exchange a safety information between roadway infrastructure (or vehicle) and vehicles.

This present paper considers I2V-VLC using an LED array (transmitter) and an in-vehicle high-speed image sensor (receiver), as shown in Fig. 1. In this system, the blinking of the transmitter's LEDs passes through an optical wireless channel and arrives at the in-vehicle receiver. The receiver converts the arrived LED light into an image and recovers data by extracting LED luminance values from the image. As one of great advantages of using the image sensor for VLC, the image sensor can individually recognize LED light of the transmitter composed many LEDs because it has an ability of a spatial separation. If we can allocate 1 bit data to 1 LED, a transmission data rate increases with increasing the number of LED on the transmitter since the image sensor can recognize each LED light. Namely, the parallel data transmission is possible by modulating each LED independently. This advantage brings significant benefit to recognize multiple information sources. Thanks to the ability of the spatial separation, the image sensor can distinguish only the pixels that sense LED transmission sources and discards other pixels, including those sensing noise sources such as the Sun. Thus, the image-sensor receiver is suitable for the situation of multiple information sources in ITS using VLC.

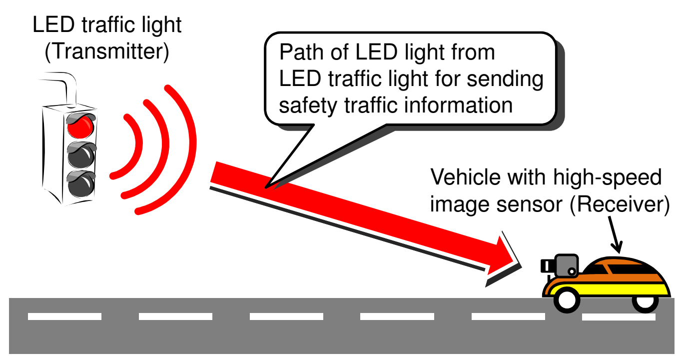


Fig. 1. Infrastructure-to-vehicle visible light communication (I2V-VLC) using the LED traffic light and the in-vehicle high-speed image sensor.

Here, let us consider an actual driving situation as shown in Fig. 2. As one can see, there are multiple light sources on the roadway, for example traffic signal and pedestrian lights, street and area lights. In this situation, the in-vehicle

Fig. 2. Captured image from vehicle while moving.

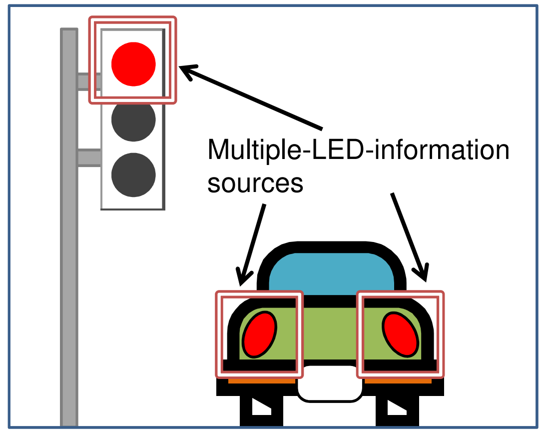


Fig. 3. Distinction example of multiple-LED-information sources.

receiver captures light sources while moving. If these light sources independently broadcast safety information, the in-vehicle receiver has to individually distinguish a light source from captured images for receiving each data, as shown in Fig.3. In order to keep robust VLC link, the receiver also has to acquire and track light sources every captured images since a size and position of each source on a captured image are different and depend on a communication distance.

In previous researches, I2V-VLC systems using an LED array (or LED traffic light) and the image sensor are proposed [5]– [10]. Especially, Refs. [6]–[8] performed I2V-VLC experiments and confirmed an effectiveness of using the image sensor for I2V-VLC. However, these experiments were performed under the condition of a single-LED array. It means that I2V-VLC performances with multiple-LED arrays are not fully evaluated.

As one of single-LED-array-acquisition methods, a simple frame subtraction method was proposed [7]. This method calculates a subtraction between two successive captured images and acquires a position of LED array, which blinks at high speed. However, its acquisition capability has low accuracy because this method is influenced a great deal by the vehicle vibration while moving. In addition, quantitative evaluations for the LED array acquisition, such as false-negative (missing of the target LED array) and false-positive (any things other than the target LED array is acquired), are not enough.

The purpose of this study is to describe and examine a multiple-LED-arrays acquisition for the image-sensor-based VLC. We propose a novel technique that distinguishes whether the LED array or not. Specifically, we employ the block matching algorithm [11] for multiple-LED-arrays-acquisition processing. The proposed method divides a captured image into a number of small domains (blocks) and determines if the LED array is present or absent using the block matching. We perform I2V-VLC experiments with multiple-LED arrays and evaluate the false-negative rate and the false positive rate of the proposed method.

The present paper is organized as follows. In Section 2, we introduce I2V-VLC system model with multiple light sources. The proposed technique for the multiple-LED-arrays acquisition is presented in Section 3, and its performance is evaluated in Section 4. Finally, we conclude the present paper in Section 5.

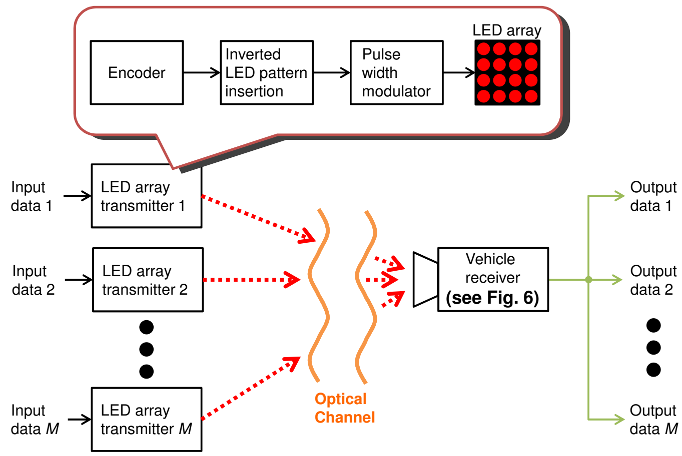


Fig. 4. I2V-VLC system model.

II. I2V-VLC SYSTEM MODEL WITH MULTIPLE-LED ARRAYS

Figure 4 shows a block diagram of I2V-VLC system model with multiple LED array transmitters.

Each transmitter consists of an encoder, an inverted LED pattern insertion unit, a pulse-width modulator (PWM), and 256 LEDs arranged in a 16×16 square matrix. The LED spacing is 20 mm. The LEDs are the same as those used in LED traffic lights in Japan. Input data is first fed into the encoder that processes channel coding [6], [9]. The tracking LED pattern insertion unit generates an inverted signal that is used for LED array tracking [7]. The signal is fed into the modulator to create LED lighting patterns of different luminance. Finally, the PWM signal is converted into a two-dimensional (2D) signal, and each LED transmits data in parallel by modulating LED luminance individually. In other words, we transmit data as a 2D-LED pattern. The LED blinking rate is once per 2 ms. The packet format is shown

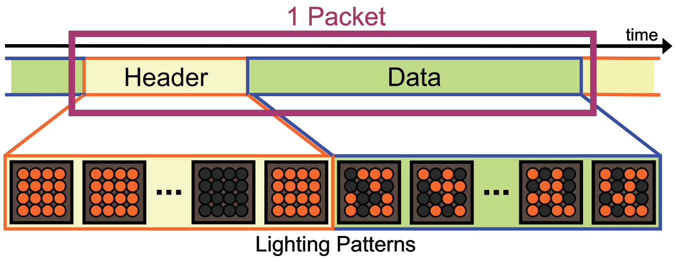


Fig. 5. Packet format.

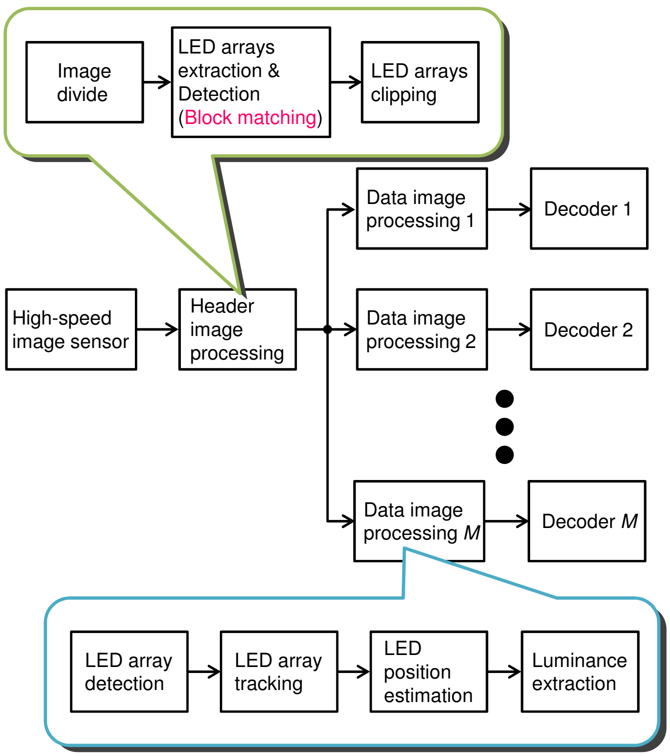


Fig. 6. Vehicle receiver for multiple-LED arrays.

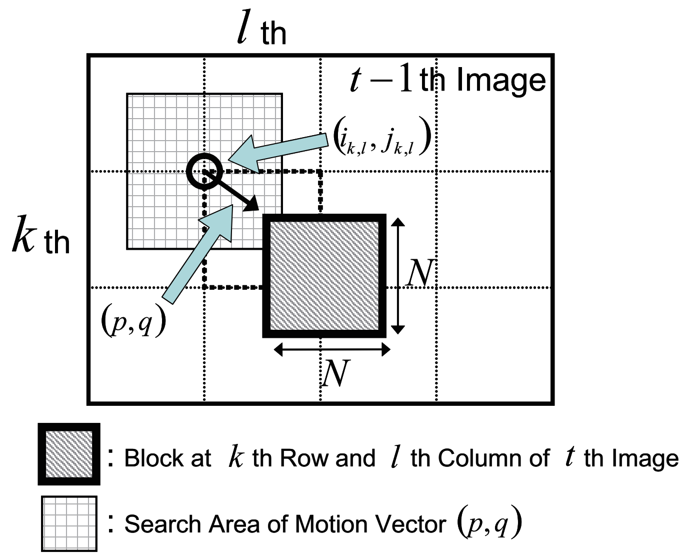


Fig. 7. Block matching.

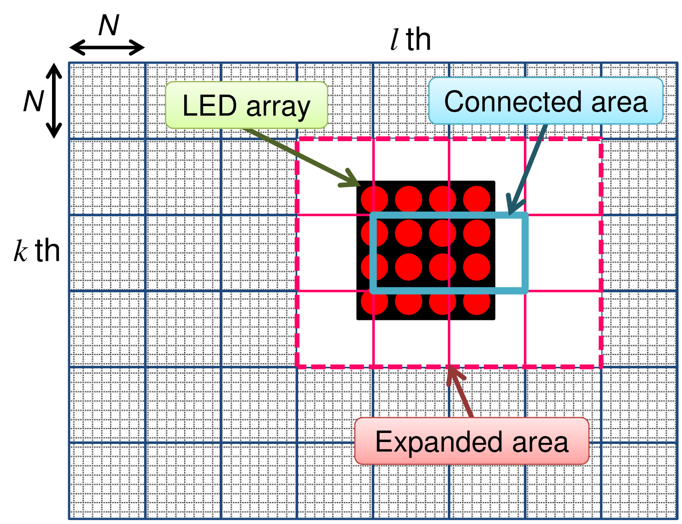


Fig. 8. LED array area clipping.

in Fig. 5. A Baker sequence of length 13 is selected for LED array detection. The data part includes the data signal and the inverted signal used for tracking [7].

The receiver consists of a high-speed image sensor, a header image-processing unit, data image-processing units, and decoders, as shown in Fig. 6. First, the images are captured at a frame rate of 1,000 fps, or every 1 ms, while the LED array blinks every 2 ms. The captured images are fed to the header image-processing unit, which distinguishes LED array transmitters from the captured images. We propose multiple-LED-arrays acquisition using the block matching in this study. The proposed method is detailed in Section 3. After the header image-processing unit, each distinguished signal is fed to each data image-processing unit, which consists of an LED array detection unit, an LED array tracking unit, an LED position estimation unit, and a luminance extraction unit. Using a Baker sequence including the transmitted LED blinking pattern, the data image processing unit first detects an LED array from an output of the header image processing. The tracking is performed by simple template matching using the tracking LED pattern that is created by adding the received LED pattern and its inverted LED pattern [7]. After the tracking, we perform LED position estimation, which outputs the position of each LED, and extract each LED luminance value from the estimated position. Finally, each output of data image-processing units is fed to each decoder, which performs decoding and outputs retrieved data.

III. Proposed Multiple-LED-Arrays Acquisition Using Block Matching

In this section, we explain the proposed multiple-LED-arrays acquisition using the block matching. The proposed method consists of an image divide unit, LED arrays extraction and detection unit, and LED arrays clipping unit.

A. Image divide unit

The first unit divides a captured image into $m \times n$ blocks to partially scan the image. In this study, a size of each block is $N \times N$ pixels.

B. LED arrays extraction and detection unit

The second unit extracts candidate areas of LED arrays from $m \times n$ blocks and detects blocks including LED arrays. In order to achieve a robust detection of LED arrays, we employ the block matching algorithm, which is a way of finding a corresponding position between two successive frames, as shown in Fig. 7.

Let us consider t th captured image (f_t) and $t-1$ th captured image (f_{t-1}). This unit using the block matching first detects a motion vector between (k, l) block of f_t $(0 < k \leq m, 0 < l \leq n)$ and any $N \times N$ pixels within f_{t-1}. The search for the best motion vector requires a criterion to calculate a similarity between search ranges of f_t and f_{t-1}. We use the sum of absolute distances (SAD), and it is described by Eq. (1).

$$SAD(p,q)_{k,l} = \sum_{j=0}^{N-1}\sum_{i=0}^{N-1} |f_{t-1}(i_{k,l}+i-p, j_{k,l}+j-q) - f_t(i_{k,l}+i, j_{k,l}+j)|, \qquad (1)$$

where $(p, q)_{k,l}$ a candidate motion vector in (k, l) block, $i_{k,l}$ and $j_{k,l}$ are the coordinates of the upper-left pixel of (k, l) block, $f_t(.)$ and $f_{t-1}(.)$ are pixel values corresponding to coordinates of f_t and f_{t-1}, respectively. When a motion vector search range is expressed in R ($(p, q) \in R$), a position vector $(p_{min}, q_{min})_{k,l}$, which makes the minimum $SAD(p, q)_{k,l}$, is described by Eq. (2).

$$(p_{min}, q_{min})_{k,l} = \arg \min_{(p,q)\in R} SAD(p, q). \qquad (2)$$

Here, we focus on $SAD(p_{min}, q_{min})_{k,l}$. If (k, l) block includes a part of LED array, $SAD(p_{min}, q_{min})_{k,l}$ contains any value. Its opposite case approaches zero. As described in Section 2, the images are captured at every 1 ms, while the LED array blinks every 2 ms. In this case, most of the background, i.e., everything except the LED array, remains the same between two successive images. Therefore, the any value of $SAD(p_{min}, q_{min})_{k,l}$ means the luminance value of the LED array or its part. We determine that the LED array or its part is included in (k, l) block when the following equation is satisfied.

$$T \leq \frac{1}{N^2} SAD(p_{min}, q_{min})_{k,l}, \qquad (3)$$

where T is a threshold to determine whether the LED array or not.

As one of advantages of using the block matching, the sub-pixel estimation is possible to find the corresponding position between f_t and f_{t-1}. Namely, the proposed method robustly extracts each LED array even if a pixel-to-pixel fluctuation between two successive images is caused depending on a vehicle vibration.

TABLE I
EXPERIMENTAL PARAMETERS.

Number of LEDs on the transmitter	256 (16 $\times$ 16 square matrix)
Number of transmitters (light sources)	2
Lightning frequency of LED	500 Hz
Camera model	FASTCAM-1024PCI 100K (Photron)
Image sensor	CMOS
Lens model	NIKKOR 35mm f/1.4 (Nikon)
Selected shutter speed	1000 fps
Image resolution	1024 $\times$ 512 pixels
Focal length of lens	35 mm
Lens diaphragm	8
Communication distance	120–30 m
Vehicle speed	30 km/h
Number of captured images F_{all}	12,800
Block size N	8
Search range of motion vector R	$-3 \leq p \leq 3, -3 \leq q \leq 3$

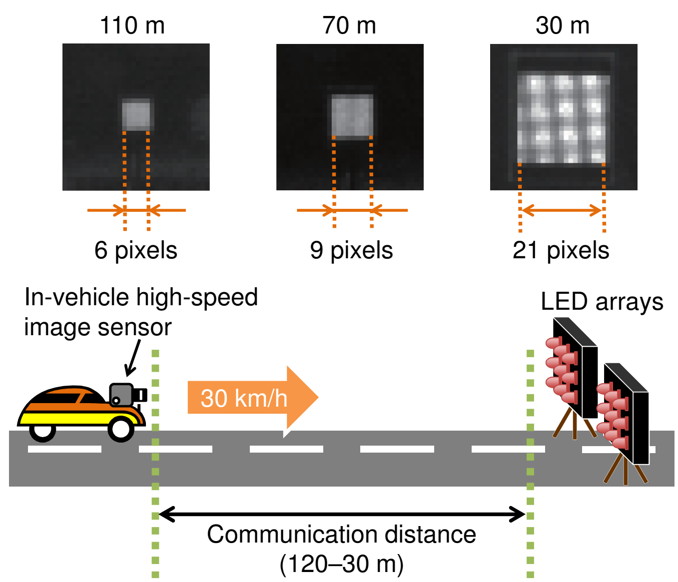


Fig. 9. Experimental situation.

C. LED arrays clipping unit

The third unit connects an extracted (k, l) block in the second unit and its neighboring extracted ones. When the block size is smaller than the size of LED array on the captured image, each LED array area on the image consists of multiple extracted (k, l) blocks, as shown in Fig. 8. Namely, we make a large area including one LED array by connecting extracted (k, l) blocks. Moreover, in order to improve an acquisition property, each connected area is expanded until its circumscribed area. Finally, each expanded area is clipped as each LED array area.

IV. Experiments and Results

This section explains the experiments of the I2V-VLC system and evaluates a performance of the proposed multiple-LED-arrays acquisition. Experimental parameters are shown in Tab. I. Here, we set the lens diaphragm value to clearly capture the background everything except LED arrays.

We have been performing the experiments under actual driving conditions. We placed two LED array transmitters, which have the identical feature each other, on horizontal ground and the image sensor on the dashboard of the vehicle. One LED array was placed in parallel with another array, and its interval is 1.6 m. The vehicle drives straight toward two LED arrays at a speed of 30 km/h, as shown in Fig. 9. The communication distance in the experiments ranges from 120 to 30 m. Figure 9 also shows actual images of the LED array area when the communication distances are 110 m, 70 m and 30 m. The experiments was performed in the daytime on the sunny day.

In order to quantitatively evaluate the performance of the proposed method, we calculate a false-negative (FN) rate and a false positive (FP) rate for the different threshold T. The FN and FP rates denote a missing rate of LED arrays and a rate when any things other than LED arrays are acquired, respectively. These rates are described by following equations.

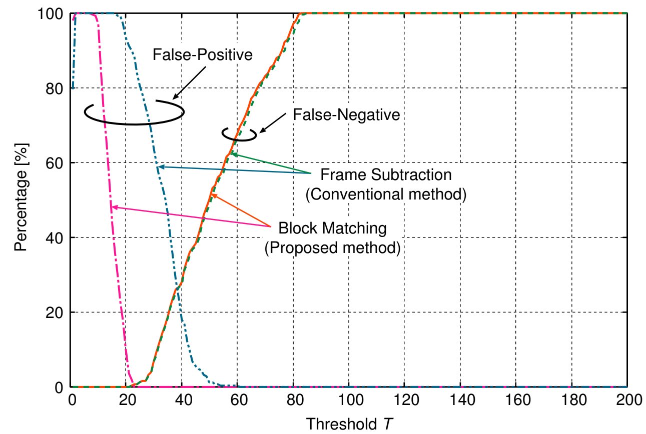
$$FN = 1 - \frac{F_{source}}{F_{all}}, \qquad FP = \frac{F_{noise}}{F_{all}}, \tag{4}$$

where F_{all} is the number of all captured images (frames), F_{source} is the number of frames when LED arrays or at least one LED array is acquired, and F_{noise} is the number of frames when one or more anything other than LED arrays are acquired.

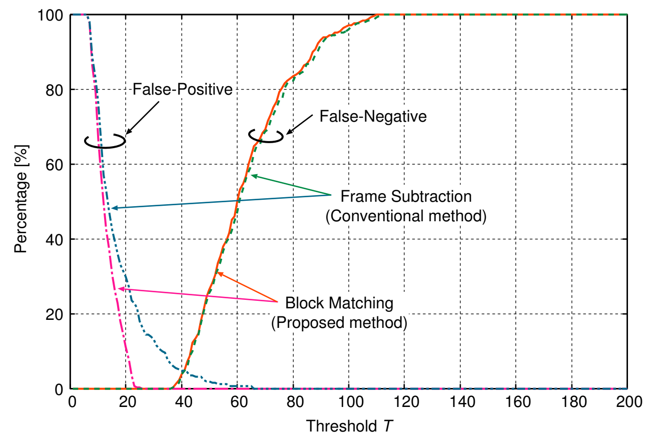
Figures 10(a)–(c) show FN and FP rates versus T for different communication distances when $N = 8$. We focus on three ranges of the distance (110–100 m, 80–70 m and 40–30 m) and plot results of two types of multiple-LED-arrays acquisitions: the block matching (the proposed method) and the simple frame subtraction method (the conventional method) [7]. As one can see, the relationship between FN and FP rates is a trade-off depending on T.

Let us focus on the results of the conventional method. We can observe that FN and FP rates of the conventional one do not become zero simultaneously when the range of communication distance is 110–100 m or 80–70 m. The reason for this is that the conventional method is influenced a great deal by the vehicle vibration while moving. When the vehicle vibration occurs, the corresponding position (pixel) between two successive frames fluctuates. The influence of this fluctuation causes a great difference pixel value within the difference image expect the LED array area. Thus, the conventional acquisition using the simple frame subtraction is low accuracy since it is difficult to determine whether the LED array or not.

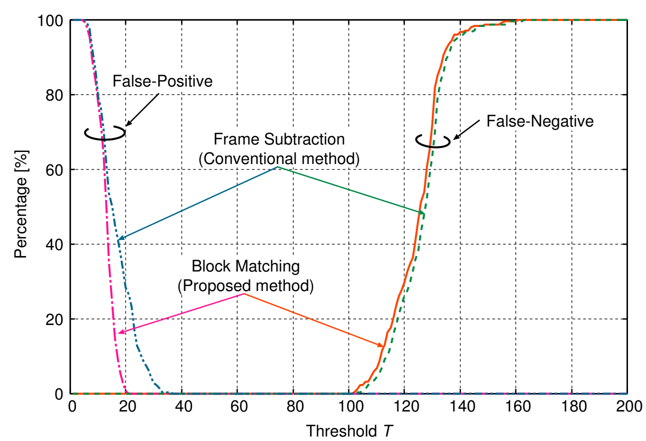
On the other hands, FN and FP rates of the proposed method simultaneously approaches zero without limit when the range of the distance is 110–100 m. Moreover, the proposed one achieves that FN and FP rates become zero simultaneously in other ranges. This is because that the proposed method can perform the sub-pixel estimation to find the corresponding position between two successive frames. In other words, the receiver can avoid the influence of the fluctuation between frames depending on the vehicle vibration.



(a) 110–100 m.



(b) 80–70 m.



(c) 40–30 m.

Fig. 10. False-Negative and False-Positive rates of multiple-LED-arrays acquisition.

Thus, the accuracy of the proposed one increases as compared with the conventional one.

Here, we evaluate the accuracy of the proposed multiple-LED-arrays acquisition with the optimal T, which is selected from Figs. 10(a)–(c). An acquisition example is shown in

Fig. 11. Acquisition example of the proposed method with the optimal T.

Fig. 11. White rectangle frames within Fig. 11 denote the clipping areas of LED arrays. We can confirm that the receiver achieves to clip whole LED array areas, as shown in Fig. 11. We have already observed almost 100% success of the clipping in all captured images by the visual confirmation. Therefore, the robust acquisition of multiple-LED arrays can be achieved by choosing the optimal T.

V. Conclusions

The present paper has proposed the novel multiple-LED-arrays-acquisition method for I2V-VLC. In order to achieve a robust detection of LED arrays, we have employed the block matching algorithm, which is a way of finding a corresponding position between two successive frames, for the proposed method. As results of experiments, we have confirmed that FN and FP rates of the proposed method simultaneously approaches zero without limit. It means that the vehicle receiver using the proposed method can avoid the influence of the fluctuation between frames depending on the vehicle vibration. Moreover, it has been observed that the proposed method can perform almost 100% success of the clipping of LED arrays. Therefore, we have achieved the robust acquisition of multiple-LED arrays.

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