A Study on On-vehicle High-speed Camera Image Processing for Parallel Visible Light Communication

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Abstract

Intelligent Transportation Systems(ITS) have been introduced to give solutions for traffic problems such as traffic accidents and congestions. Assistance of safe driving is one of the major significant area in ITS. On-vehicle and Infrastructure cameras play an important role in many ITS deployments related to assistance for safe driving. Those systems detect vehicle local information by cameras and driver is assisted regarding that information.

Recently, high-speed cameras are also used in ITS as well as in other scientific research, military test, and industry. High-speed cameras can capture more information of fast moving objects and changing objects in high frequency compared to the normal cameras. Our research group introduces a road-to-vehicle Visible Light Communication(VLC) system using an on-vehicle high-speed camera as a receiver and an LED traffic light as a transmitter. Driver can be assisted at signalized intersection by sending traffic information to vehicles through this system.

VLC is a wireless communication method using luminance, transmitting data by modulating blinking light. Many of conventional VLC systems use Photo Diode(PD) as receiver. However, the proposed system uses a high-speed camera as a receiver. Here, the data is sent by blinking

LEDs at high frequency. Those lighting patterns are captured for demodulation by processing the images from the high-speed camera at high frame rate. This image processing includes finding the transmitter, tracking the found transmitter consecutively, and capturing the lighting patterns of transmitter at each consecutive frame. This thesis presents algorithms for those image processing steps considering the features of high-speed image capturing, and available literature on these kind of studies is limited. In addition, all of those image processing steps should be conducted in real time. However, it might be difficult to realize this in software, since the images are taken at high frame rate. Even, to conduct it in real time on hardware, image processing algorithms should include approaches for processing time reduction. For this reason, all algorithms are presented considering the processing time reduction approaches as well.

Outdoor experiments were conducted to confirm the effectiveness of each proposed algorithm separately. Then the communication possibility of proposed VLC system was also evaluated using the new algorithms. It showed that finding, tracking and lighting pattern capturing can be effectively conducted with the proposed algorithms. By applying them, data communication can be conducted through the proposed VLC system at a distance between $20m$ and $40m$ far from the transmitter in a driving environment.

Publications

Jounal papers

[1] H. Chinthaka. N. Premachandra, T. Yendo, M. P. Tehrani, T. Yamazato, T. Fujii, M. Tanimoto and Y. Kimura,“ Edge-Based Tracking of an LED Traffic Light for a Road-to-Vehicle Visible Light Communication System, ”*Journal of Korean Society of Broadcast Engineers*, Vol. 14, No. 3, pp. 475-487, July 2009.

[2] H. Chinthaka. N. Premachandra, T. Yendo, M. P. Tehrani, T. Yamazato, H. Okada, T. Fujii and M. Tanimoto,“ LED Traffic Light Detection Using High-speed-camera Image Processing for Visible Light Communication, ”*Journal of The Institute of Image Information and Television Engineers*, Vol. 65, No. 3, pp. 354-360, March 2011.

International conferences

[1] H. Chinthaka. N. Premachandra, T. Yendo, M. P. Tehrani, T. Yamazato, T. Fujii, M. Tanimoto and Y. Kimura,“ Tracking a LED Traffic Light for Visible Light Communication System, ”*Proceedings of the International Workshop on Advanced Image Technology 2009*, 0008, January 2009.

[2] H. Chinthaka. N. Premachandra, T. Yendo, T. Yamazato, T. Fujii, M. Tanimoto and Y. Kimura,“ Detection of LED Traffic Light by Image Processing for Visible Light Communication System, ”*Proceedings of the 2009 IEEE Intelligent Vehicles Symposium*, pp. 179-184, June 2009.

[3] H. Chinthaka. N. Premachandra, T. Yendo, M. P. Tehrani, T. Yamazato, H. Okada, T. Fujii and M. Tanimoto,“ Identification of Emitting LED Array for Achieving Road-to-Vehicle Communication, ”*Proceedings of the International Workshop on Advanced Image Technology 2010*, 130, January 2010.

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Domestic conferences in Japan

[1] H. Chinthaka. N. Premachandra, T. Yendo, M. P.

Tehrani, T. Yamazato, H. Okada, T. Fujii, M. Tanimoto and Y. Kimura,“ Tracking of LED Traffic Light for Read-to-Vehicle Communication System, ”*Proceedings of the Society of Automotive Engineers of Japan (JSAE) Annual Congress Proceedings(Fall)*, 93-9, October 2009.

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[4] H. Chinthaka. N. Premachandra, T. Yendo, M. P. Tehrani, T. Yamazato, H. Okada, T. Fujii and M. Tanimoto,“ LED Traffic Light Detection Using a High-speed-camera for a Road-to-vehicle Visible Light Communication System, ”*9th Forum of Information Technology(FIT2010)*, September 2010.

Awards

[1] FIT 2010 Best paper award

[2] FIT 2010 Young researcher award

[3] 2008 Nagoya University outstanding graduate student award

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Chapter 1

Introduction

According to the fast world development, the number of motor vehicles on the roads are getting increased in every year. There are approximately 600 million passenger cars worldwide[1], there were about 806 million cars and light trucks on the road in 2007. Now, driving a motor vehicle is a part of our lives.

1.1 Motor vehicle benefits

Traffic can make make our lives comfortable benefiting on-demand transportation, mobility, independence and so on[2]. The societal benefits may include: economy benefits, such as job and wealth creation, of automobile production and maintenance, transportation provision, society wellbeing derived from leisure and travel opportunities, and revenue generation from the tax opportunities. The ability for humans to move flexibly from place to place has far reaching implications for the nature of societies[3].

On the other hand, with the increment of the motor vehicles on the roads, the traffic problems such as accidents and congestions also rapidly increase.

1.2 Traffic problems and their impacts

Traffic congestion can have a number of effects on drivers, the environment, health and the economy. One of the most harmful effects of traffic congestion is its impact on the environment. Despite the growing number of hybrid vehicles on the road, cars stopped in traffic still produce a large volume of harmful carbon emissions. Drivers who encounter unexpected traffic may be late for work or other appointments, causing a loss in productivity for businesses and in the drivers' personal lives. Traffic delays may also slow down the shipping of cargo if delivery trucks can't remain on schedule due to a congested route. Drivers who become impatient may be more likely to drive aggressively or dangerously. This contributes to poor health for those affected by the stress and puts other drivers in danger. One beneficial effect of traffic congestion is its ability to encourage drivers to consider other transportation options. In cities with frequent traffic congestion, individuals often choose a subway, light rail or bus service.

Motor vehicle crashes kill about 1.2 million people a year worldwide, and the number will grow to more than 2 million in 2020 unless steps are taken, a study released by the World Health Organization and the World Bank has found. Traffic accidents can cause physical, financial and mental effects for everyone involved. Drivers and passengers can suffer from injuries and even death. Vehicles in traffic accidents are damaged and may be in need of minor or costly repairs or may even be completed totaled and no longer drivable. Additional effects of traffic accidents can include emotional and mental distress as people can suffer from post-traumatic stress from being involved in the accident or from losing a loved one due to a traffic accident.

Cars and other vehicles release different air pollutants such as carbon monoxide, nitrogen dioxide, ultrafine particles and volatile organic compounds, that can have negative effects on not only our environment but also on human health. Since last few decades, humans have been finding the solutions for traffic problems with the development of Information Technology(IT).

1.3 Solutions for traffic problems

Intelligent Transportation Systems(ITS) has been introduced to give solutions for traffic problems, such as accidents and congestion. ITS is a new transport system which is comprised of an advanced information and telecommunications network for users, roads and vehicles. Figure 1.1 shows the structure of the ITS network.

ITS contributes much to solving problems such as traffic accidents and congestions. IT enables elements within the transportation system such as vehicles, roads, traffic lights, traffic signs, and so on to become intelligent by embedding them with microchips and sensors and empowering them to communicate with each other

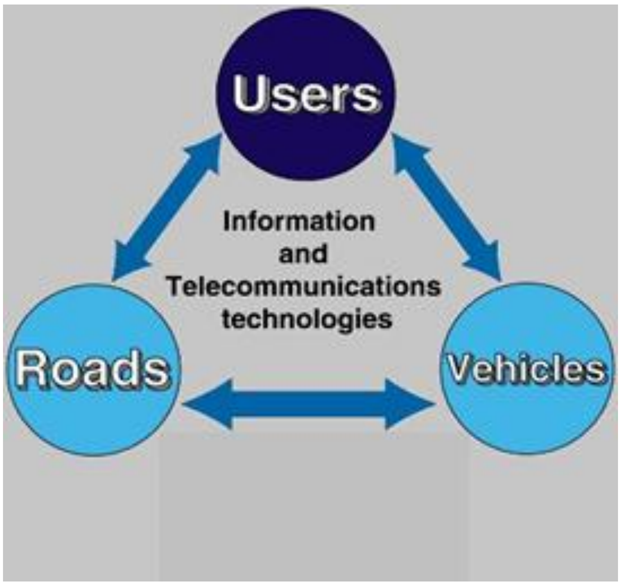


Figure 1.1: ITS network

through wireless technologies. In the leading nations in the world, ITS bring significant improvement in transportation system performance, including reduced congestion and increased safety and traveler convenience. Applying Information Technology to a country's transportation network delivers five key classes of benefits by:

1. Increasing driver and pedestrian safety.
2. Improving the operational performance of the transportation network, particularly by reducing congestion.
3. Enhancing personal mobility and convenience.

4. delivering environmental benefits.

5. Boosting productivity and expanding economic and employment growth.

1.4 Advanced ITS deployments

Japan, United States, Europe, Singapore, and South Korea are the regions and countries where ITS is mainly deployed[4].

Those countries deploy technologies and applications regarding the each country's road systems, vehicle driving lane(left or right), whether conditions, and etc. Japan leads the world in Intelligent Transportation Systems based on the importance ascribed to ITS at the highest levels of government, the number of citizens benefiting from use of an impressive range of operationally deployed ITS applications, and the maturity of those applications[5].

According to the ministry of land, infrastructure, transport and tourism in Japan, there are nine main ITS developing areas:

- Advances in navigation systems
- Electronic toll collection systems

- **Assistance for safe driving**
- Optimization of traffic management
- Increasing efficiency in road management
- Support for public transport
- Increasing efficiency in commercial vehicle operations
- Support for pedestrians
- Support for emergency vehicle operations

Assistance for safe driving is a one of major studying area in ITS. The driver is assisted to drive safely by providing necessary local information of the vehicle. Many studies have been conducted to capture the local information of the vehicle using on-vehicle cameras. For example, traffic sign detection[6][7][8], traffic light detection[9][18][19], road surface condition detection[10][11], obstacle detection [12][13][14], pedestrian detection[15][16][17] and so on.

A considerable number of traffic accidents occurred at road intersections. Japan metropolitan police department statistics shows that 48% of all automobile crashes occur at intersections in year

2009. Misjudged time for vehicles to clear intersection, misjudged speed and closeness of oncoming traffic, failure to obey traffic signals are some of main reasons for those accidents. As an approach to reduce intersection traffic accidents, a road-to-vehicle Visible Light Communication(VLC) system at signalized intersection is proposed by our research group for ITS. The following information can be provided to assist driver at intersection with utilization of this system:

- Color changing time of traffic light,
- Image information of blind intersection local areas,
- Road surface condition and peripheral traffic condition, and so on.

1.5 Purpose of the thesis

Some road-to-vehicle VLC systems for assisting drivers have been proposed in the literature[30][31][32]. Those systems use Photo Diode(PD) as a receiver. However the road-to-vehicle VLC system explained in this thesis uses high-speed camera as a receiver.

The advantages of the high-speed camera receiver are detailed in Chapter 2.4.4. This system conducts communication between a vehicle and a signalized intersection, using an LED traffic light as a transmitter and an on-vehicle high-speed camera as a receiver.

In this system, an LED traffic light blinks light synchronized with a $500Hz$ clock signal. For capturing the lighting pattern of the blinking transmitter, a camera should have a high frame rate. Conventional video cameras (video cameras with a frame rate of e.g. $30fps$) cannot be used. For this reason, a high-speed camera (receiver) is used as receiver. In the experiments, a high-speed camera fixed on the vehicle captures images in $1000fps$, while the vehicle is moving. When a high-speed camera is used as receiver, finding the transmitter, tracking the found transmitter, and capturing each lighting pattern of the blinking transmitter while tracking are essential to conduct communication. For this finding and tracking, it is difficult to use normal traffic light finding and tracking methods mainly considering the shape information. The reason is that the shape of the traffic light is not properly appeared in the images due to LED blinking. In the literature Iwasaki et al.[43]

proposed methods for these finding and tracking. In their methods, finding is conducted defining a special blinking pattern and tracking is conducted defining the transmitter borders using some lighting LEDs as detailed in the Chapter 4.2. However, that defined blinking pattern cannot be used for communication. Furthermore, the LEDs in the defined borders can also not be used for communication. With these definitions, communication time decreases and continuous communication cannot be conducted since special defined pattern is frequently appeared at the emission sequence, furthermore, data rate decreases since LEDs for defining transmitter borders cannot be used for communication.

Except finding and tracking, capturing the lighting pattern of the transmitter is also very important to conduct demodulation.

In this thesis, the new high-speed camera image processing algorithms are introduced for

- Finding the transmitter
- Tracking the found transmitter
- Capturing the each lighting pattern of the blinking

to conduct communication. No definitions are used in the new algorithms, and finding and tracking are conducted under the LED blinking for communication, resulting no affection on the data rate and communication time. The studies have not been conducted so much for these kind of detections, and this thesis mainly focuses on those problems.

For developing new algorithms, the features of high frame rate image capturing are used. For examples, the movement of near by frames are small and almost stable, and the size of objects changes little in the near by frames.

In this VLC system, image processing in the receiver should be real time, meaning that, processing should be conducted within $1msec$. However, it is difficult to achieve this such little computational time on a computer. It can be achieved using hardware. Though, the algorithms should have simple processing steps to achieve such a short computational time with hardware. Due to these conditions, the algorithms are developed considering the processing time reduction approaches as well.

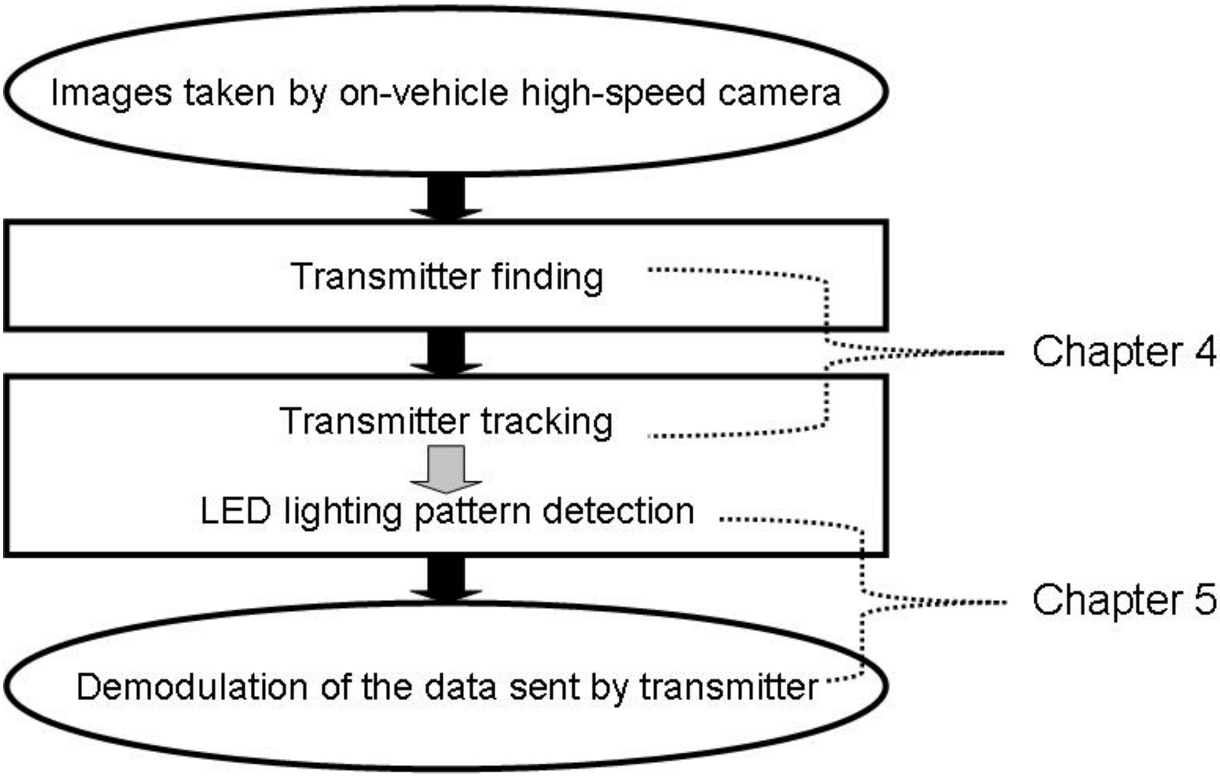


Figure 1.2: Necessary image processing steps for the receiver

1.6 Organization of the thesis

This thesis includes six chapters to discuss the background, related works and the project work. This chapter discusses the positive and negative traffic impacts, solutions for those negative impacts and the purpose of the thesis. In the Chapter 2, VLC introduction and literature review on VLC studies are presented. As mentioned above, in this thesis, VLC is applied to road-to-vehicle communication. Proposed system by our research group for applying VLC in road-to-vehicle communication is presented in the Chapter 3.

Figure 1.2 shows the necessary image processing steps for the receiver to demodulate the information sent by the transmitter. Chapter 4 presents the algorithms developed for finding the transmitter and tracking the found transmitter. Chapter 5 presents the algorithm for detecting lighting patterns of the transmitter and the communication experiments results. Finally, conclusions and future works can be found in the Chapter 6.

Chapter 2

Literature review

2.1 VLC

Visible Light Communication(VLC) is a wireless communication method using luminance, transmitting data by emitting light. It is able to transfer data by emitting light source, and able to receive them with a light sensor. There are several advantages in this communication method compared to other wireless communication methods, such as radio waves and infrared light. The visible light is not harmful to human body, and the data can be transmitted using VLC even through a high voltage application. The wireless transmission network can be easily established through the VLC device attached to the fittings lightings.

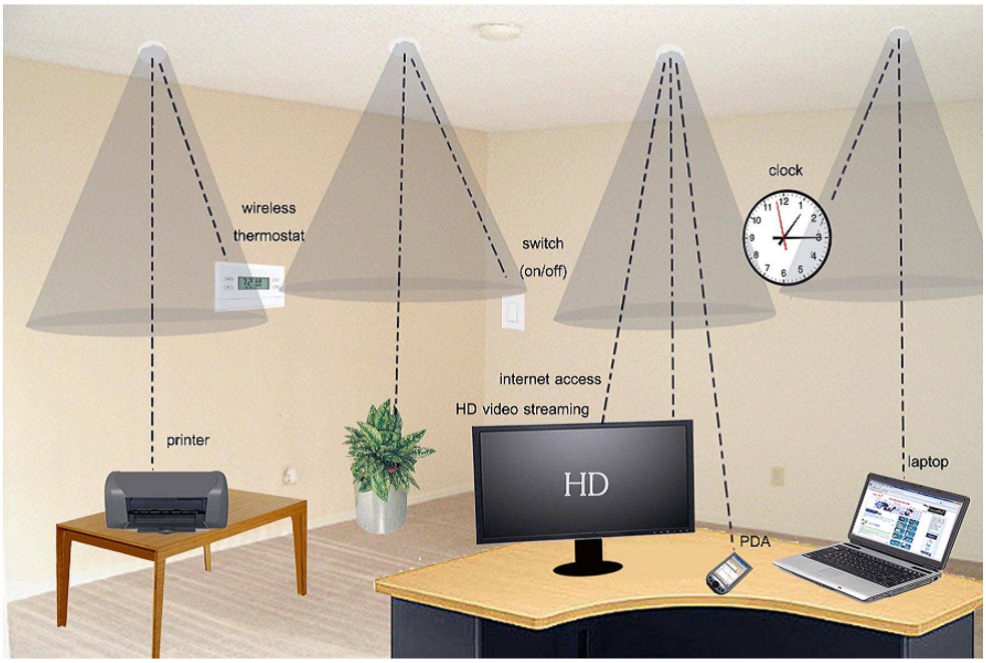


Figure 2.1: Indoor VLC using existing light sources

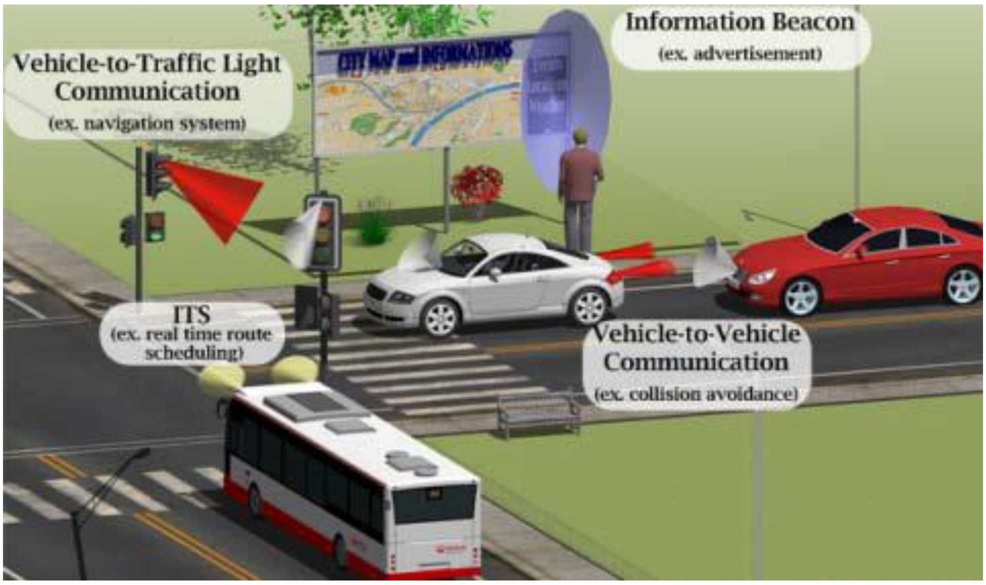


Figure 2.2: Outdoor VLC using existing light sources

In addition, VLC is resistant to electromagnetic noise and can ensure a high security. It can be used at the places where radio waves cannot be used, for examples, hospitals and areas around precision machines. There are not legal limitations for any existing light source, such as room illuminations and displays to be used. Figure 2.1 and 2.2 show the possible VLC development using existing indoor and outdoor light sources respectively.

As a new wireless communication method, VLC studies have been started several years ago. Almost all the studies have been conducted utilizing fluorescent light sources and LED light sources as transmitters.

2.2 VLC utilizing fluorescent light

2.2.1 Possibility of fluorescent light utilization

Fluorescent light is a reliable and high efficient light source. Compared with some other sources of illumination it can be modulated at high data rates, offering the opportunity for communications as well as illumination. VLC systems have been investigated considering these features.

2.2.2 Fluorescent light transmitters

Deron et al.[20] have proposed an optical transceiver system which transmits information by modulating the arc in a fluorescent light. In this system, transceiver system that frequency modulates the light output of a fluorescent lamp to achieve a relatively high bandwidth communication channel. A portable receiver decodes the information encoded in the fluorescent light. The received digital data stream can be used to deliver a visual(text) or audio message, or can be processed directly by a computer or other information handling system. For example, the transceiver system can be used to provide a continuous, personal audio signal to the visually impaired people.

Liu et al.[21] have introduced an accurate and simple indoor guidance system utilizing VLC for the visually impaired people. Figure 2.3 shows an image of the system. Here, fluorescent light platform is used as transmitter and it sends current position and walking guidance to visually impaired people. This information is received by smart phone connecting with a visible light receiver. The maximum data rate of this system is $10kbps$.

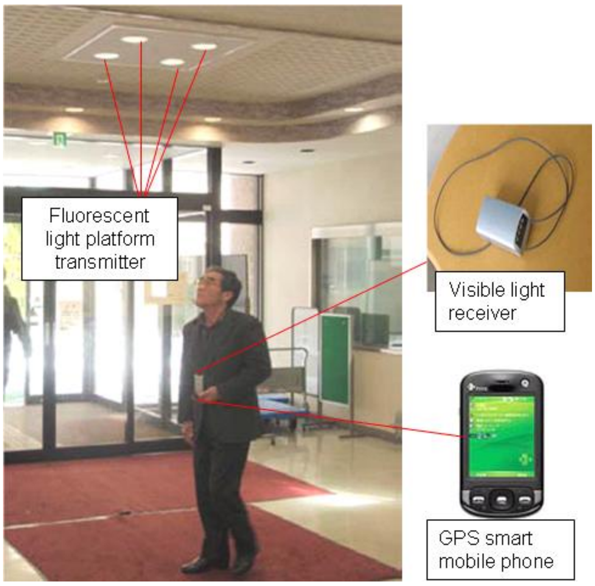


Figure 2.3: Indoor guidance system utilizing VLC

2.3 VLC utilizing LED

2.3.1 High motivation of LED utilization

LED (Light Emitting Diode) emits light by using the semiconductor element. The element can be used almost permanently. For instance, longevity will confront a incandescent light for 1000 hours, a fluorescent light for 6000 hours, and the LED for 20000 hours.

It means the longevity of LED is 20 times longer than a incandescent light and 3 times or more longer than a fluorescent light. Little power consumption is another features of LED that power consumption is a little compared with the incandescent light and the fluorescent light. For instance, it is 54 watts for the incandescent light and 12 watts for fluorescent light, 2.2 watts for the LED comparing by the ratings power consumption. In a word, the power consumption of LED is about 1/5 than a incandescent light and about 1/25 than a fluorescent light. Moreover, it leads to carbon dioxide (CO2) reduction because power consumption is a little, and it may be said that LED is eco-friendly illumination. And LED is mercury free and therefore do not harm the environment and the human health. It is difficult to damage LED by external shock and LED is high tolerance to humidity as well. Due to these advantages, It is also predicted that in the very near future, the white LEDs will replace the conventional incandescent and fluorescent lamps due to their cleaner low power energy, which is ecological to our daily life. It is, therefore, considered as the lighting in the next generation.

Moreover, longevity hardly changes for LED even if it blinks frequently though when blinking frequently for the fluorescent light to having a short life general. With this blinking frequency and other above mentioned advantages, LEDs are well suited to modulate data into visible light[22].

2.3.2 Indoor VLC with LED

A considerable number of VLC systems have been developed by utilizing LED as transmitters. At the beginning step of VLC studies, Pang et al.[23] have introduced a system to broadcast the audio data using LEDs. This system consists of an audio signal source that provides the modulated audio signal for transmission. The audio data is transmitted by switching the LEDs in high frequency. A photo-detector is used to receive the transmitted data by detecting high frequency variation in the light flux.

Komine and Nakagawa[24][25] have achieved VLC using illumination light. It is a communication between PCs and illumination light, and considered as an alternative method for the wireless LAN.

As illustrated in the Fig. 2.4, in this system, existing LEDs are used as a lighting device as well as a communication device, and

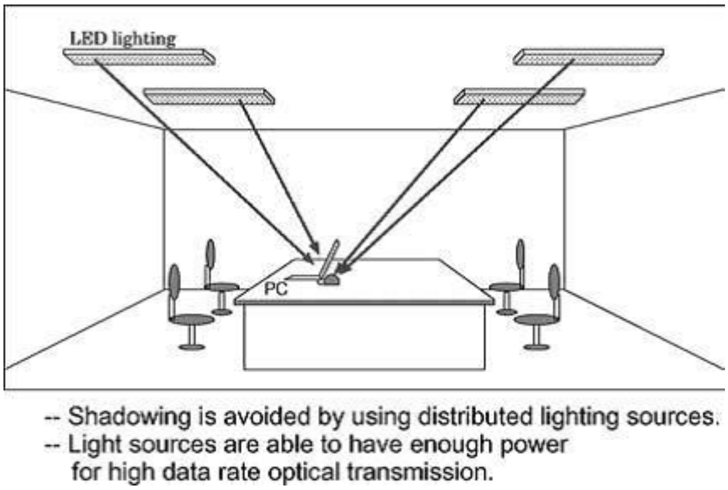


Figure 2.4: Visible light wireless communication

shadowing is avoided by using distributed light sources. The function is based on the fast switching of LEDs and the modulation of the visible-light waves for free-space communications. Here, the VLC can achieve high speed data transmission with a low implementation complexity.

As another indoor VLC system, Son at el.[26]. have proposed a VLC link based on optical access network using LED and electro absorption transceiver, which is capable of connecting with the optical access network easily. This electro absorption transceiver is based on electro absorption modulator, and it is used as an optical network unit in order to be connected with wireless transceiver based on white LED, without additional radio frequency and optical devices. Here, $5Mbps$ downlink and uplink data transmission of wireless VLC link based on an optical access network has been demonstrated experimentally.

2.4 VLC in ITS

Above mentioned systems achieve VLC at indoor environment. Development of the outdoor VLC is more challenging due to the influence of changing external light sources such sun light. However, recently, outdoor VLC systems have also been proposed and many of them attempt to apply VLC in ITS.

2.4.1 Vehicle to vehicle VLC

The LEDs are also used for car tail and head lights. These car lights can also be used to develop VLC techniques. Intel Corporation has developed high accuracy car positioning system based on VLC, by using existing LED car lights[27]. Figure 2.5 illustrates the outline of this car positioning system.

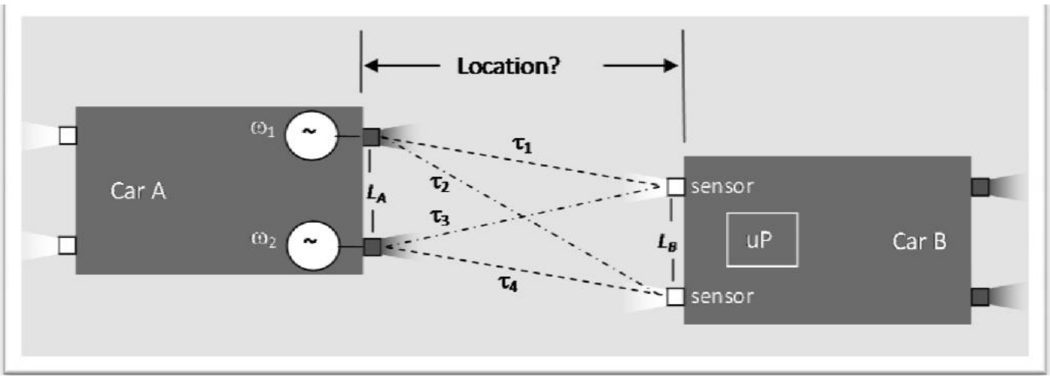


Figure 2.5: Outline of the car positioning system with VLC

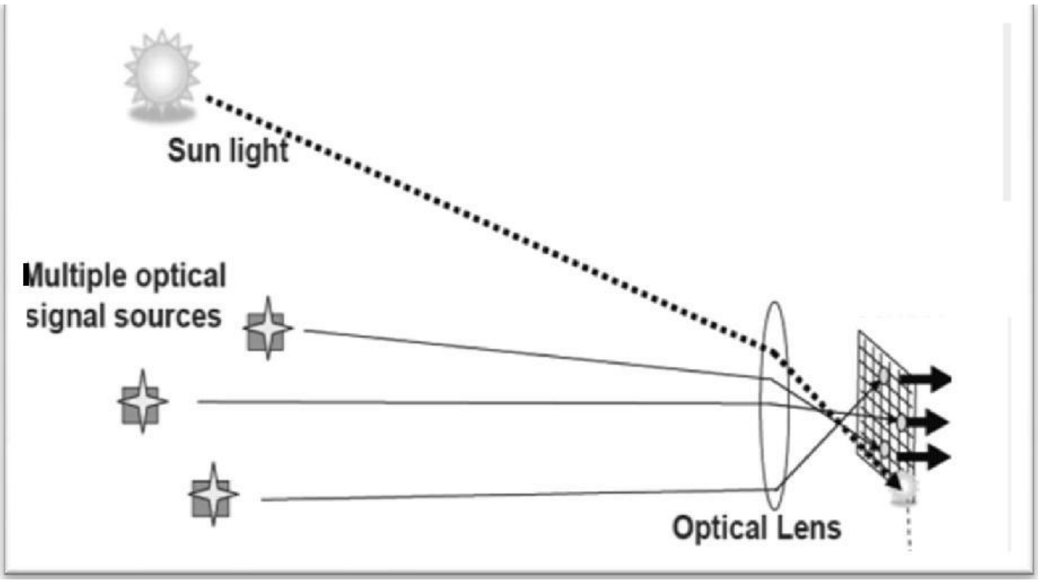


Figure 2.6: Multiple optical source separation using a lens and image

Here, as Fig. 2.5 illustrates, car A amplitude modulates each taillight with a precise frequency RF tone. Meanwhile, each headlight of car B contains a photo detector sensor array behind a lens that receives the signals from the taillights and processes the tone data in order to calculate the relative position between the cars. Tone frequencies that have been investigated range between 20MHz and 50MHz. It should be noted that the distances LA and LB are known and can be exchanged between the cars. And at the receiver, as Fig. 2.6 illustrates, an image and optical lens combination is used to spatially separate multiple light sources. The pixels of the image are identified that are being illuminated by modulated sources and then sources are paired up per vehicle for processing. The processing consists of measuring the phase difference of arrival at the car caused by the difference in the propagation path length.

2.4.2 Road to pedestrian VLC

Pedestrian lights are mainly installed at signalized intersections. Pedestrians cross the roads following color of the light, and this visible lighting can also be used to achieve road to pedestrian VLC. As a pedestrian ITS work, Suzuki et al.[28] have introduced a support system for visually impaired person by utilizing VLC technology at signalized intersections.

As illustrated in the Fig. 2.7, in this system, a pedestrian LED traf-

Figure 2.7: VLC utilizing pedestrian traffic light

fic light at signalized intersection is used as transmitter. A portable visible light receiver has been developed to receive the information sent by the transmitter. Pedestrian can listen to sound information on earphone or headphones connected to this visible light receiver. Here, the correct moving direction for visually impaired person is guided by changing the hearing sound. This system has been evaluated in the outdoor environment and has shown possibility to apply as a pedestrian support system. It uses frequency modulation($190KHz$, carrier wave) as modulation method and it can only send signal to visually impaired person.

2.4.3 Road to vehicle VLC

Road to vehicle VLC can be achieved utilizing the existing LED traffic lights. LED traffic lights are getting popular around the world as well as in Japan. There are roughly 2 million traffic lights in Japan, and 10% of all systems has already changed to LED type. The cost of LED type is 1.5 times expensive than traditional Incandescent type. But, all traffic light would be LED type in the future[29]. All LED features and benefits explained in the section 2.3.1 are directly related to LED traffic light as well. Other benefits of LED traffic light include:

- Elimination of catastrophic failures. Unlike an incandescent bulb which has only one filament, an LED traffic light is made out of a matrix of several dozen LEDs. The signal continues to function even if several of these miniature diodes stop working. On the other hand, when the filament of an incandescent bulb fails, the display goes dark requiring immediate replacement.

- LED traffic lights are brighter compared to incandescent traffic lights, which enhances intersection safety.
- Elimination of phantom effect. Incandescent traffic lights use reflectors behind the bulbs. For signals on east-west approaches during morning and evening hours, all colors seem to light up when the sun rays fall directly on these signals. This problem is eliminated when LED traffic lights are used because there are no reflectors in them.

With the high frequency blinking ability, visual quality and other significant features, it is highly possible to use LED traffic light for road-to-vehicle VLC.

2.4.4 Impacts of high-speed camera receiver

Okada et al.[31] has been applied VLC in ITS using an LED traffic light as a transmitter and a photo Diode(PD) as a receiver. That system can transmit data maximum of $2Mbps$ in the static environment. However, the Bit Error Rate(BER) $< 10^{-6}$, when the distance between transmitter and receiver is less than $40m$. Over the $40m$, it is difficult to conduct data communication since BER $> 10^{-6}$. Additionally, in their system, all the LEDs in the transmitter is considered as single transmitter as shown in Fig. 2.8. Each LED or small group of LEDs in the transmitter cannot be identified individually, when a PD is used. For this reason, parallel data communication cannot be conducted with PD receiver.

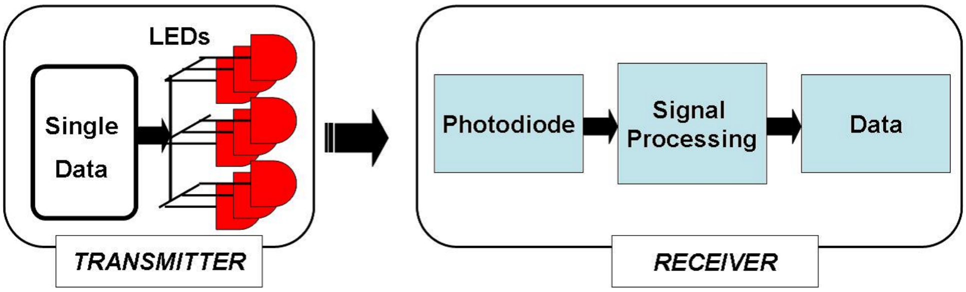


Figure 2.8: Road to vehicle VLC with PD

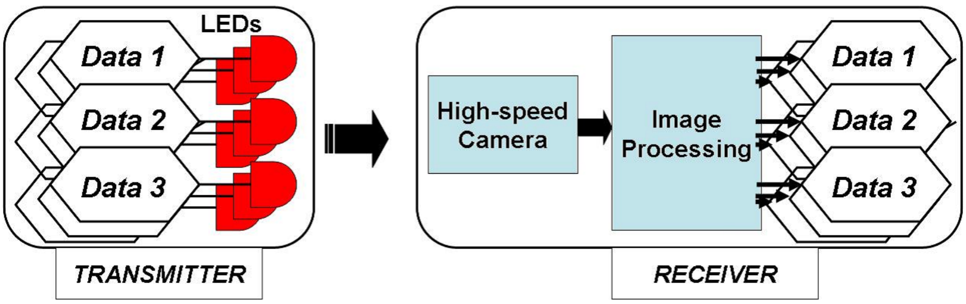


Figure 2.9: Road to vehicle VLC with high speed camera

Figure 2.9 illustrates the outline of the proposed VLC system using an LED traffic light(LED array) as a transmitter and a high-speed camera as a receiver. If the LEDs in the transmitter could be recognized individually, it is possible to use each of them as a separate sub-transmitters communicating in parallel at the same time. In other words, each LED transmits different data in parallel and they are received at the same time. As a result, we can dramatically increase the communication speed by modulating each LED individually. Moreover, we can communicate with several transmitters and receive different information in parallel. These are the main advantages of using a camera as a receiver(Fig. 2.9). However, using a camera as a receiver has some disadvantages. The camera should have high frame rate to achieve good communication speed. For this purpose, image processing in the receiver should be in real time and it might be harder on a computer. It is necessary to implement the system on hardware to achieve this much less processing time.

Some studies have been conducted on this VLC system. These studies include inventing the effective modulation methods[33][34][35] and image processing for the receiver[43]. This thesis also proposes image processing algorithms for the receiver mainly considering the features of high-frame rate image capturing, those can achieve better communication performances compared to the previous works.

The road-to-vehicle VLC system using a high-speed camera as a receiver is more detailed in the next chapter.

Chapter 3

VLC system with high-speed camera receiver

3.1 System structure

This chapter describes the proposed road to vehicle communication system using a high-speed camera receiver. As mentioned in the section 1.3, data communication between the road and moving vehicle is conducted through this system. As Fig. 3.1 illustrates, existing LED traffic lights on the roads can be used as transmitter to apply this system in the real world. An on-vehicle high-speed camera is used as a receiver. Fig. 3.2 illustrates the main structure, here the modulation is conducted by blinking the LEDs in the transmitter at high frequency. At the receiver, the sent data is demodulated by

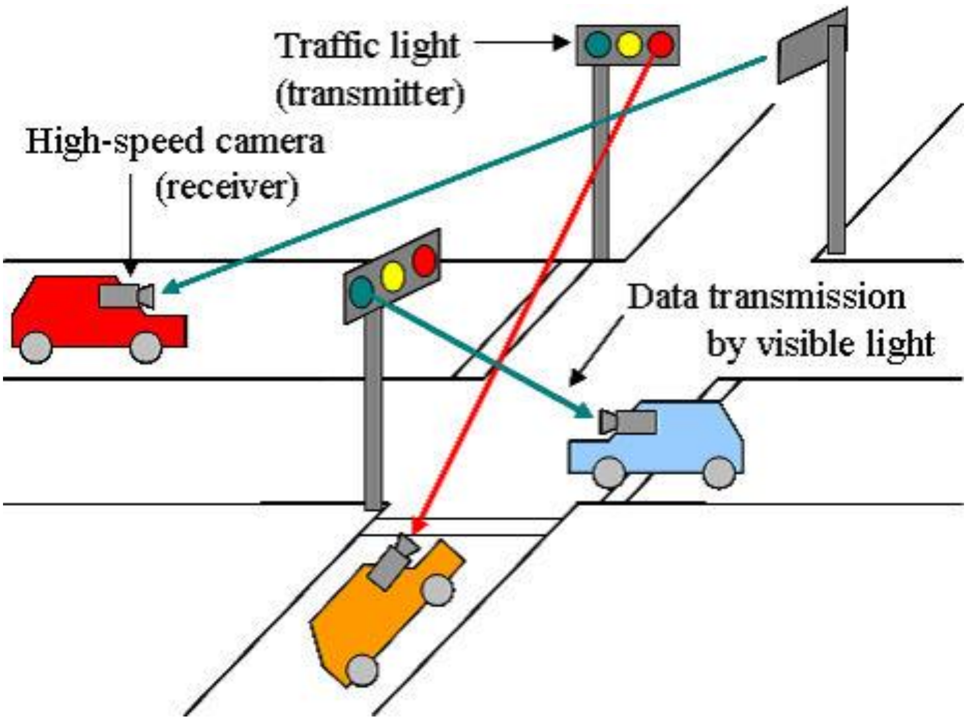


Figure 3.1: Possibility of conducting road-to-vehicle VLC using high-speed cameras and existing LED traffic lights on the roads

capturing the blinking pattern of the transmitter. The images taken by high-speed camera are processed to capture blinking pattern.

3.2 Transmitter

The transmitter(LED array) used for the experiments is square in shape as illustrated in Fig. 3.3 and it consists 256(16×16)LEDs. Each LED individually or small neighboring group of LEDs individ-

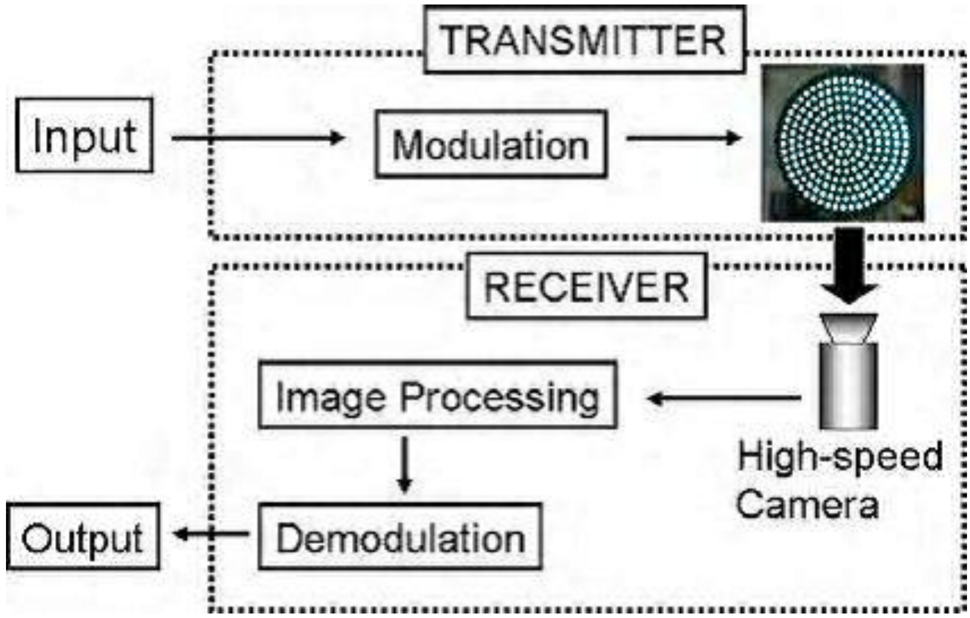


Figure 3.2: Structure of proposed VLC system

ually can be considered as sub-transmitters in the communication experiments.

3.2.1 Blinking of the transmitter

In this thesis, we conduct communication experiments at a distance between $20m$ and $70m$ from the transmitter. The high-speed camera takes images with resolution of $1024 \times 512 pixels (I_{org})$. When the transmitter is far from the $40m$, the transmitter is appeared in the image approximately with $16 \times 16 pixels$. If the distance between transmitter and receiver exceeds $40m$ the resolution of the camera

Figure 3.3: LED array

is not enough to identify each LEDs separately. For this reason, each LED cannot be used as one sub-transmitter. In this paper, we set 4 neighboring LEDs as one sub-transmitter. Here, the blinking is conducted keeping 4 neighboring LEDs at the same situation(ON or OFF). With this setting, 64(8 $\times$ 8) sub-transmitters(s_t) can be used for parallel communication and the size of the transmitter(LED array) in the image takes approximately 8 $\times$ 8$pixels$ representing a sub-transmitter by 1$pixel$, when the camera is 70m far from the transmitter. According to this setting, at the distance between $20m$ and $70m$ from the transmitter, sub-transmitter can appear in the images at least with $1pixel$. The communication speed(C_s) is $32kbps$ and this value can be calculated following the Equation (3.1).

$$C_s = k \times \frac{log2^{s_t}}{f_r} \tag{3.1}$$

$$where\ k = \frac{e_f}{f_r}$$

In the above Equation (3.1), f_r and e_f mean the frame rate of the high-speed camera and LED blinking frequency of the transmitter(LED array) respectively. As mentioned above, in this paper $f_r = 1000fps$ and $e_f = 500H_z$, according to this, $k = 0.5$.

There are some image processing techniques are necessary to capture the LED blinking from the images taken by the high-speed camera. Another issue is the modulation method. Since this is a unique communication method using visible light and image, it requires particular modulation method which considers the characteristics of the communication. Studies have been conducted to invent an effective modulation method[33][34][35]. This thesis use the method introduced by Nagura et al.[34], here, a turbo code is used as the error correcting scheme. The transmitter LEDs generate a nonnegative pulse with a width of T_b, where T_b is the bit duration. By changing the width of T_b, LEDs can express the luminance. Let the data rate be $R_b(= 1/T_b)$, then the bit rate of the transmitter becomes $256R_b$ in the case of that each LED transmits a different bit. However, in this thesis, bit rate of the transmitter becomes $64R_b$, as mentioned above, each 4LED group transmits a different bit.

3.3 Receiver

To capture the high frequency blinking of LEDs, a camera should have a high frame rate. The conventional video cameras (video cameras with a frame rate of $e.g. 30fps$) cannot be used for this purpose. Figure 3.4 illustrates the high-speed camera which is used

Figure 3.4: High-speed camera

as the receiver in the experiments and it can take images in high frame rates. As mentioned above, it takes images in $1000fps$ in the experiments.

3.3.1 High-speed camera

Recently, high-speed cameras are getting popular and they are also applied in ITS as well as in other scientific research, military test, and industry[36∼41]. High-speed cameras can capture more information of fast moving objects and changing objects in high frequency, compared to the conventional video cameras. Cameras from companies like Photron and Vision Research can record 800 $\times$ 600$pixels$ at 4800fps, or 2.3 giga samples per second[42]. These devices use a single image sensor and are typically limited to storing just a few seconds of data because of the huge bandwidths involved in high-speed video. The short recording duration means that acquisition must be synchronized with the event of interest. But, studies have been conducted to increase the recoding time. Wilburn at el.[42] have focused on this problem introducing an interesting high-speed capturing system using a normal camera array. Their system compresses data from many cameras in parallel. At high frame rates, this array architecture supports continuous streaming to disk from all of the cameras. This allows us to record unpredictable events, in which nothing occurs before the event of interest that could be used to trigger the beginning of recording.

Cameras have got a significant development in last several years and variety of cameras with attractive features can be seen in the market. Due to this fast development, long time recording high speed cameras would be available at the market to buy in near future. According to the event of interest, specific image processing technique may also be necessary when these high-speed cameras are used.

In the proposed VLC system, several second image recoding in $1000fps$ is enough to conduct experiments.

3.3.2 Necessary processing for receiver

In the receiver, images taken by high-speed camera should be processed to capture the lighting pattern of the transmitter. Demodulation is conducted using these patterns. This image processing is conducted for following purposes;

1)Transmitter detection

- Finding the transmitter
- Tracking the transmitter

2)Lighting pattern detection

The studies have not so much been conducted for those kind of purposes. This thesis mainly focuses on developing an effective image processing algorithms for them. An effective image processing algorithms are developed for each purpose as described in the next two chapters.

Chapter 4

Transmitter detection

This chapter presents the transmitter detection methods by processing the images taken by the high-speed camera which is used as receiver. This detection includes two steps, Finding and tracking. First, transmitter is found from an original image taken by high-speed camera, and track it only processing a defined cut out image area in consecutive frames as detailed in the next section.

4.1 Main processing flow

Figure 4.1 illustrates the main flow of finding and tracking the transmitter. Here, first the transmitter is found from an original image(I_{org}), taken by the camera, and then cut out an image

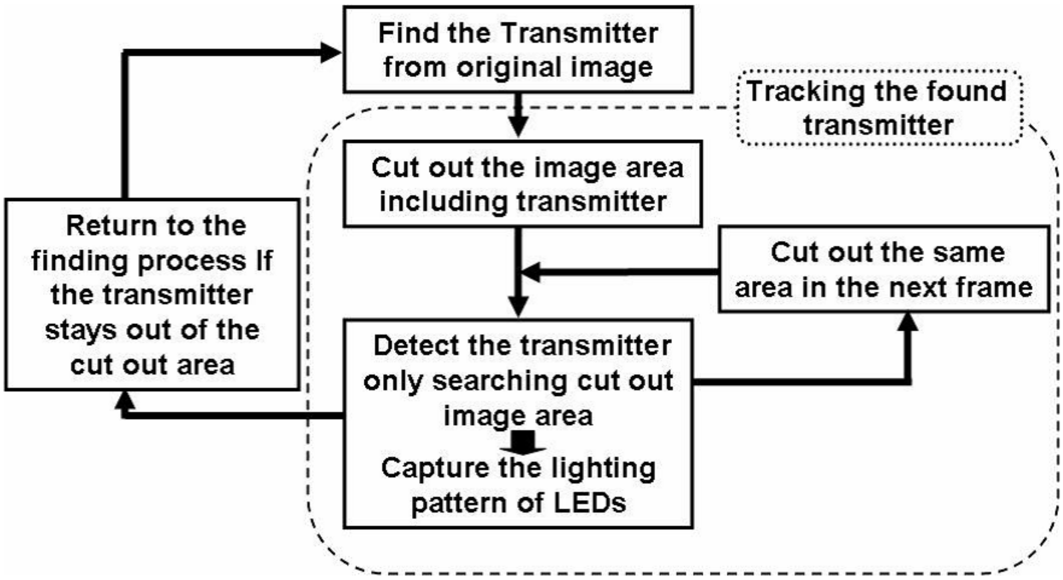


Figure 4.1: Main processing flow

area(I_{cut}) including the transmitter from that original image as indicated in the Fig. 4.2. The size of the I_{org} is $1024\times512 pixels$. The size of the I_{cut} is $128\times128 pixels$ and it is indicated using the white square in the Fig. 4.2. The found transmitter is tracked detecting it only searching the corresponding I_{cut} in consecutive frames after finding. The transmitter(LED positions) is kept almost center area of I_{cut} while tracking. If the transmitter stayed out from I_{cut}, process returns to the transmitter finding step as illustrated in the Fig. 4.1. When the vehicle is $70m$ far from the transmitter, the side length of the transmitter in the image (l_{min}) is $8 pixels$. This size extends to

Figure 4.2: An example of the (I_{cut}) on an (I_{org}) taken by high-speed camera

$36 pixels (l_{max})$ when the vehicle moved to a position which is $20m$ far from the transmitter. The tracking is automatically stopped when the side length of transmitter gets over the l_{max}.

The transmitter is found processing the I_{org}, but it is tracked only processing the I_{cut} in consecutive frames. This is a kind of technique to reduce the processing time. Since it needs more complicated processing for tracking on inter frame relationships than finding.

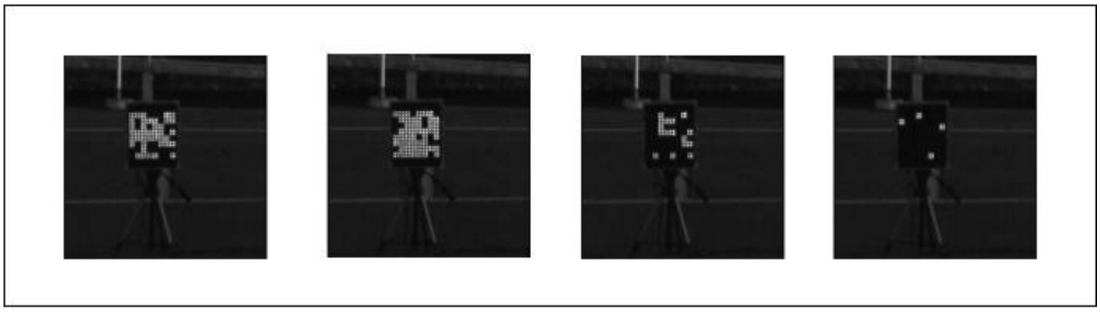


Figure 4.3: Consecutive frames of blinking transmitter

4.2 Previous approaches

In this thesis, transmitter LEDs blink randomly at $500Hz$ to conduct communication. This blinking cannot be seen by human eye, but, can be captured by the high-speed camera. Figure 4.3 illustrates the few consecutive frames of blinking transmitter taken by high-speed camera.

Shape information combined with color information are the main techniques used for normal traffic light finding methods[18][19]. These methods required fix shape. But, in this case, they cannot be used since the shape of the traffic light changes in every frame due to the blinking(see Fig. 4.3). For this reason, in the previous works of our research group[43][44], a specific blinking stage was defined to make it easy to find the transmitter. But, this specific blinking cannot

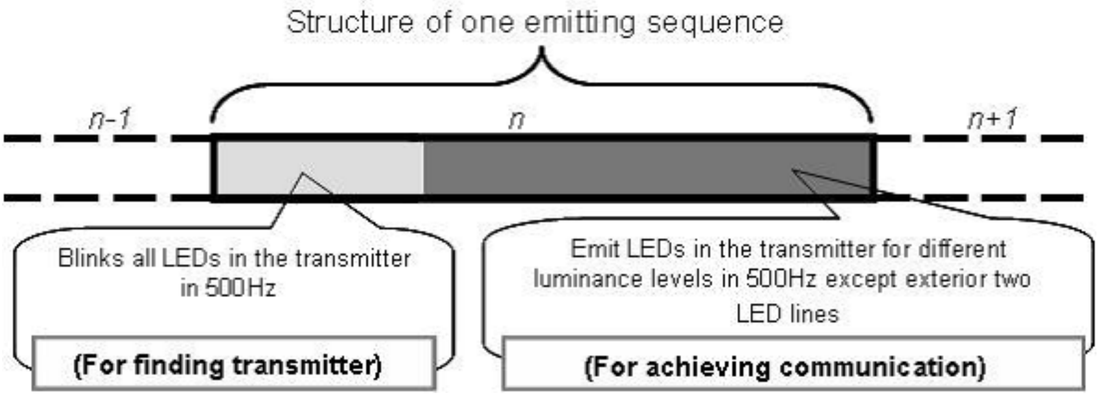


Figure 4.4: Structure of the blinking sequence(before improvement)

be used for communication. With this definition, communication time decreases and continuous communication cannot be conducted since special defined pattern is frequently appeared at the emission sequence.

Template matching is mainly used for normal traffic light tracking[18][19]. For applying these methods in our case, the traffic light should have the borders clearly. For this reason, in the previous works of our research group[43][43], the LEDs in the two exterior lines of the transmitter were kept lighting (without blinking) to have clearly defined borders. But, those LEDs in the two exterior lines could not be used for communication. As a result, the data rate decreases with this definition.

In the previous work, as Fig. 4.4 illustrates, the LEDs in the transmitter blink sequence by sequence. In the first stage of the sequence, all LEDs blink at the same time in $500Hz$. This is the above mentioned blinking stage for finding the transmitter. In the second stage of the sequence, LEDs blink randomly at $500Hz$ to conduct communication, except LEDs in the two exterior lines. In the previous work, as mentioned above, those non-blinking two exterior LED lines(defined transmitter borders) are kept to make it easy to track the found transmitter in consecutive frames.

When the vehicle installed with high-speed camera moves toward the transmitter, lighting transmitter is expected to appear on the images from high-speed camera once in two frames, at the first blinking stage. Since, the transmitter LEDs blink in $500Hz$ and the high-speed camera takes images in $1000fps$. Figure 4.5 illustrates few consecutive frames from on-vehicle high-speed camera under this condition, and transmitter appears on consecutive frames as expected. In the previous work, Iwasaki et al.[43] proposed a method for finding the transmitter using this feature, subtracting the two near by frames.

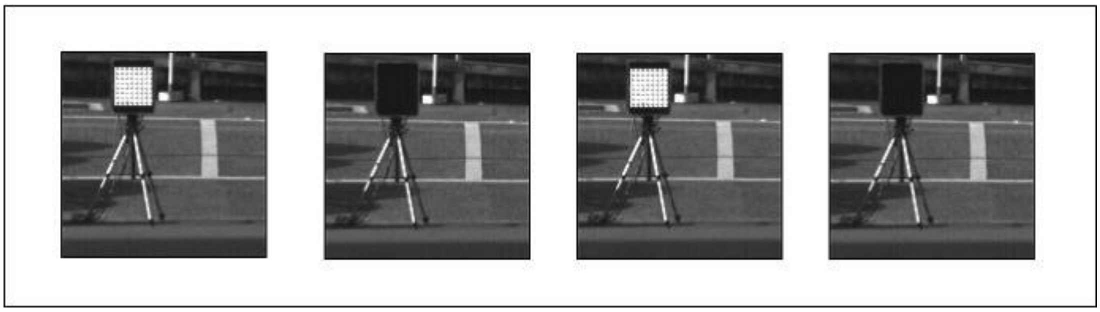


Figure 4.5: Transmitter images of first blinking stage

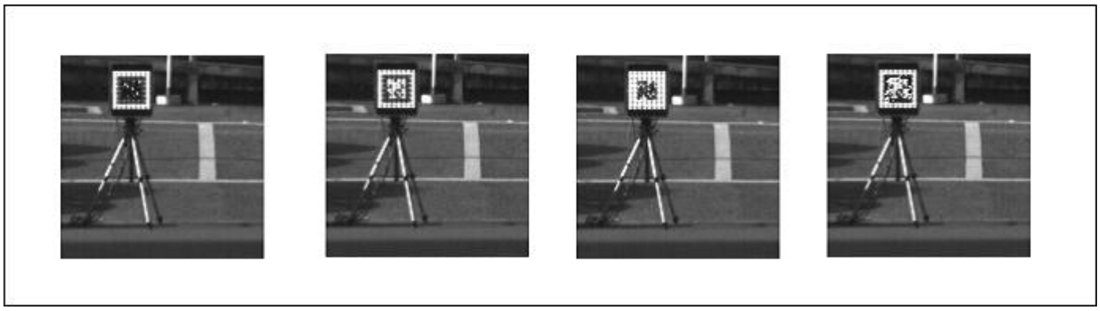


Figure 4.6: Transmitter images of second blinking stage

Figure 4.6 illustrates few consecutive frames taken by on-vehicle high-speed-camera at the second blinking stage. As detailed above, the defined borders of the transmitter clearly appear. The transmitter was tracked using those borders in the previous works[43], using the template matching almost as normal traffic light tracking methods.

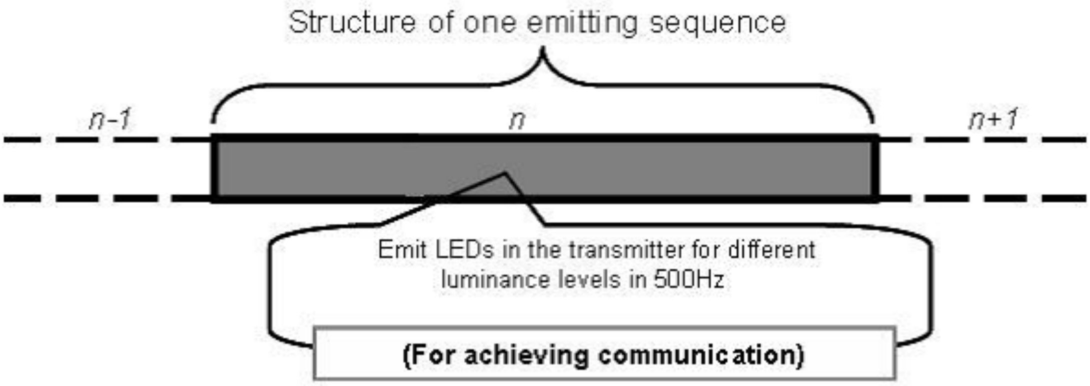


Figure 4.7: Structure of the blinking sequence(after improvement)

4.3 New approaches

In this thesis, the first blinking stage is removed from the sequence and the non-emitting defined border lines are also removed from the second blinking stage as illustrated in the Fig. 4.7. The new algorithms are proposed for finding and tracking the transmitter only using randomly blinking of LEDs(see Fig 4.3). It means, that finding and tracking can be conducted under the LED blinking for communication.

Due to above improvements, it is not necessary to have two parts in the blinking sequence(see Fig. 4.4). In addition, all LEDs can be used for communication and continuous communication can be conducted which was not possible previously. As results, communication time and data rate can be increased when the new algorithms are applied. The new algorithms are detailed in the next two sections.

4.4 Finding algorithm

This section presents a new finding method only using the LED blinking for communication. Finding algorithm is developed mainly considering features of high frame rate image capturing by high-speed camera such as differences between nearby frames are small and sizes of the objects in the image do not change much in nearby frames. However, the pixel values of transmitter area varies in nearby frames due to the blinking of the transmitter LEDs. Considering these features, transmitter is found from an original image(I_{org}) by accumulating the differences between current frame and few previous consecutive frames. Here, the transmitter is found by processing large images(image size: $1024 \times 512 pixels$), but, algorithm consists of simple processing steps to minimize computational time as well.

4.4.1 Generation of differences image

In this algorithm, absolute differences between current frame and some just previous consecutive frames are calculated following the Equation (4.1).

$$D_{total} = \sum_{n=1}^{m} |D_t - D_{t-n}| \tag{4.1}$$

Figure 4.8: An example of Differences Image(DI)

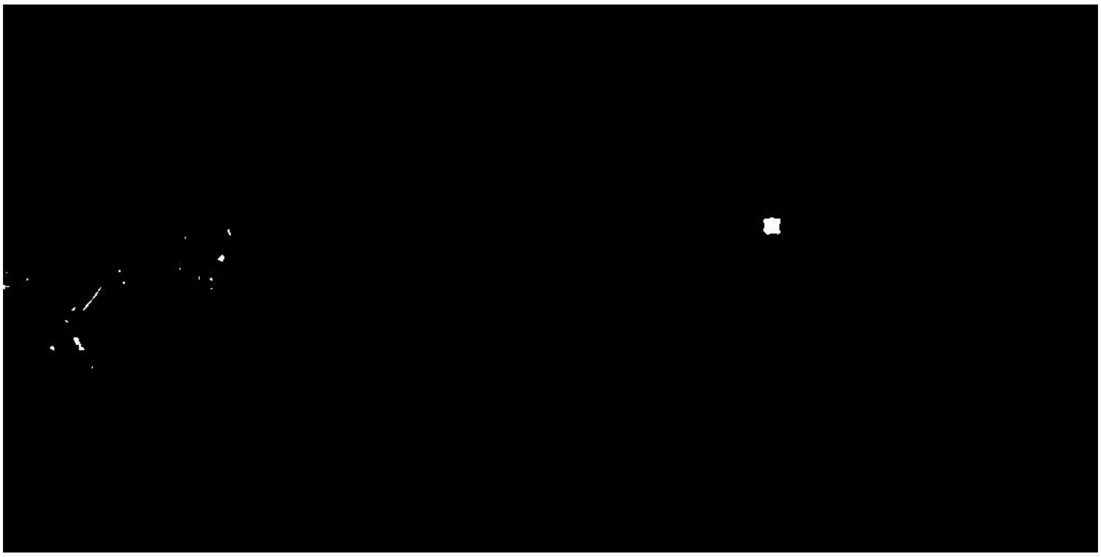


Figure 4.9: Binarized DI

D_t represents the current frame and m represents the number of previous frames used for this differences calculation. The total differences(D_{total}) are projected to the new image. In this thesis, this image is called as Differences Image(DI). Fig. 4.8 illustrates an example of DI. The transmitter area is clearly highlighted there, since differences are relatively stronger than other areas due to the LED blinking of the transmitter.

4.4.2 Binarization and morphology operation

This DI is processed for binarization to have transmitter area with white pixels as shown in the Fig. 4.9. The threshold(B_{ths}) for binarization is decided experimentally, in the the experiments, $B_{ths} = 20$.

In some cases, after this binarization process, transmitter is not appeared as a single component. Fig. 4.10 illustrates a this kind of example and there, the transmitter appeared with few components. In those cases, to connect all component together, morphological operation is conducted to the binarized DI. In this process, first image is dilated two times and then eroded it two times. Figure 4.11 illustrates the image of Fig. 4.10 after the morphology operation, and transmitter is appeared there as a single component.

There are some noises also remained after these processing steps (see Fig. 4.11), which means that some objects other than the transmitter exist there. In addition, those noises may create white pixel components having nearly similar geometry of the transmitter. For this reason, first the transmitter candidates are selected, and then the transmitter is confirmed from the candidates.

Figure 4.10: An example of binarized DI before morphology operation

Figure 4.11: Image of Fig. 4.10 after morphology operation

4.4.3 Candidates selection

The candidates are selected depending on the geometrical information of the transmitter in the image. In this study, we plan to conduct communication at a distance between $20m$ and $70m$ from the transmitter. When the vehicle moves this distance the side length of the transmitter in the image takes maximum length(l_{max}) and minimum length(l_{min}). l_{max} : almost $20m$ far from the transmitter, l_{min} : almost $70m$ far from the transmitter. The transmitter candidates are selected following the conditions indicated by (4.2) and (4.3), calculating the circumscribing rectangle of each component in the image.

$$l_{min} < (C_h, C_w) < l_{max} \tag{4.2}$$

$$Aspectratio(C_h, C_w) < 1.2 \tag{4.3}$$

C_w and C_h mean the width and height of circumscribing rectangle belongs to the searching component respectively. Regarding to noise, multiple candidates also appeared in some cases, and single candidate appeared in many cases. Figure 4.12 and 4.13 illustrate examples of single and multiple candidate appearance respectively. In both cases, it is necessary to confirm the transmitter.

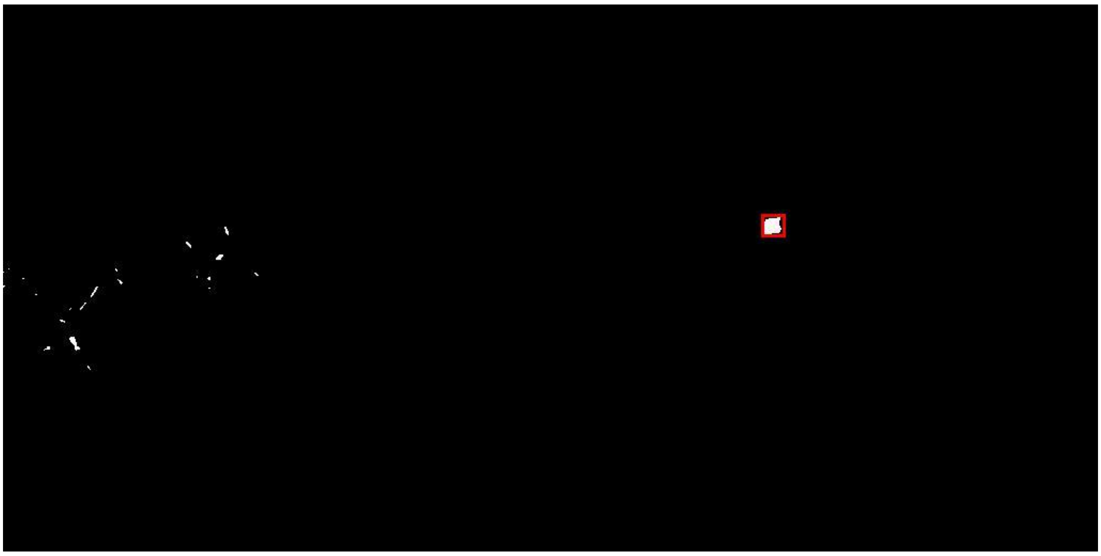


Figure 4.12: An example of single candidate appearance

4.4.4 Transmitter confirmation

This confirmation is conducted by searching the differences density (D_{den}) and the average intensity(L_{avg}) in the corresponding candidates areas in the DI. Fig. 4.14 shows corresponding DI for Fig.

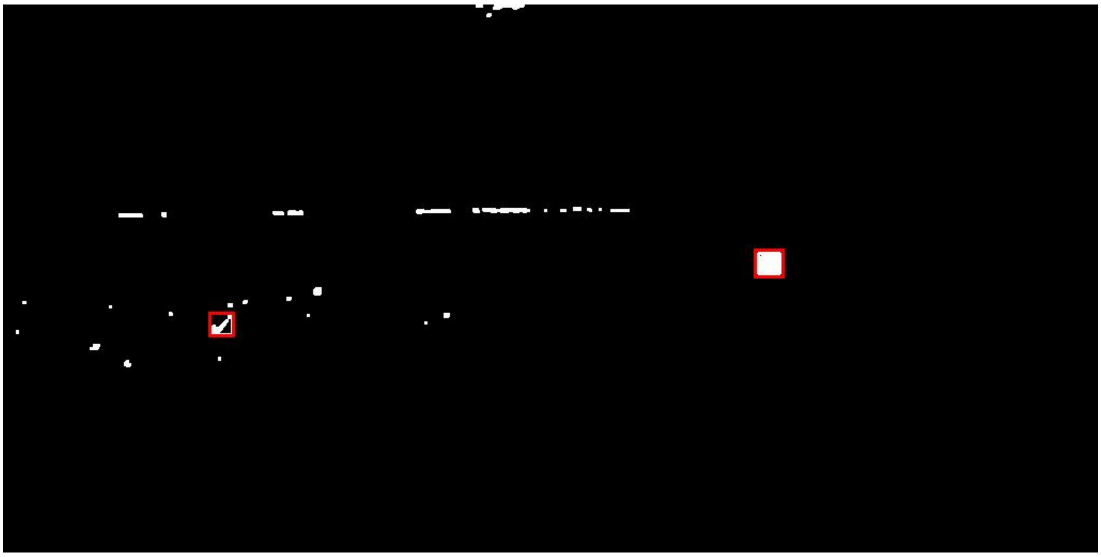


Figure 4.13: An example of multiple candidate appearance

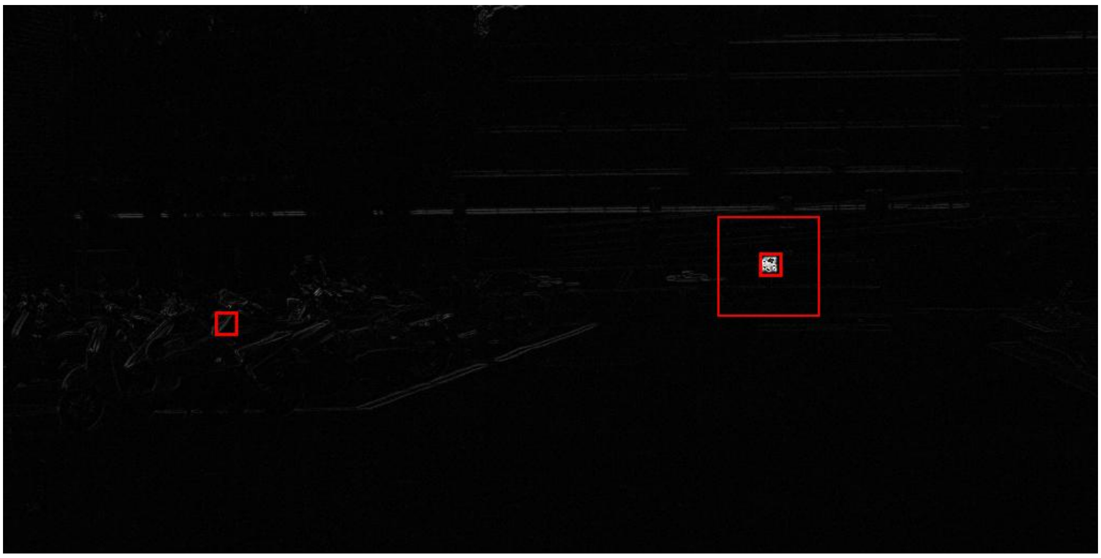


Figure 4.14: Corresponding candidates areas on DI and transmitter confirmation result for the example shown in Fig. 4.13.

4.13. D_{den} and L_{avg} are calculated following the Equation (4.4) and (4.5) respectively.

$$D_{den} = \frac{D_{pix}}{T_{pix}} \tag{4.4}$$

$$L_{avg} = \frac{\sum L_{pix_i}}{T_{pix}} \tag{4.5}$$

D_{pix} and T_{pix} in the above equations represent the number of differences pixels(pixel value> B_{ths}, $B_{ths} = 20$) and total number of pixels inside the candidate respectively. In addition, the L_{pix_i} represents the intensity value of each pixel inside the candidate. The candidate under below condition(indicated by (4.6)) is confirmed as transmitter.

$$D_{den} \times L_{avg} > threshold \tag{4.6}$$

In the Fig. 4.14, the transmitter confirmation result is also indicated using cut out image area(I_{cut}) with larger red square. D_{den} and L_{avg} values inside the transmitter area take relatively stronger values than other objects created by noises, due to LED blinking of the transmitter.

4.5 Tracking algorithm

After finding the transmitter, it is tracked only searching the I_{cut} in consecutive frames from high-speed camera. Here, the images are taken in $1000fps$, processing is only conducted for I_{cut} to minimize the processing time. In this thesis, tracking is conducted without using a defined border like previous works. As described in the section 4.3, the borders of the transmitter might not properly appear due to

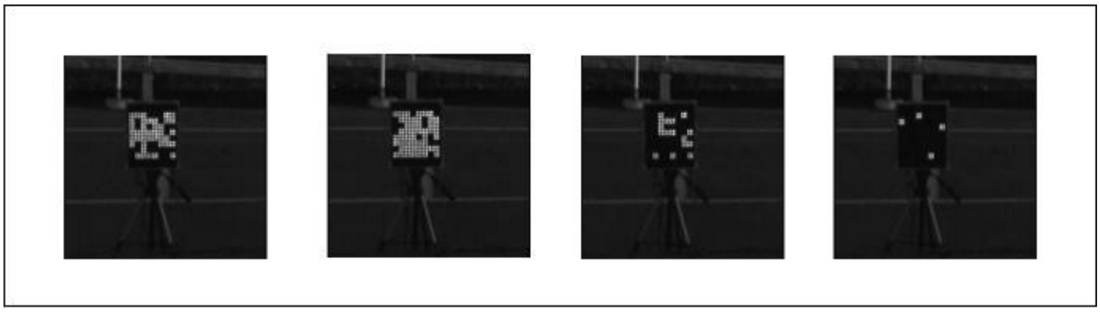


Figure 4.15: An examples of consecutive I_{cut}

transmitter LED blinking(see Fig. 4.15). However, in some cases, the borders can be detected by calculating circumscribing rectangle of lighting LEDs in the I_{cut}. The transmitter borders(position) in the two left images of Fig. 4.15 can be detected through this edge-based method. But, the transmitter borders in the two right images cannot be detected. In these cases, the movement of the transmitter position is measured on optical flow. Thus, proposed tracking algorithm tracks the transmitter on a edge-based step and a optical flow based step. If the edge-based step could not detect transmitter, its position is detected on optical flow as illustrated in the Fig. 4.16. The size of the transmitter can only be updated in the edge-based step. This tracking method is detailed below.

4.5.1 Edge-based step

Edge detection is an interesting computer vision problem, and many methods have been proposed[45∼49]. In this thesis, canny edge detector[49] is used since it can mark many real edges in the image as possible. In addition, it can mark edges once(without creating noise) as close as possible to the edges in the real image.

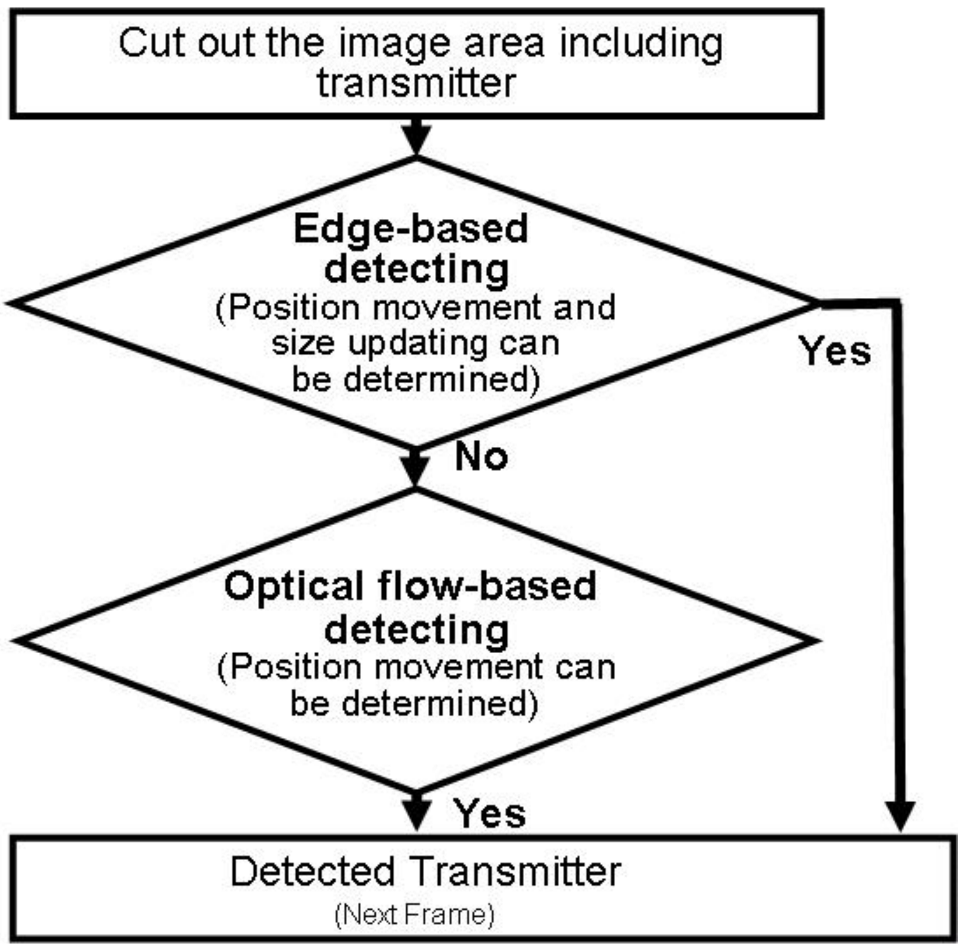
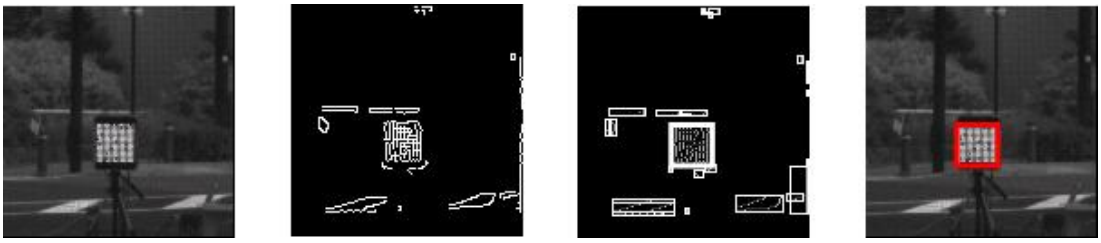


Figure 4.16: Tracking flow



(a) (b) (c) (d)

Figure 4.17: Edge-based step; (a)Arbitrarily frame; (b) Edge detection; (c) Calculation of CR and candidate selection; (d) Transmitter confirmation

As Fig. 4.17 illustrates, in this step, first edge detection is conducted for I_{cut}. Then the Circumscribing Rectangle(CR_i) of each edge component is calculated. The geometry of each CR_i,($height : CR_{h_i}$, $width : CR_{w_i}$) is compared with geometry of detected transmitter in the previous frame($height : PF_h$, $width : PF_w$). The Circumscribing Rectangles under following three conditions (indicated in (4.7), (4.8) and (4.9)) are selected as transmitter candidates.

$$PF_h - offset < CR_{h_i} < PF_h + offset \tag{4.7}$$

$$PF_w - offset < CR_{w_i} < PF_w + offset \tag{4.8}$$

$$| CR_{h_i} - CR_{w_i} | \leq 2pixels \tag{4.9}$$

The transmitter is confirmed regarding position movement between current frame and previous frame(m_{cp}). The CR which is $m_{cp} < threshold$ is confirmed as transmitter. Transmitter can be detected, at least 33% with this edge-based step.

4.5.2 Optical flow-based step

If the transmitter could not be detected by edge-based step, its current position is measured by using the optical flow. Many studies have been focused on studying the optical flow. Lucas and Kanade method[50], Horn and Schunck methods[51], Buxton and Buxton method[52] and Block-based method[53∼56] can be introduced as some of commonly used methods. Optical flow is used for different tracking purposes, such as pedestrian tracking[60][61], vehicle tracking[62][63], and so on. In this study, it is applied to achieve part of the transmitter tracking.

In this thesis, the transmitter position movement have to be measured in consecutive frames. Transmitter position is mainly moved in consecutive frames due to vibration of on-vehicle camera. This movement is comparatively small, and it can also be assumed that feature points in I_{cut}(Transmitter local area) takes constant and small movement due to high frame rate image capturing by high-speed camra. The Lucas and Kanade method includes similar assumptions, that the movement of the image contents between two nearby frames is small and approximately constant[56][58][59]. For these reasons, Lucas-Kanade method is used in this thesis.

If the transmitter could not be detected in the edge-based step, preprocess the previous frame(called as base frame) using a Gaussian low pass filter. The deformation matrix(D) is calculated using directional derivatives at each pixel in the base frame following Equation (4.10).

$$D = \begin{bmatrix} d_{xx} & d_{xy} \\ d_{yx} & d_{yy} \end{bmatrix} \tag{4.10}$$

where, for example, d_{xx} represents the 2nd order derivative in the x direction. The eigenvalues of D are calculated, and perform non-maxima suppression. In this thesis, it is assumed that the local minima exists in the 5×5 neighborhood. The best N number of feature points are selected using the eigenvalues in order of priority, following the pyramidal implementation of the Lucas Kanade feature tracker[57]. Here, as Fig. 4.18 illustrates, the approximate transmitter area is not used for feature point selection. The errors can be occurred in feature point selection due to LED blinking. The image area for feature point selection(I_{fp}) is defined following the Equation (4.11).

$$I_{fp} = I_{cut} - (BF_w + offset) \times (BF_h + offset) \tag{4.11}$$

where, BF_w and BF_h are the width and height of detected transmitter in the base frame. After that, gain the corresponding set

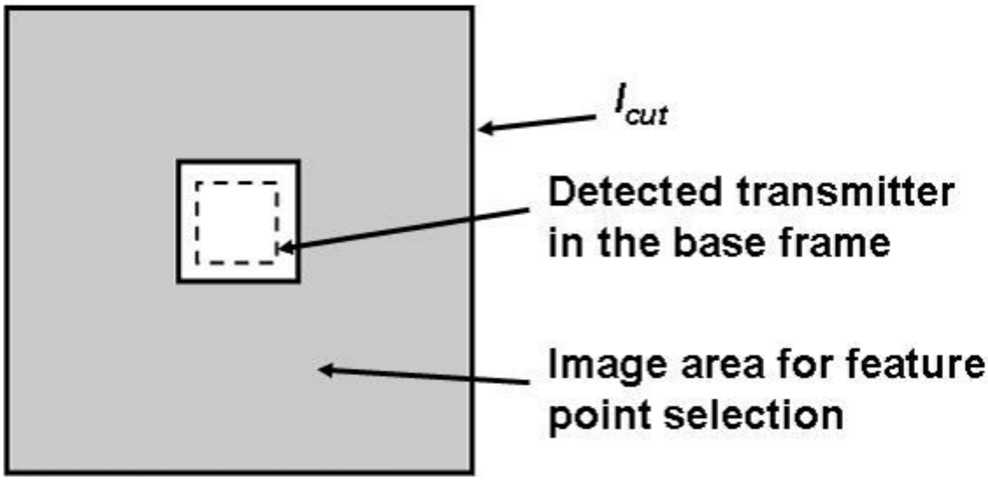
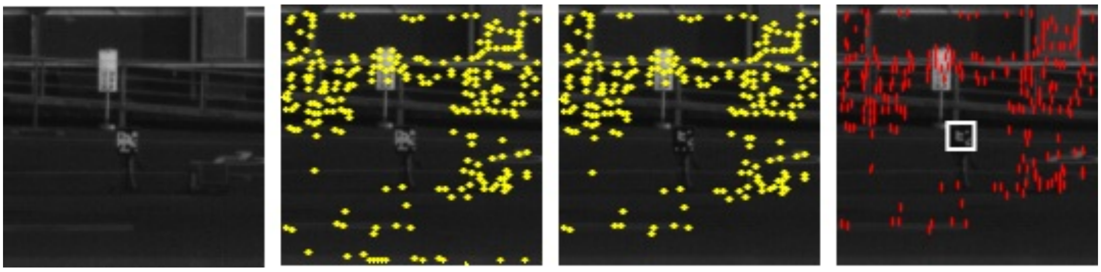


Figure 4.18: Image area for feature point selection

of feature points in the current frame on Lucas-Kanade's optical flow[50]. The movement of the transmitter is measured using the movement of the feature points. Here, the maximum frequency of the feature point movement(distance(FP_{dis}^{max}) and direction(FP_{dir}^{max})) between current frame and base frame is selected as the movement of the transmitter. If the corresponding feature points in current frame decreased into $0.7N$ points while continuous tracking, feature points are renewed. The transmitter position is detected on optical flow until it is detected by edge-based method again. Figure 4.19 illustrates the main steps of transmitter detection by optical flow.



(a) (b) (c) (d)

Figure 4.19: The main steps of optical flow-based tracking, (a) Arbitrarily previous frame(based frame); (b) Selected feature point on based frame; (c) Corresponding feature points on current frame; (d) Movement of the feature points between based and current frames (movement is shown by red dashes on current frame) and detected transmitter on current frame.

4.6 Experimental results

The outdoor experiments were conducted to confirm the effectiveness of the proposed transmitter detection algorithms.

4.6.1 Experimental environment

In the experiments, the high-speed camera was installed on a vehicle. Figure 4.20 illustrates the an image of the high-speed camera (*Photron, Fastcam 1024PCI 100K*) installed on the experimental vehicle.

Images were captured while driving the vehicle between $30km/h \sim 40km/h$, towards the transmitter. The moved distance of the ve-

Figure 4.20: High-speed camera installed in the experimental vehicle

hicle is $70m$ to $20m$, from the transmitter. The vehicle was driven on roads, having a similar road surface condition as normal roads in Japan.

Transmitter LEDs blink light in $500H_z$ and gray scale images of blinking transmitter were captured by high-speed camera in $1000fps$ with a size of $1024 \times 512 pixels$. The cut out image area(I_{cut}) was $128 \times 128 pixels$. All the experiments were conducted on a computer having configuration of Intel(R) CoreTM 2 Duo, $3.00GHz$ and $2.00GB$ RAM.

4.6.2 Transmitter finding results

Figure 4.21∼4.25 illustrate the examples of transmitter findings, when the vehicle pass positions in between $70m \sim 60m$, $60m \sim 50m$, $50m \sim 40m$, $40m \sim 30m$ and $30m \sim 20m$ far from the transmitter. Here, the found transmitter is indicated using cut out image area(I_{cut}) on them.

Table 4.1 illustrates transmitter finding results. Each sequence in the Table 4.1 includes approximately $6000 frames$. These sequences were captured under sunny, cloudy, and very dark(night) conditions. In the experiments, the number of previous frames used for the

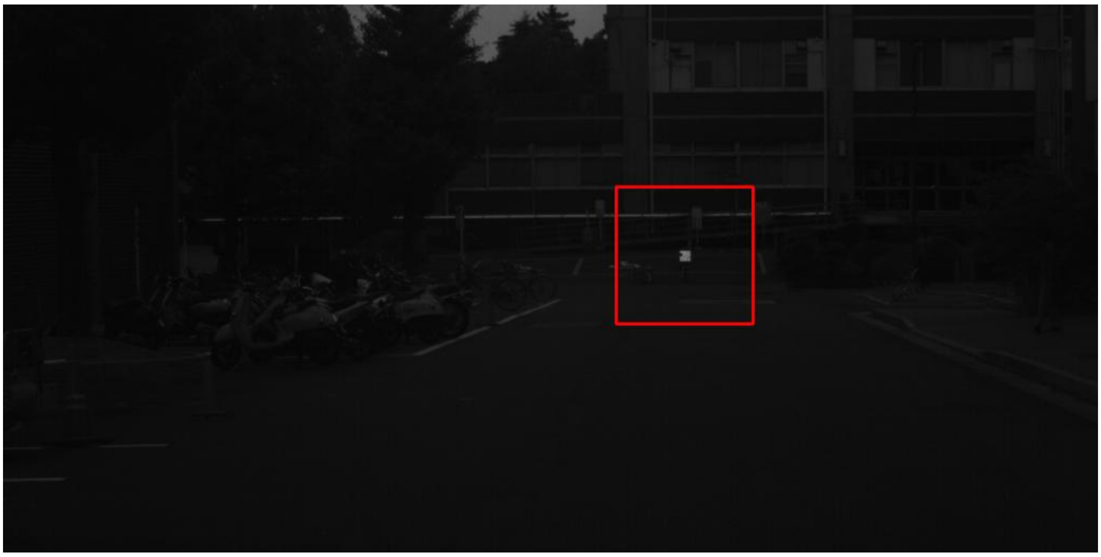


Figure 4.21: Found transmitter(70m∼ $60m$ far from the transmitter)

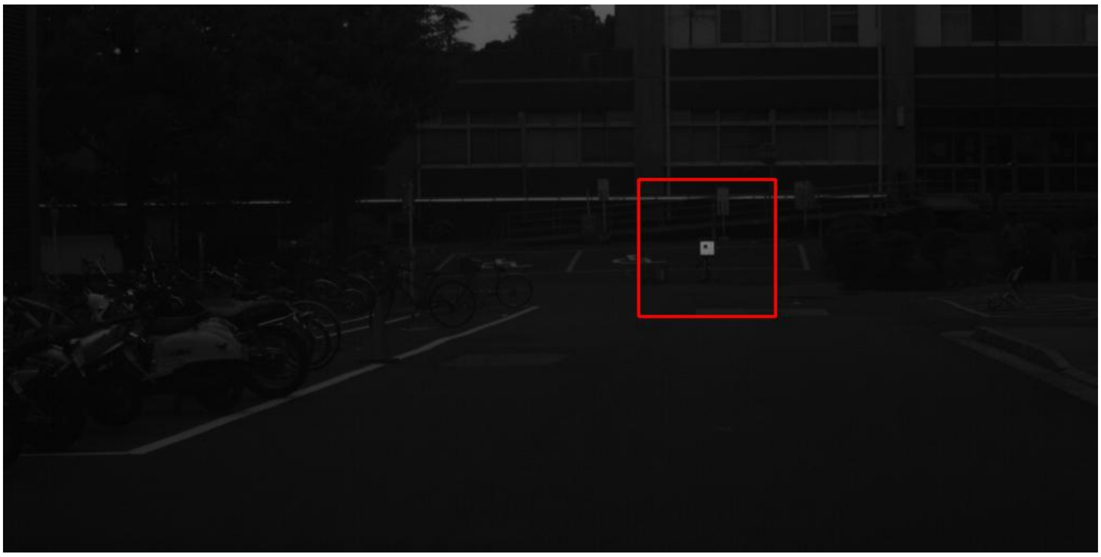


Figure 4.22: Found transmitter($60m \sim 50m$ far from the transmitter)

Figure 4.23: Found transmitter($50m \sim 40m$ far from the transmitter)

Figure 4.24: Found transmitter($40m \sim 30m$ far from the transmitter)

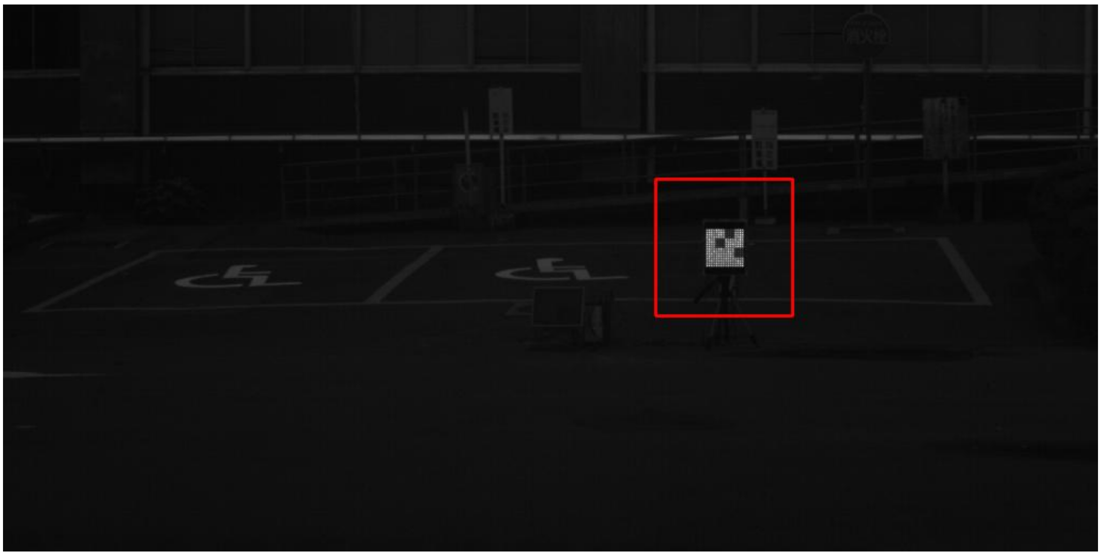


Figure 4.25: Found transmitter($30m \sim 20m$ far from the transmitter)

Table 4.1: Finding results

Sequence	Expected findings	Findings	Success rate%	False findings
1	1176	1170	99.48	0
2	568	549	96.65	0
3	1140	1127	98.85	0
4	1183	1175	99.32	0
5	908	908	100.00	0
6	1213	1197	98.68	0
7	1215	1201	98.84	0
8	1209	1179	97.51	0

differences calculation(m) was set as five. This value was decided by conducting a sub-experiment.

In this method, transmitter is found in every five frames. The expected findings means number of maximum findings can be happened when the transmitter is found in five frames by five frames. Success rate shows successfully found percentage out of expected findings.

4.6.3 Tracking result

The found transmitter is tracked using proposed tracking algorithm. As mentioned above as well, transmitter is kept inside I_{cut} while tracking. Figure 4.26 illustrates some tracking results in consecutive frames. In this figure, the red squares indicate the tracked transmitter by edge-based step and yellow squares indicate the tracked transmitter by optical flow-based step. The red dashes indicate the movement of the feature points. In between, Fig. 4.26(c) and (e) it does not show any dashes, meaning that there is not a movement between these three frames. When a moving on-vehicle high-speed camera takes images in $1000fps$, sometimes there is not a movement between few frames. Figure 4.26(a), (b), (f) and (k) are some examples for detecting the transmitter by edge-based step. As illustrated in the Fig. 26(g)$\sim$(j), the transmitter is tracked in consecutive frames on optical flow.

While the camera is moving in a horizontal direction and if the objects are far from the camera, the affection on angular motion of the camera is more than the one on the horizontal direction. Regarding this issue and the above mentioned features of high frame rate image capturing, the movement of the transmitter takes similar movement as background. According to the experiments, it is hard to track more than 105 continuous frames only on optical flow. And,

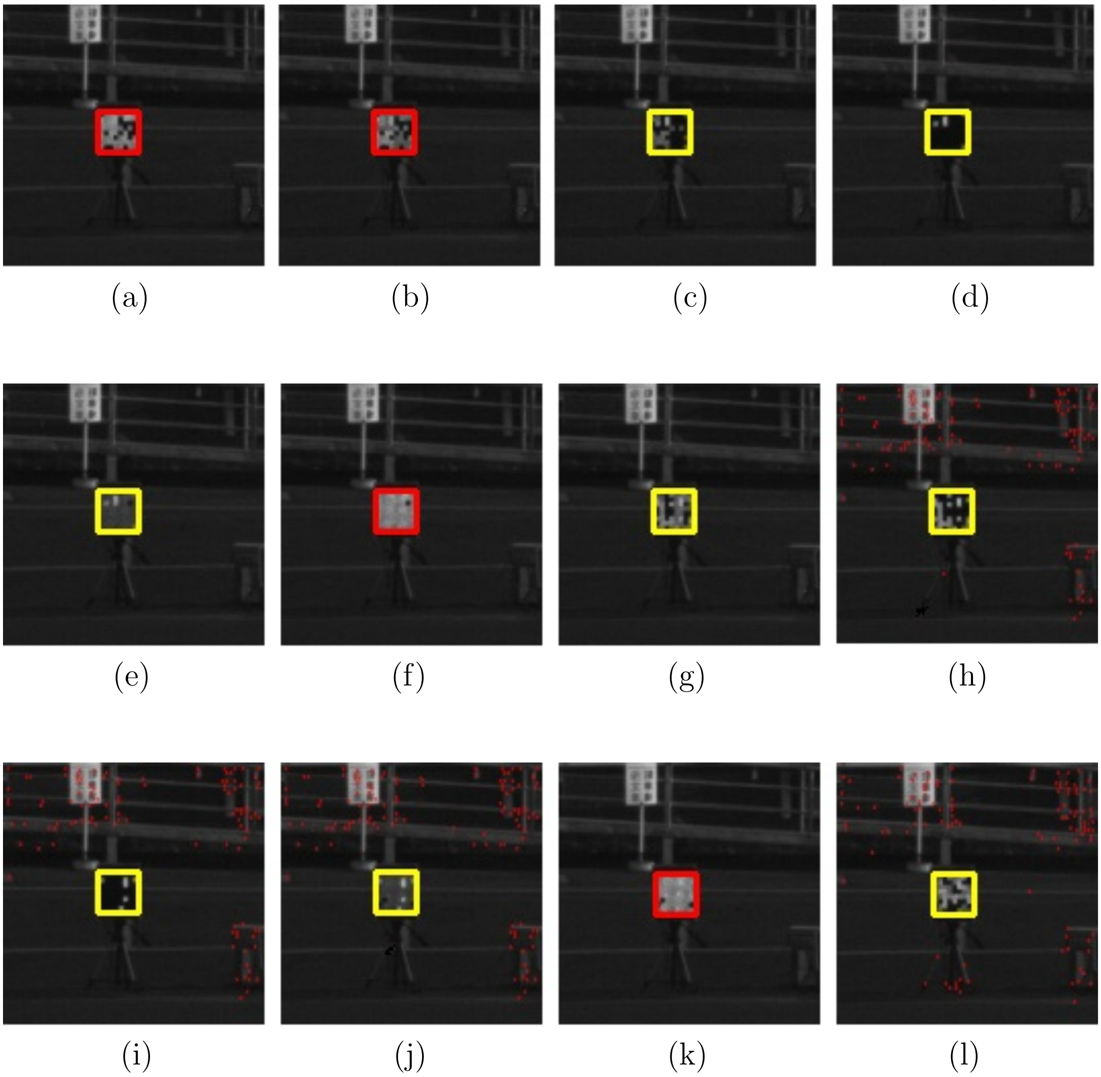


Figure 4.26: Tracking results

with the combination of edge-based method it only need to track maximum of 40 continuous frames on optical flow, since edge-based step involve at least 33% of entire tracking. As a result, it is possible to track the transmitter effectively with this combination.

All the experiments were conducted on a computer having configuration as above explained. Average computational time in the finding and tracking steps are $25ms/5frames$(transmitter is found in $5frames$) and $0.03ms/frame$ respectively. Tracking can be conducted in real time, but, finding cannot be achieved in real time. Both of these algorithms were developed considering the processing time minimization. These finding algorithms can be implemented in real time on a more powerful computer or on hardware, since it includes simple image processing steps.

This chapter introduced transmitter finding and tracking methods for the receiver. To conduct Visible Light Communication(VLC), the lighting patterns of the transmitter LEDs should be detected. The next chapter first presents about lighting pattern detection, and then presents communication experimental results of proposed VLC system by applying the proposed image algorithms.

Chapter 5

Lighting pattern detection and communication

This chapter presents the lighting pattern detection of blinking transmitter which appear on each continuous frame taken by high-speed camera. Furthermore, communication possibility using those patterns at a driving environment is also present.

The image of the transmitter area detected by tracking method, is only processed to capture the lighting pattern of each frame.

5.1 LED blinking pattern

When the distance between transmitter and vehicle exceeds $40m$, the resolution of the camera is not enough to capture all transmit-

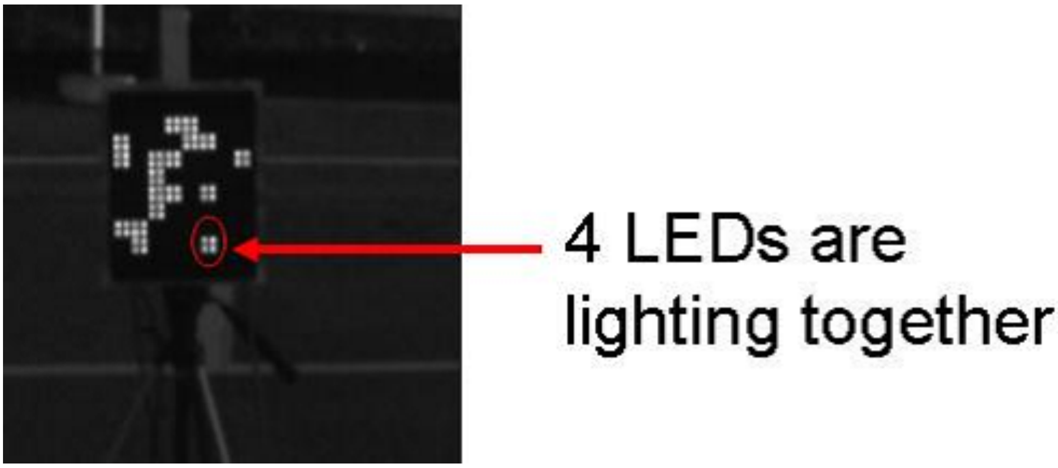


Figure 5.1: An example of transmitter image under blinking conditions

ter LEDs individually. For this reason, 4 neighboring transmitter LEDs blink light synchronized with a 500Hz clock signal, and binary blinking is conducted. Figure 5.1 illustrates an image taken under these blinking conditions.

As detailed section 3.2.1, the communication speed is $32kbps$.

In this thesis, communication is conducted at a distance between $20m$ and $70m$ from the transmitter. The side length of the transmitter in the images almost varies from $36pixels$ to $8pixels$ when a vehicle move this distance. Thus, the appointed image for processing is small(always smaller than cut out image area(I_{cut})). However,

(a) (b) (c) (d) (e)

Figure 5.2: Appearance of the transmitter in the images from different distances, $(a)70m \sim 60m, (b)60m \sim 50m, (c)50m \sim 40m, (d)40m \sim 30m, (e)30m \sim 20m$ far from the transmitter

the blinking transmitter is installed in a out door environment. The pixel values for lighting LEDs in the images are mainly depended on the distance between the camera and the transmitter, affection of other outdoor light sources such as sun light at the day time, outdoor illumination at the night time. In addition, it depends on the whether condition and the affection due to high frame rate image capturing of blinking transmitter.

Figure 5.2 illustrates the images of the transmitter taken at the different distances far from the transmitter. As shown in the Fig. 5.2(d), even the distance is shorter, moire phenomenon was occurred due to the miss match between blinking transmitter and shutter speed of the camera. For this reason, the pixel value distribution of the lighting LEDs is not stable(see Fig. 5.1(d)). A robust method is needed to distinguish lighting and non-lighting LEDs under these circumstances, not possible to use a constant threshold.

5.2 Distinguishing of lighting and non-lighting LEDs

In this thesis, discriminant analysis(similar as Othsu binarization method)[64][65][66] is applied to distinguish the pixels belongs to the lighting LEDs and non-lighting LEDs. By globally applying discriminant analysis to transmitter image(I_{tra}) is not robust enough for this distinguishing.

In the discriminant analysis, first image is divided into two classes and then calculate variance within two classes(${\sigma_W}^2$) or the variance between two classes(${\sigma_B}^2$) following the Equation (5.1) and (5.2) respectively.

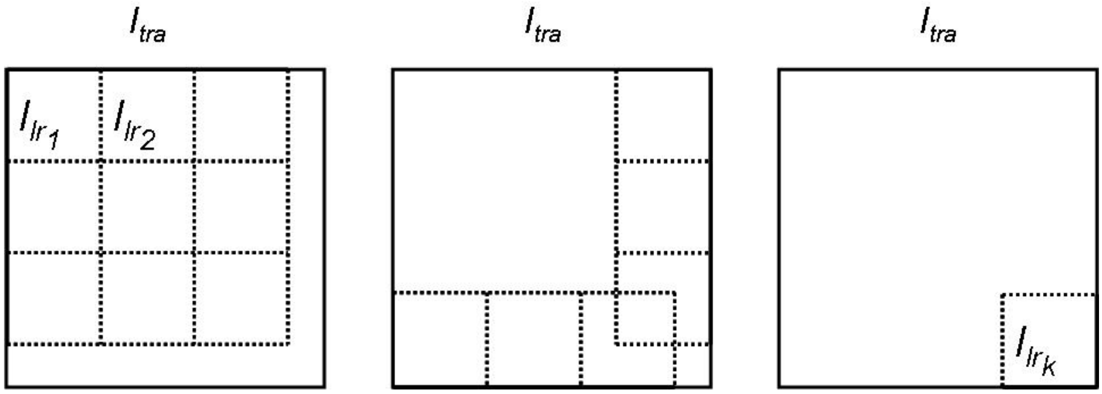
$$ {\sigma_W}^2 = \omega_1 {\sigma_1}^2 + \omega_2 {\sigma_2}^2 \tag{5.1} $$

$$
\begin{aligned}
{\sigma_B}^2 = \ & \sigma^2 - {\sigma_W}^2 \\
& = \quad \omega_1(\mu_1 - \mu)^2 + \omega_2(\mu_2 - \mu)^2 \\
& = \quad \omega_1\omega_2(\mu_1 - \mu_2)^2
\end{aligned} \tag{5.2}
$$

$where\ \mu = \omega_1\mu_1 + \omega_2\mu_2$

The weights ($\omega_{1_i}\ and\ \omega_{2_i}$) are the probabilities of the two classes separated by t_i, ($i = 0 \sim 255$). The threshold(t) to verify the lighting and non-lighting LEDs can be determined, when ${\sigma_B}^2$ takes maximum value or ${\sigma_W}^2$ takes minimum value. But, in the implementation, calculation of ${\sigma_B}^2$ is quicker since, weights and averages of two classes are only calculated as indicated in Equation (5.2). Considering this point, ${\sigma_B}^2$ is used to gain the t.

In this thesis, discriminant analysis is not globally applied to entire (I_{tra}). Here, first, image is divided into local regions(I_{lr}) from left to right and up to down as indicated in the Fig. 5.3(a). The size of (I_{lr}) $= 8 \times 8 pixels$. But, it is impossible make this division with



(a) (b) (c)

Figure 5.3: Division of I_{tra} into I_{lr_k}

exact $8 \times 8 pixels$, except image size takes $(8 \times n) \times (8 \times n) pxels$, $n < 5$. Then the remaining image is divided as indicated in the Fig. 5.3(b) and (c). As Fig. 5.3(b) and (c) illustrate, some parts of the regions are overlapped each other. This division is conducted to locally calculate the ${\sigma_B}^2$ inside I_{tra} . Thus, this overlapping is not so affected. This division is conducted, if the transmitter image area(I_{tra}) $> 16 \times 16 pixels$. The t_k for each I_{lr_k} are separately calculated. The minimum value of t_k ($t_{k_{min}}$) is globally used to distinguish the lighting and non-lighting LEDs.

As mentioned above, white pixels are set for the lighting LEDs and black pixels are set for the non-lighting LEDs as shown in Fig.

(a) (b) (c) (d) (e)

Figure 5.4: Distinguishing of lighting and non-lighting LEDs globally applying discriminant analysis (same as Otsu method)

(a) (b) (c) (d) (e)

Figure 5.5: Distinguishing of lighting and non-lighting LEDs using proposed method

5.5. Figure 5.4 and 5.5 show the distinguishing of the lighting and non-lighting LEDs in the images globally applying discriminant analysis and proposed method respectively. Here, the white pixels are set for the lighting LEDs and black pixels are set for the non-lighting LEDs. According to experiments, proposed method is effective to verify the lighting and non-lighting LEDs. After this verification, LED positions in the images are determined.

5.3 LED position and pixel value determination

As mentioned above, 4 neighboring LED groups in the transmitter are used as sub-transmitters. So, the 4LEDs in each group has same lighting situation at every moment. According to this grouping, the total number of LED groups are 64(8×8). In this thesis, it is necessary to identify each group separately and their lighting situation(ON or OFF) as well. According to the distance between transmitter and high-speed camera, the size of the transmitter in the images appears with $t \times t\, pixels,\;\; here\;\, t = 8 \sim 36$. Here, in most cases, the binarized(binarized by proposed method) I_{tra} cannot be divided into 64 sub-regions with the pixel units. Images are divided on sub-pixel units in these kind of situations[68∼71]. In this thesis, binarized I_{tra} is divided in to 64 sub-regions using the sub-pixel units. Figure. 5.6 illustrates the sub-regional devision. It consider that, each sub-region is corresponded to each 4LED group in the transmitter.

The pixel value P_v of each 4LED group is picked up following the Eqaution (5.3).

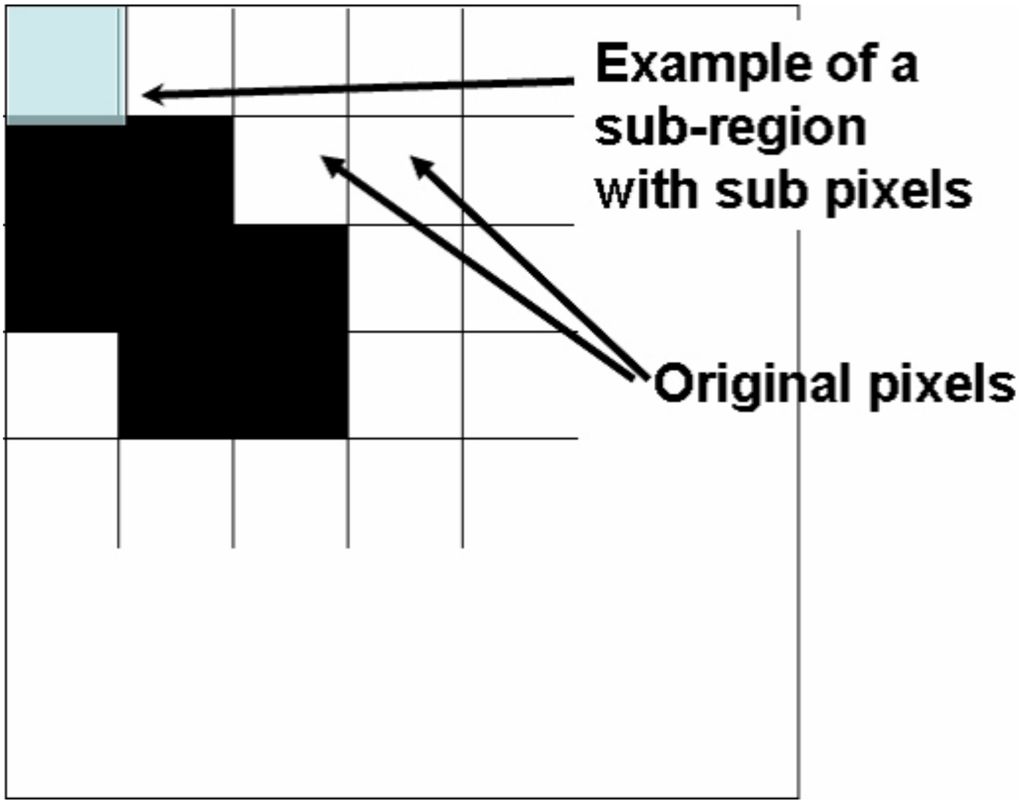


Figure 5.6: Sub-regional division of I_{tra} using sub-pixel

$$P_v = \begin{cases} 255 & (A_w > A_b) \\ 0 & \end{cases} \tag{5.3}$$

The A_w and A_b mean the white and black overlapping areas in the sub-region respectively. The pixel value, distributed in maximum area of each sub-region is selected as the pixel value for corresponding 4LED group. Then the lighting pattern in entire I_{tra} is determined considering pixel values of all sub-regions.

5.4 Experimental results

Experiments were conducted to confirm the effectiveness of the proposed lighting pattern detection algorithm. Additionally, the communication possibility of proposed road-to-vehicle VLC system was also evaluated in a driving environment by applying all the proposed image processing algorithms in this thesis.

5.4.1 Experimental environment

In the experiments, the high-speed camera was installed on a vehicle and images were captured while driving between $30km/h \sim 40km/h$, towards the transmitter. The moved distance of the vehicle is from $70m$ to $20m$, from the transmitter. Transmitter blinks light in $500H_z$ and grayscale images of blinking transmitter were captured by high-speed camera in $1000fps$ with size of $1024 \times 512 pixels(I_{org})$. Proposed transmitter detection algorithms presented in the Chapter

Sequence	d_1 : $20m \sim 30m$	d_2 : $30m \sim 40m$	d_3 : $40m \sim 50m$	d_4 : $50m \sim 60m$	d_5 : $60m \sim 70m$
1	100%	99.8%	98.0%	90.2%	79.9%
2	100%	99.9%	96.1%	91.1%	70.1%
3	100%	99.9%	97.0%	92.2%	71.1%
4	100%	99.6%	94.6%	85.6%	74.1%

Table 5.1: Average percentage of capturing the 4LED groups lighting situation when the vehicle move at d_1, d_2, d_3, d_4 and d_5 distance far from the transmitter

4 were used for finding and tacking. The cut out image area(I_{cut}) was $128 \times 128 pixels$ in tracking. This chapter mainly describes the results of lighting pattern(capturing the lighting situation of 4LED groups individually) detection of the transmitter in consecutive frames and the measurement of BER.

All the experiments were conducted on a computer having configuration of Intel(R) CoreTM 2 Duo, $3.00H_z$ and $2.00GB$ RAM.

5.4.2 Lighting pattern detection results

Four image sequences were captured under above mentioned experimental environment and different outdoor conditions such as sunny, cloudy, and very dark(night). All the sequences include approximately $25000frames$(here, each sequence includes approximately $6400frames$). There are 64, 4LED groups(sub-transmitters) are existed in each frame. Table 5.1 shows the results of capturing the lighting situation(ON or OFF) of 4LED groups individually. Here the average percentage of capturing the 4LED groups lighting situation is used for evaluation. This average percentage at the different distances(d_1, d_2, d_3, d_4, d_5) from the transmitter are shown in Table 5.1. When the vehicle moves at a distance between $20m$ and $40m$, the lighting situation of 4LED groups could be captured in very high accuracy. But, when the vehicle moves at a distance between $40m$ and $70m$, results are not so good.

5.4.3 Communication ability evaluation

The Bit Error Rate(BER) was measured to evaluate the communication ability of proposed road-to-vehicle VLC system. Figure 5.7 illustrates results of four communication experiments. Here, when the vehicle moves at the distance between $70m \sim 20m$ from the transmitter, BER values were measured. These experiments were conducted under different outdoor conditions and they are indicated by different colors as; Red : very dark(night time), Pink : cloudy, Yellow : cloudy, Blue : sunny. The communication speed

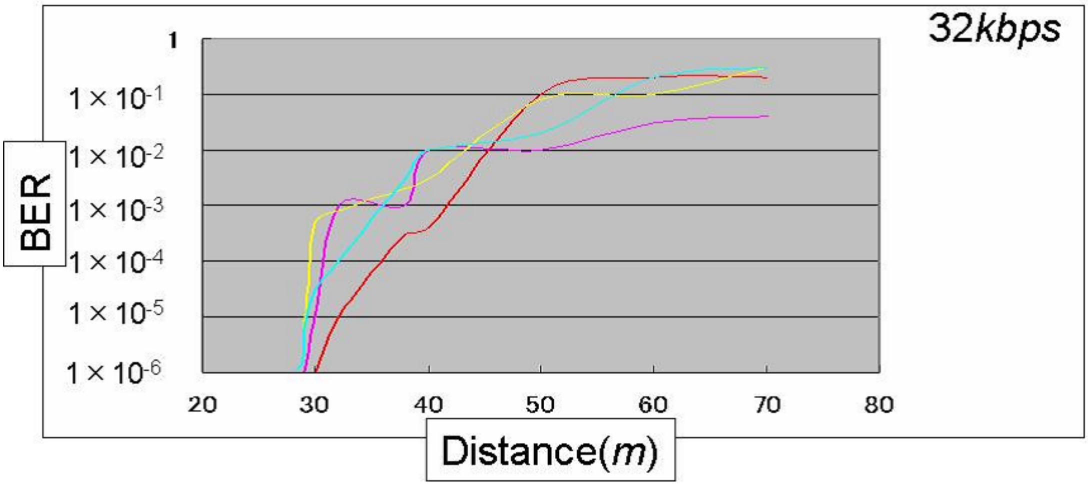


Figure 5.7: Communication possibility evaluation

was 32*kbps*.

According to these results, it is possible to achieve small video, audio and text data transmission, at a distance between $20m \sim 30m$ since the $BER < 10^{-6}$. The audio and text data transmission can be conducted at a distance between $30m \sim 40m$ since, almost $BER < 10^{-3}$.

As mentioned above, here 4 neighboring LED groups in the transmitter are used as a sub-transmitter. According to this data rate is 32kbps with the contribution of all the LEDs in the transmitter. However, this can be achieved when the transmitter is tracked by the proposed tracking algorithm in this thesis. In the previous method[43] with same LED grouping, data rate was 4kbps, since the LEDs in exterior lines of the transmitter are used to define the borders for tracking. According to this, the data rate could be increased 8times with the new tracking method.

Chapter 6

Conclusions and Future works

6.1 Conclusions

This thesis presented new image processing algorithms for a road-to-vehicle Visible Light Communication(VLC) system. That system is introduced for Intelligent Transport system(ITS) using an LED traffic light(LED array) as a transmitter and a high-speed camera as a receiver. Here, the transmitter sends data by blinking LEDs at high frequency and a high-speed camera receives that data by capturing lighting pattern of the transmitter at high frame rate. For capturing the lighting pattern, finding the transmitter and tracking the found transmitter are absolutely necessary. Additionally, the finding and tracking should be conducted without affecting the communication performance of the system. The data rate and communication time decreased with previous algorithms. Another issue is that the algorithms should have processing time reduction approaches to have real time processing at least on the hardware. In this thesis;

- New Transmitter finding, tracking, and lighting pattern detection algorithms were proposed, mainly considering the features of high frame rate image capturing by high-speed camera. These new algorithms include processing time reduction approaches as well.

According to the outdoor experiments under different conditions;

- Proposed algorithms were effective for desired finding, tracking and lighting pattern detection.

With the proposed algorithms;

- It is possible to increase the communication performance of the road-to-vehicle VLC system compared to previous algorithms.

In the literature, as mentioned above, there are some studies for this transmitter detection(finding and tracking). The data rate and communication time could be increased with the new algorithms.

Since with the previous algorithms, all LEDs in the transmitter cannot be used for communication and continuous communication cannot be conducted.

The data transmission performance of the proposed road-to-vehicle VLC system was evaluated in a outdoor driving environment. According to the evaluation, it is possible to transmit small video, audio and text data at a distance between 20m and 30m from the transmitter. The audio and text data can be transmitted at a distance between between 30m and 40m from the transmitter. When the vehicle moves almost over 45m far from transmitter, it is difficult to conduct communication.

This road-to-vehicle system uses a high-speed camera as a receiver. Similar kind of systems in the literature use Photo Diode(PD) as receiver. Compared with the systems with PD receivers, still the performance of this system with high-speed camera has less performance. The data rate of system with PD is higher than this system. However, studies are conducted to improve this system. More better performance can be expected in the future.

I believe that proposed road-to-vehicle VLC system will be very helpful to assist drivers at signalized intersections. Therefore, it will contribute to reduce the increasing traffic accident at intersections as a part of ITS techniques. Furthermore, there is growing interest to apply VLC as wireless communication in ITS as well as other communication purposes.

6.2 Future works

In this thesis, all the experiments were conducted on a computer. However, to apply this system in the real world, algorithms have to be implemented on hardware.

Communication performance was not so good when the vehicle moves over approximately $45m$ from the transmitter. For this reason, system should be improved to achieve long distance communication.

All the experiments were conducted keeping vehicle speed $30km/h \sim 40km/h$. The communication possibility has to be evaluated driving the vehicle at faster speeds.

In this thesis, no experiments were conducted under bad weather conditions such as rain and snow. Conducting road-to-vehicle VLC under those conditions is also challenging and interesting future work. Some improvements of the hardware and software would be necessary to achieve this.

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