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# High-speed Stroboscope for Specular Reflection Removal of DC Illumination

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*Abstract*— **Separation between specular reflection components and diffuse reflection components is an important subject in robotics and machine vision. Hence, the author's group has developed a method to separate a diffuse image from an image of high-speed video with specular reflection components. The method is based on an estimation technique based on luminance variation due to flicker of a light with an AC source. However, the method has a serious issue that it is limited for lights with an AC source. This study gets rid of the limitation by implementing a high-speed strobe light to the camera and produce flickers by artificial means. Experimental results show the validity of the proposed method.**

## I. Introduction

In recent years, there has been a growing need for collecting the inherent features of an object, such as shape and texture of a substance, in the field of robot vision. However, a lot of studies have reported the affect of the specular reflection light, which causes a robot to lose its environmental applicability. Therefore, separation between specular reflection components and diffuse reflection components is an important subject in robotics.

The most common method for preventing specular reflection is to use a polarization filter [1]. A polarization filter reduces the intensity of specular reflection components. However, its effectiveness varies greatly with the light incidence angle and it is unable to completely remove some components. Other methods for removing specular reflections include changing the light source position [2] and separating the specular reflection components by changing the camera position while keeping the light source position constant [3]. However, both methods require mechanical systems for moving the light source or the camera. Besides these methods, there is a method that involves separating the specular reflection components from a single image based on a dichromatic reflection model [4]. This method has the advantage of being able to separate specular reflection components by performing image processing of one photograph, but has the limitations that the chromaticity of the light source must be known and the specular reflection components cannot be separated from low-saturation colors such as gray.

This study deals with a technique for removing specular reflections by exploiting the characteristics of high-speed cameras. High-speed cameras can take photographs of rapid motion and rapidly varying phenomena that cannot be imaged by conventional video cameras. High-speed cameras have been used in practical applications in many fields [5], [6]. In recent years, vision chips [7], [8] that have parallel processing architectures have been developed for realizing high-speed image processing systems, which allow real-time processing for high-speed cameras. A real-time robot vision system with high-speed image processing [9] is a good candidate for high-performance motion control systems. Many researchers are also trying to find ways to overcome problems associated with high-speed cameras such as AC illumination flicker [10]. AC illumination flicker is rarely detected in human vision since human eyes have a limited sensitive frequency range [11]. Using a high-speed camera with a frame rate that exceeds this range can enable advanced image processing that surpasses human vision.

The author's group has proposed a method for specular reflection removal with a high-speed camera and have verified the validity in experiments[12], [13]. The method exploits the fact that specular reflection components correlate directly with variations in the light source illumination that cause specular reflections (hereafter, referred to as the "specular reflection light source"). Supposing the relationship between the specular reflection components and the variation in the specular reflection light source is linear, it is possible to estimate the image when the specular reflection light source is unlighted. As a result, diffuse reflections from other light sources are collected [12]. Furthermore, technical issues on moving objects were executed since the ability to deal with moving objects is strongly required for robot vision systems[13]. However, a strong limitation remained that only AC illuminations are allowed for the specular reflection light source. The method is limited to AC illuminations since it is based on flicker information. This paper therefore proposes a method to overcome the issue by implementing a high-speed strobe light to the camera. The proposed method accomplishes specular reflection removal of DC illumination by producing flickers artificially.

This paper is structured as follows. First, Section II describes the basic theory, including the method for specular reflection removal of AC illumination. Next, Section III explains how a high-speed camera with high-speed strobe light can be used to remove specular reflection of DC light source. Section IV describes the experiments that were conducted and discusses their results. Finally, Section V gives the conclusions.

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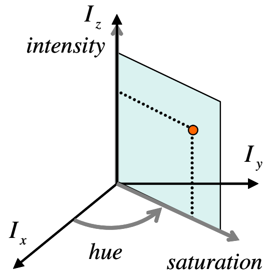



Fig. 1. Color space

## II. Basic theory

### A. Color space and reflection model

This paper applies the color space used by Miyazaki et al. [14]. This color space is obtained from (1) that represents a linear transformation in the RGB color space consisting of the luminance values $I_r$, $I_g$ and $I_b$.

$$\begin{pmatrix} I_x \\ I_y \\ I_z \end{pmatrix} = \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{pmatrix} \begin{pmatrix} I_r \\ I_g \\ I_b \end{pmatrix} \tag{1}$$

Fig. 1 shows the color space consisting of the newly obtained luminance values $I_x$, $I_y$ and $I_z$. Here, $I_z$ represents the intensity. The distance from the origin to the point $(I_x, I_y)$ in the X–Y plane is a parameter known as saturation, which indicates the degree of color brightness. The angle that X axis forms with the line segment between the origin and the abovementioned point $(I_x, I_y)$ is called hue whose value determines the tone of color.

This paper explains the method in this color space while the method can be applied to any other color spaces given by linear transformation of the RGB color space.

Experiments were performed using a high speed camera to investigate the luminance variation in the color space. Table I shows the specifications of the high-speed camera used in this study.

TABLE I
Specifications of the experimental system

| | |
|---|---|
| Maximum frame rate | 1200 [FPS] |
| Number of pixels | 336 × 96 |
| Pickup device | 1/1.8″ size CMOS |

In a room in which sunlight enters, two 40 W fluorescent lamps were turned on and a paper covered with a transparent acrylic plate was photographed by the high-speed camera. The photographs were taken in shadow to avoid direct sunlight.

Initially, the camera position was adjusted so that specular reflections of the fluorescent lamps on the acrylic plate could be photographed. Fig. 2 shows the luminance values of points in a photograph taken using the high-speed video camera. Each two points in white and red printed matters were selected. When the fluorescent lamps were powered by an AC 50-Hz power supply, the luminance values of pixels varied with a frequency of 100 Hz. The fluorescent lamps flicker twice during one cycle of the AC power supply. In other words, the luminance variation frequency is doubled. Some previous studies have assumed that the light comes from a white light source. They used the reflection models in which $I_x$ and $I_y$ are unaffected by specular reflection. However, the results of this study reveal that $I_x$ and $I_y$ vary even when a light source generates light that appears white, such as light from a fluorescent lamp.

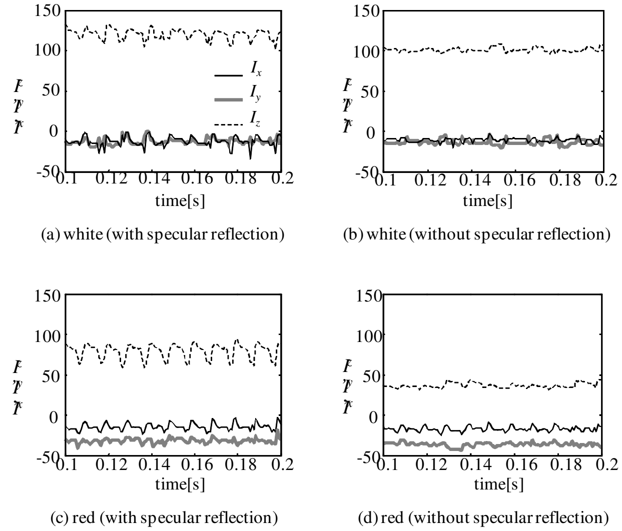



Fig. 2. Luminance variation at different points

The method presented in this paper separates and removes the specular reflection light using the dichromatic reflection model [15]. This model presents the reflection light spectrum by using a linear sum of the spectra of the specular and diffuse reflection components. The dichromatic reflection model is expressed as follows:

$$\boldsymbol{I} = \boldsymbol{I}_s + \boldsymbol{I}_d, \tag{2}$$

where $\boldsymbol{I} = (I_x, I_y, I_z)$, $\boldsymbol{I}_s$ denotes the luminance of the specular reflection component and $\boldsymbol{I}_d$ denotes the luminance of the diffuse reflection component.

### B. Method for removing reflection of AC light source[12]

Fig. 3(a) and (b) show the maximum and minimum illumination images selected from images produced by the high-speed video camera. There are few specular reflection components in the minimum illumination image (b). Although images printed on the paper under the acrylic plate are discernable by human eye, specular reflection components still remain. The following method is for estimating the effect of removing specular reflection components based on varying luminance values.

Supposing the variations in the luminance values are linear, an approximation line can be drawn to indicate the variations in the luminance values. As shown in Fig. 4, points of luminance values theoretically exist along the extended


Fig. 3. Images at maximum and minimum illuminance

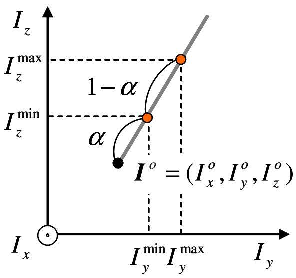



Fig. 4. Estimation of luminance without specular reflection

approximation line when the specular reflection components are zero. These points can be estimated by simple calculation.

The method obtains the luminance values $\boldsymbol{I}^{max}$ and $\boldsymbol{I}^{min}$ for maximum and minimum intensities, respectively, and extends a line between these two points. When the luminance value of the $i$th frame is $\boldsymbol{I}(i)$, the maximum and minimum intensities are calculated as follows:

$$I_z^{max} = \max_{i_p - n < i \leq i_p} I_z(i) \tag{3}$$

$$I_z^{min} = \min_{i_p - n < i \leq i_p} I_z(i). \tag{4}$$

Here, $i_p$ denotes the present frame number and $n$ denotes the number of frames used to search for the maximum and minimum values.

When $i = i_{max}$ in (3) and $i = i_{min}$ in (4), $\boldsymbol{I}_{max}$ and $\boldsymbol{I}_{min}$ are calculated using the following equations:

$$\boldsymbol{I}^{max} = \boldsymbol{I}(i_{max}) \tag{5}$$

$$\boldsymbol{I}^{min} = \boldsymbol{I}(i_{min}). \tag{6}$$

When the ratio of the minimum illumination to the maximum illumination is denoted by $\alpha$, the luminance value $\boldsymbol{I}^o$ when the illumination of a specular reflection light source is zero is calculated using the following equation:

$$\boldsymbol{I}^o = \boldsymbol{I}^{max} - \frac{1}{1-\alpha}(\boldsymbol{I}^{max} - \boldsymbol{I}^{min}). \tag{7}$$

Fig. 3(c) shows one of the examples extracted using (7). The specular reflection of a fluorescent light is clearly removed by the method. The way of setting up parameters such as $\alpha$ and $n$ are shown in [12] and [13], respectively.

### *C. Assumptions of the previous method*

The reflection removal method of AC illumination is based on the following two assumptions:

- The illumination from a specular reflection light source varies at a frequency less than half the frame rate of the camera.
- A light source other than the specular reflection light source exists and the illumination variation of this light source is not proportional to that from the specular reflection light source.

This method detects variations in a specular reflection light source and estimates the new image based on the variation. For this reason, it cannot be applied to a light source that does not have illumination variations or is undetectable due to the high frequency of the illumination variations.

Although the method with a high-speed camera is an effective solution, these assumptions provide strong limitation. Since there are many environments without AC and other light source existing together, the assumption of them is not appropriate from the viewpoint of practical use. The following section introduces a method to overcome the issue.

## III. Reflection removal method of DC illumination

### *A. Principle*

The method described in the previous section is to remove all the reflection components of AC powered light source. In other words, the method is not to decouple the specular reflection light in principle, but it is to separate the reflection light source with illumination variation and the same reflection without illumination variation in a certain frequency band.

The fact indicates the possibility of extracting reflection of AC light source instead of DC light source. When the value of reflection components of AC light source is set $\boldsymbol{I}^a$, the following equation is applicable:

$$\boldsymbol{I}^a = \boldsymbol{I} - \boldsymbol{I}^o \tag{8}$$

The value $\boldsymbol{I}^a$ always changes with the illumination of light source. The average of $\boldsymbol{I}^a$ is the image that appears to human eyes. Now, this paper assumes that the average value $\boldsymbol{I}^{a,av}$ corresponds to the middle value between max. and min. values. Then, the value $\boldsymbol{I}^{a,av}$ is calculated as follows:

$$\boldsymbol{I}^{a,av} = \frac{(\boldsymbol{I}^{max} - \boldsymbol{I}^o) + (\boldsymbol{I}^{min} - \boldsymbol{I}^o)}{2} \tag{9}$$

Substitution of (7) into (9) gives,

$$\boldsymbol{I}^{a,av} = \frac{1}{2} \cdot \frac{1+\alpha}{1-\alpha} \cdot (\boldsymbol{I}^{max} - \boldsymbol{I}^{min}). \tag{10}$$

Equation (10) gives a value that is different from the actual average value when the waveform of luminance variation of the light source is not up-down symmetric. However, (10) is applied because smooth calculation can be performed at a short time constant in comparison with the averaging or the low-pass filter, the computation cost is small, and there are

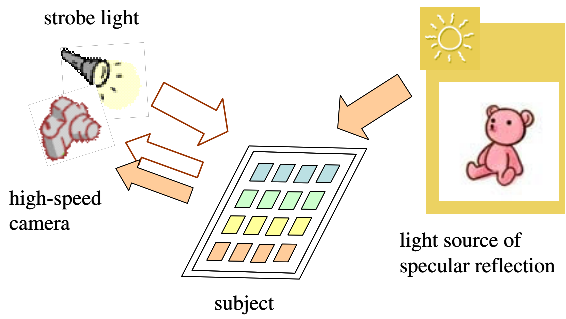



Fig. 5. Mechanism of decoupling light without any flicker

Fig. 6. Experimental system

a few problems in practical use if the error rate is uniform on all pixels.

By using (10), reflection of the DC light source can be removed as long as an AC illumination exists. Here, DC light source includes natural lights without large illumination variation, such as the sun. If AC illumination does not exist, a high-speed strobe light is required to artificially produce AC illumination. The mechanism for the abovementioned content is displayed in Fig. 5. When the light source generating the specular reflection light does not produce illumination variation, the electronic flash whose illumination varies at a short time constant is used to irradiate a subject to be photographed. The high-speed camera can get the sum of the reflection components of both light sources, so that the components of light sources are separated using the theory described above. And then, the extraction of only the reflection components of light irradiated by the electronic flash makes it possible to create an image without the specular reflection.

### B. Setup of high-speed strobe light

When the flash frequency is low, a blink of light source may give an unpleasant feeling to human eyes. However, human eyes do not detect a blink of light when the electronic flash's frequency is raised to more than some 10 Hz. Further, since the average amount of light irradiation becomes smaller for a shorter emission time, a subject can be photographed with the low-level light, momentary high-level illumination and low sensitivity to human eyes. This subsection shows the way of setting up the frequency and the duty ratio of the high-speed strobe light.

Fig. 6 shows the electronic flash and the high-speed camera, CASIO EX-F1. The electronic flash has 4 pieces of high power 10W LED connected in series and can flicker in max. 1,000Hz frequency. However, this experiment applies flickering in 200Hz frequency. It is necessary to reduce the duty ratio to avoid annoying users with the light. On the other hand, in order to offer high image quality with the lowest power strobe light, it is desirable that strobe light should be emitted continuously during the exposure time. Thus, the method of keeping the duty ratio at the lowest level without deteriorating the image quality is shown in Fig. 7.

On the experiment system, the sampling frequency of camera is 6 times the emission frequency of electronic flash. In other words, the camera produces 6 images while the electronic flash flickers 1 time. It can be said that the maximum difference of luminance can be acquired if one or more fully-illuminated and unilluminated images exist among 6 images. Assuming that the sampling time of high-speed camera is almost the same as the exposure time of that with the latter set as long as possible, the strobe light must be emitted for at least $1/f_c$ sec as the sampling time of camera. When the electronic flash and camera can be synchronized, the duty ratio to obtain the shortest emission time, $1/f_c$ sec, of strobe light is described as allows:

$$D = \frac{1}{f_c} \div \frac{1}{f_l} \tag{11}$$

Here, the value $f_l$ is the emission frequency of electronic flash.

When the electronic flash and camera cannot be synchronized, the full emission time of strobe light may not be secured depending on the shutter timing. As shown in Fig. 7, however, when the strobe light is made to emit for a certain time more than 2 times the sampling time of camera, one or more images can be always created with the strobe light surely emitted. As a result, when the electronic flash and camera are not synchronized, the lowest duty ratio is given as follows:

$$D = 2 \cdot \frac{1}{f_c} \div \frac{1}{f_l} \tag{12}$$

Since the experiment system used in this study offers the values of $f_c = 1,200$[Hz] and $f_l = 200$[Hz] without synchronization, the following equation is given:

$$D = 2 \cdot \frac{1}{1200} \div \frac{1}{200} = 33.3[\%] \tag{13}$$

### C. Comparison with Other Methods

Table II compares the features of six methods for removing specular reflections. This table shows that the proposed method overcomes the problems associated with other previously proposed methods.

## IV. Experiment

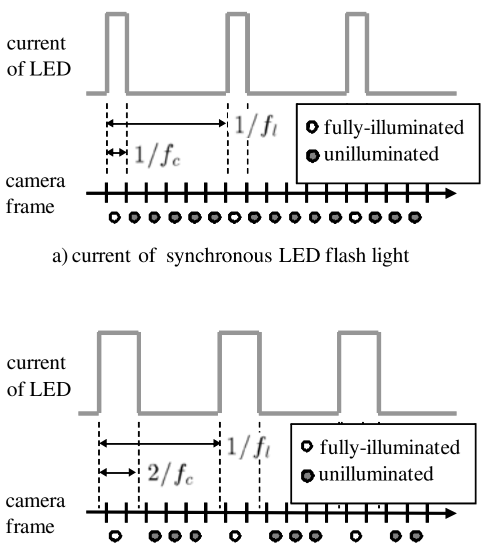
### A. Specular reflection removal of DC illumination

Fig. 8 shows the specular reflection removal result using the abovementioned camera CASIO EX-F1. In this experiment, an acrylic plate was laid on a photograph of a castle. A bear doll illuminated by a DC light source was put behind

TABLE II

COMPARISON WITH OTHER METHODS

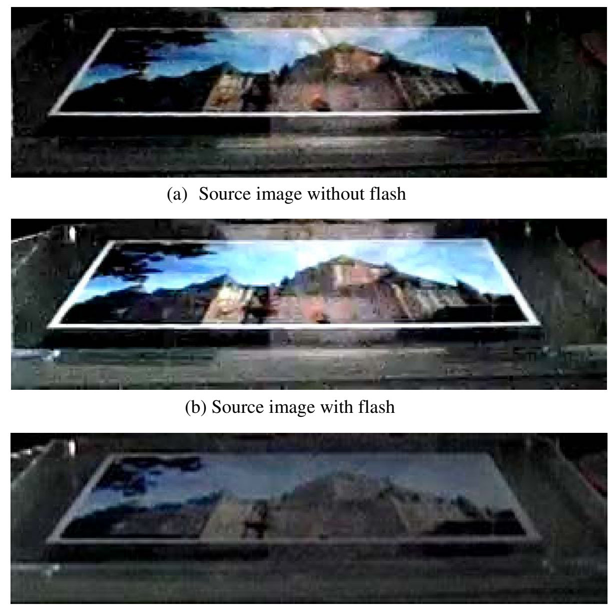
| | Angle dependency | Transferring mechanism | Estimation of achromatic color | Limitations on light source |
|---|---|---|---|---|
| Polarization filter[1] | high | unnecessary | available | small |
| Light displacement[2] | low | necessary | available | small |
| Camera displacement[3] | low | necessary | available | small |
| Estimation based on color model[4] | low | unnecessary | difficult | small |
| High-speed camera[12], [13] | low | unnecessary | available | large |
| Proposed method | low | unnecessary | available | small |




a) current of synchronous LED flash light

b) current of asynchronous LED flash light

Fig. 7. Current of LED flash light and sampling frequency



(a) Source image without flash

(b) Source image with flash

(c) Estimated image

Fig. 8. Specular reflection removal of DC illumination

the plate so that its specular reflection image appears on the plate. Both source images of Fig. 8(a) and (b) include specular reflection of a bear doll. Based on these images, an estimated image was derived by (10) as shown in Fig. 8(c). The result shows that reflection image of the bear doll disappeared without any recognizable errors.

### B. Experiment with high-resolution camera

Although the result in Fig. 8 shows specular reflection removal without recognizable errors, the image is quite grainy. There are two possible causes: low-resolution of the camera; and short exposure time. It is necessary to find out the cause since low image quality due to short exposure time may result in performance limitation of the proposed method. Therefore, an experiment of specular reflection removal is executed with a high-resolution camera. Fig. 9 shows the result. Canon EOS 7D with 2592×1728 pixels was used then. Although the camera is not a high-speed video camera, a high-speed stroboscope was simulated by using images of continuous shots. The images of 1 msec exposing time were sorted so that the images with and without flash come by rotation. The sorted sequential images are appropriate for the simulation since they are equivalent to the video acquired by a high-resolution high-speed camera as long as the object stands still.

It was confirmed that the image quality was improved by a high-resolution camera. The result indicates that the cause of the grainy image was low-resolution of the camera instead of short exposure time.

### C. Comparison with polarization filter

Fig. 10 shows the results of removing vertical reflection by the proposed method using CASIO EX-F1. Fig. 10 (c) is the estimated image without specular reflection that was derived from the maximum and minimum illuminance images (a) and (b). On the other hand, the image (d) is the result of specular reflection removal using a polarization filter. Since the incident angle is almost perpendicular to the surface, specular reflection components remained in the image (d). These results demonstrate the advantage of the proposed method over using a polarization filter. In this image, removal of specular reflections based on the dichromatic reflection model [15] is difficult since all the white pixels (which mainly correspond to the blank area on the paper) were all assessed as pixels with specular reflection.

(a) Source image with flash

(b) Estimated image

Fig. 9. Specular reflection removal of DC illumination(High resolution)

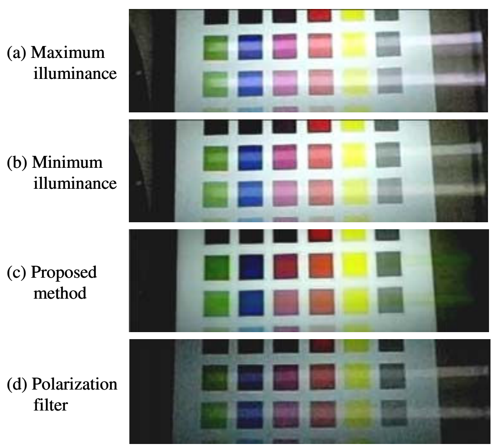



Fig. 10. Removal of vertical reflection

### *D. Evaluation of Image Processing Time*

One of characteristics of this proposed method is that the images are processed using a few samples and a simple system. It is desirable to shorten the image processing time for real-time robot vision. The results of evaluating the image processing time are presented below.

The processing time for 1,800 frames with 336×96 pixels was 10.28 s. The program was executed in Visual C++ 2005 Express Edition on a Windows-XP-based personal computer with a 3.00 GHz Intel Pentium4 CPU. Only image data reading and specular reflection removal were performed; image output on a display was not performed. The processing time for 1,800 frames was 1.57 s for image data reading operation. Therefore, the difference of 8.71 s from the frame processing time mentioned above is the time required for this proposed method. The image processing time is equivalent to 4.84 ms per frame. This result implies that hardware components such as a vision chip will be required to perform real-time processing at the same frame rate as a high-speed camera. Otherwise, real-time image processing will only be possible using a non-specialized calculation platform if the output frame-rate is reduced.

## V. Conclusion

This paper proposes specular reflection removal using a high-speed camera with a strobe light. Flickers generated by the strobe light enables specular reflection removal of not only AC but also DC light sources. Specular reflection removal of both AC and DC light sources is highly expected to improve the adaptability of robot vision systems. Furthermore, the method is appropriate for real-time systems since the method has a small computation cost. Developing a real-time vision system with FPGA or DSP is our future work.

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