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Specular Reflection Removal on High-speed Camera for Robot Vision

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Abstract— **High-speed cameras make it possible to detect luminance variations in images of a scene under AC illuminations. This paper proposes a method for estimating an image when AC illumination components are eliminated. If the eliminated illumination component is the source of specular reflection, the image produced only contains the diffuse reflection components of other illuminations. Removal of the specular reflection enhances the adaptability of a robot vision system to real environments. Experimental results show the advantage of the proposed method over using previous methods. The results also show that the method is applicable to moving objects while some errors are generated depending on the illumination frequency and the speed of the objects.**

I. Introduction

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 [1], [2]. In recent years, vision chips [3], [4] 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 [5] is a good candidate for high-performance motion control systems.

On the other hand, many researchers are also trying to find ways to overcome problems associated with high-speed cameras such as AC illumination flicker [6]. AC illumination flicker is rarely detected in human vision since human eyes have a limited sensitive frequency range [7]. Using a high-speed camera with a frame rate that exceeds this range can enable advanced image processing that surpasses human vision.

This study proposes a method for removing specular reflections by exploiting the characteristics of high-speed cameras. In the optical phenomenon of specular reflection, light incident from a single direction is strongly reflected to a single outgoing direction. Specular reflection completely depends on the light source used. It causes variations in the luminance at each pixel. Specular reflection removal is an important subject in vision because specular reflections often make it difficult to distinguish the colors of objects.

The most common method for preventing specular reflection is to use a polarization filter [8]. 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 [9] and separating the specular reflection components by changing the camera position while keeping the light source position constant [10]. 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 [11]. 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.

The method introduced in this study 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]. This paper discusses the effectiveness of this method in robot vision in comparison with previous methods. Additionally, experiments with moving objects were executed since the ability to deal with moving objects is strongly required for robot vision systems.

This paper is structured as follows. First, Section II describes the basic theory, including the definition of color space and the reflection model. Next, Section III explains how a high-speed camera can be used to measure illumination variations and describes the measurement results. Based on these results, Section IV proposes an algorithm for removing specular reflection components. Section V describes the experiments that were conducted and discusses their results. Finally, Section VI gives the conclusions.

II. Basic theory

A. Color Space

This paper applies the color space used by Miyazaki et al. [13]. 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.

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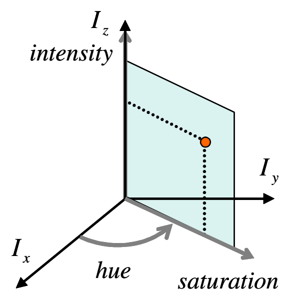


Fig. 1. Color space

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

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 study performs calculations in this color space since an intuitive color space can be obtained using a simple algorithm.

B. Reflection Model

The method presented in this paper separates and removes the specular reflection light using the dichromatic reflection model [14]. 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.

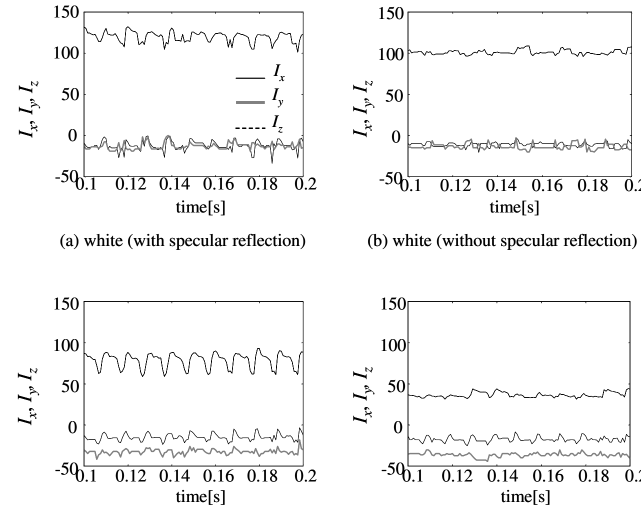
III. Taking Photographs with a High-Speed Camera

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

Experiments were performed using this camera to verify the effectiveness of the specular reflection removal method. 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.



(a) white (with specular reflection) (b) white (without specular reflection)
(c) red (with specular reflection) (d) red (without specular reflection)

Fig. 2. Luminance variation at different points

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.

IV. Method for Removing Specular Reflection Components

A. Algorithm

Fig. 3 shows 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. Therefore, this paper proposes the following method 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

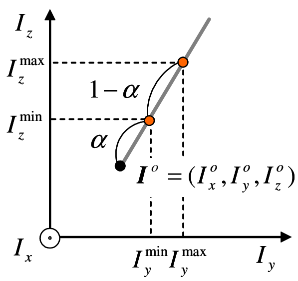


Fig. 4. Estimation of luminance without specular reflection

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

This paper 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 ith 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 α, the luminance value $\boldsymbol{I}^o$ when the illumination of a specular reflection light source is zero is calculated using the following equation:

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

The luminance value when the illumination of a specular reflection light source is zero is lower than that of the generated image. The luminance value $\boldsymbol{I}^r$ for this compensation is equal to the product of $\boldsymbol{I}^o$ and the factor β.

$$\boldsymbol{I}^r = \beta \boldsymbol{I}^o = \beta \left(\boldsymbol{I}^{max} - \frac{1}{1-\alpha} \left(\boldsymbol{I}^{max} - \boldsymbol{I}^{min} \right) \right) \tag{8}$$

If the whole screen is assumed to be uniformly illuminated, the factor β corresponds to the ratio of the actual illumination to the illumination when the specular reflection light source is unlighted.

This algorithm has a problem in that the noise is not reduced by using longer shooting times. On the other hand, it has the advantage that it requires a simple system and few samples n to estimate the value of the removed specular reflection. The maximum and minimum intensities should be searched for more than a half-cycle of the flicker. The range of n, the searching sample number, is shown as follows:

$$\frac{\omega_s}{2\omega_i} \leq n \tag{9}$$

where ω_s and ω_i denote the sampling frequency and the illumination flicker frequency, respectively.

B. Assumptions for the Proposed Method

The following two assumptions are made in this study:

- 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 can detect variations in a specular reflection light source and based on the variation, it can also estimate the luminance when the illumination is zero. 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.

If no other light source is present, the estimated luminance becomes zero in theory when the illumination from a specular reflection light source is zero. Therefore, another light source is required in addition to the specular reflection light source. When the illumination variation of this light source is proportional to that of the specular reflection light source, the estimated luminance becomes zero as well as above to give careful attention. For example, this method cannot be applied when there is a fluorescent lamp with a common power supply with the fluorescent lamp that is the specular reflection light source. In contrast, this method can be applied with different waveforms with illumination variations when an incandescent lamp with a common power source is used with a fluorescent lamp as the specular reflection light source.

C. Comparison with Other Methods

Table II compares the features of five methods for removing specular reflections. This table shows that the proposed method overcomes the problems associated with other previously proposed methods, although it is subject to the above-mentioned conditions.

TABLE II
COMPARISON WITH OTHER METHODS

	Angle dependency	Transferring mechanism	Estimation of achromatic color	Limitations on light source
Polarization filter	high	unnecessary	available	small
Light displacement	low	necessary	available	small
Camera displacement	low	necessary	available	small
Estimation based on color model	low	unnecessary	difficult	small
Proposed method	low	unnecessary	available	large

D. Noise Amplification Estimation

As mentioned in the previous section, the proposed method requires another light source in addition to the specular reflection light source. However, a lot of noise is produced when the illumination of this additional light source is low or when the two waveforms of the illumination variations are similar to each other. Furthermore, noise becomes problematic when the illumination variation of the specular reflection light source is low. Trial calculations of the effect of noise on the proposed method are performed below. The calculated errors for the luminance values $\boldsymbol{I}^{max}$ and $\boldsymbol{I}^{min}$ (i.e., the maximum and minimum values of the intensity) are denoted by $\Delta\boldsymbol{I}^{max}$ and $\Delta\boldsymbol{I}^{min}$, respectively. Equation (8) can then be extended as follows:

$$\boldsymbol{I}^{r} + \Delta\boldsymbol{I}^{r} = \beta\Bigg(\boldsymbol{I}^{max} + \Delta\boldsymbol{I}^{max} - \frac{1}{1-\alpha}\left(\boldsymbol{I}^{max} + \Delta\boldsymbol{I}^{max} - \boldsymbol{I}^{min} - \Delta\boldsymbol{I}^{min}\right)\Bigg), \quad (10)$$

where $\Delta\boldsymbol{I}^{r}$ denotes the error of the estimated value. This error is obtained by subtracting (8) from (10).

$$\Delta\boldsymbol{I}^{r} = \frac{\alpha\beta}{1-\alpha}\Delta\boldsymbol{I}^{max} + \frac{\beta}{1-\alpha}\Delta\boldsymbol{I}^{min} \quad (11)$$

Equation (11) indicates that noise is amplified when α is close to 1 and β is large.

E. Error Generated by Moving Objects

The proposed method estimates each luminance value under the assumption that each pixel detects the same point on the object in all n searching frames. Therefore, the method may produce some errors with a video with moving objects. The principle of the error generation is quite similar to that of the well-known frame difference method [16]. Since the frame numbers i_{max} and i_{min} are always different, (8) includes the function of the frame difference method and the function generates errors in the present method. The range of absolute difference between i_{max} and i_{min} are shown as follows:

$$\frac{\omega_s}{2\omega_i} \leq |i_{max} - i_{min}| \leq n. \quad (12)$$

(a) Minimum illuminance ($\alpha = 0.0$)
(b) $\alpha = 0.3$
(c) $\alpha = 0.5$
(d) $\alpha = 0.7$

Fig. 5. Specular reflection removal results

As the frame difference is smaller with shorter sampling period, the affect of the error depends on the illumination flicker frequency ω_i. The affect also depends on the speed of the moving object.

V. EXPERIMENT

A. Using a Fluorescent Lamp

Experiments for removing the specular reflection of a fluorescent lamp were conducted in a bright environment illuminated by sunlight using the proposed method. Fig. 5 shows the experimental results. The actual image (a) was produced at the minimum illumination of the specular reflection light source and is equivalent to the experimental result using $\alpha = 0.0$. The estimated images (b), (c) and (d) were created by setting $\alpha = 0.3, 0.5$ and 0.7, respectively. The factor β was set to 1.0 in all the experiments. It was found that little specular reflection light remains when $\alpha = 0.3$, and that specular reflection light is not visible when $\alpha = 0.5$ and it is removed almost completely. It seems that excessive compensation was performed because a point where specular reflection is generated has a low luminance and it is black when $\alpha = 0.7$. It was confirmed that the specular reflection light can be completely removed by selecting an appropriate value of α. The details of the setting of α is described in [12].

Fig. 6 shows the result of edge detection [15] on an image that contains specular reflection. To detect an edge, an output absolute value of a differential filter was calculated for every axis in color space and binary conversion was performed based on the sum of the calculated values. A Laplacian filter was adopted as the differential filter. An edge caused by specular reflection was detected in an image to which the proposed method was not applied. However, it was confirmed that edges of printed material could be correctly detected even at places where specular reflection is present in an image to which the proposed method is applied.

(a) without removal of specular reflection

(b) with proposed method

Fig. 6. Edge detection results

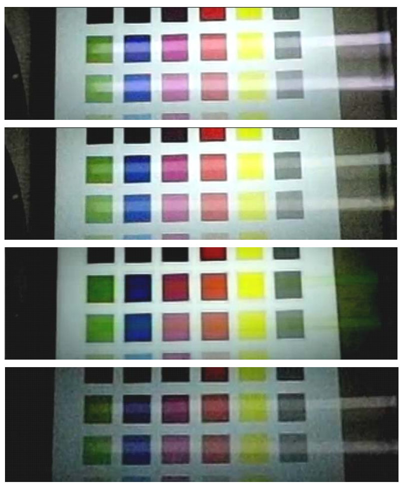


Fig. 7. Removal of vertical reflection

Fig. 7 shows the results of removing vertical reflection by the proposed method. Fig. 7 (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 [14] 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.

B. Using an Incandescent Lamp

Experiments to remove the specular reflections from a 100 W incandescent lamp were conducted in the same environment. Fig. 8 shows the results of these experiments. The factor β was set to 1.0 in all experiments. The actual image (a) was produced at the minimum illumination. As shown in the image (b), the specular reflection was almost totally removed when $\alpha = 0.85$. However, a little specular reflection remained from the filament of the incandescent lamp, which always emits light. Since the incandescent lamp is heat driven, the illumination variations are small. For this reason, it is necessary to make the value of α close to 1. However, noise increases as the value of α approaches 1, deteriorating the image quality.

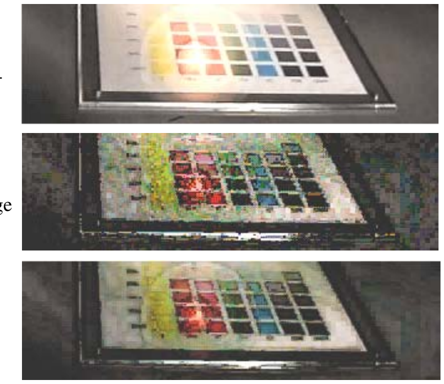


Fig. 8. Results for an incandescent light

The noise in many images obtained by the high-speed camera can be controlled by applying a low-pass filter (LPF) to the time axis.

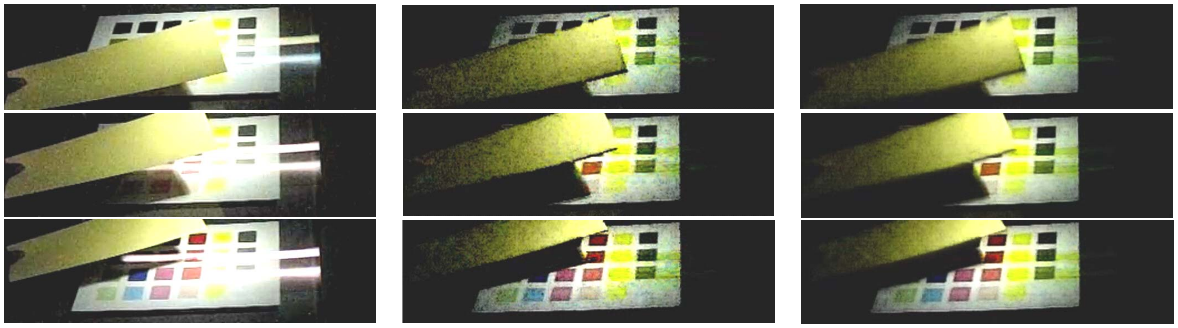
$$\boldsymbol{I}^f(i) = \boldsymbol{I}^f(i-1) + \frac{g}{t_s}(\boldsymbol{I}^r(i) - \boldsymbol{I}^f(i-1)), \tag{13}$$

where $\boldsymbol{I}^f(i)$ denotes the output of the ith sample with an LPF, g denotes the cutoff frequency of the LPF and t_s denotes the sampling time.

Fig. 8(c) shows the noise reduction result. The result indicate that an LPF improves the image quality, although this necessitates using a longer shooting time.

C. Affect of a Moving Object

Fig. 9 shows the result when a piece of yellow paper got across the visual field of the camera at about 0.3 m/s. The source images with specular reflection components are shown in Fig. 9(a). Fig. 9(b) shows the estimated images without specular reflection components. Fig. 9(c) shows the noise reduction images using an LPF. α and the cutoff frequency of the LPF g were set to 0.7 and 12.0 rad/s, respectively. The estimated images show that the method is applicable for moving objects while it produces some errors. The errors are seen as the blackened edge of the yellow paper in Fig. 9(b) and (c). The blackened area corresponds to the area detected by the frame difference method at a sampling frequency of ω_s/n. In this experiment, a portion of the specular reflection components remained in the estimated image since the pixels corresponding to the specular reflection light source were overexposure. The result implies that the method requires exposure adjustment for accurate estimation.



(a) source images (b) estimated images (c) estimated images with an LPF

Fig. 9. Results with a moving object

D. Evaluation of Image Processing Time

As described in Section IV-A, 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 was 10.28 s for a program 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 filtering and image output on a display were 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. Based on this, it is estimated 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.

VI. Conclusion

This paper proposes a method for removing specular reflections by utilizing the characteristics of high-speed cameras. Based on the luminance variations of pixels, it estimates the colors of pixels when a specular reflection light source is unlighted. Since no specular reflection component is included in the pixel values when the light source is unlighted, an image with only diffuse reflection light is obtained. The proposed method enabled specular reflection light to be removed using a single camera without moving the light source or the camera in actual experiments. Experimental results show the advantage of the proposed method over using previous methods. The results also show that the method is applicable to moving objects while some errors are generated depending on the illumination frequency and the speed of the objects.

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