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Crosstalk Coefficient Estimation for Three-Wavelength Single-shot Interferometry by Model Fitting Technique

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Crosstalk compensation is an essential technique in three-wavelength single-shot interferometry which uses a commercially available RGB LED illuminator and a color camera in the imaging system. To estimate the crosstalk coefficient more easily than the conventional method, we have developed a new method which does not require three images. Instead, it estimates the coefficients from a single image by fitting the observed RGB data to a model function which is derived from a crosstalk model and an interference model. The test results agreed well with those by the conventional method.

Key words: crosstalk coefficients, crosstalk compensation, three-wavelength, interferometry, single-shot

1. Introduction

The surface profile measurement method based on optical interference is widely used in industry as an ultra-high-precision three-dimensional measurement method, but there is a problem that the accuracy is greatly reduced in an environment with disturbance such as vibration. As a solution to this problem, a single-shot interferometry method called the spatial carrier fringe method [1)-7)] has been proposed in which the reference plane is tilted and carrier fringes are introduced to obtain the three-dimensional shape from a single fringe image (**Fig. 1**). The surface shape can be obtained from one interference fringe image obtained by this method by the Fourier transform method [2)], the spatial phase synchronization method [3)~5)], the local model fitting method [6) 7)], etc.

However, this method has a problem that the measurement range is narrow because the step between adjacent pixels is less than 1/4 of the light source wavelength when the height is obtained from the obtained phase. To solve this problem, the authors have proposed a multi-wavelength single-shot measurement method and succeeded in measuring a 350 nm step

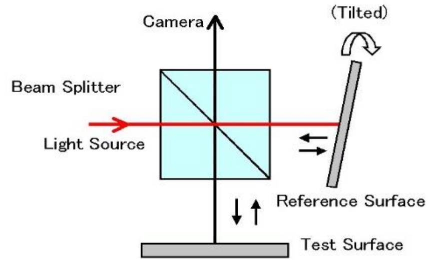

Fig. 1 Optics of spatial carrier method.

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Fig. 2 RGB-LED illuminator.

difference [8)9)] for two wavelengths and a 1μm step difference for three wavelengths. [10)11)].

The imaging system consists of a commercially available 3-color LED lighting device (CCS, model HLV-3M-RGB-3W) and a color camera (Bastler, model sca640 -70gc) shown in **Fig. 2**. The LED peak wavelengths (catalog value) are 470 nm, 530 nm, and 627 nm.

Figure 3 shows the spectral sensitivity characteristics of the color camera used and the peak wavelengths of the three LEDs. When these three LEDs are turned on and a color camera is used for imaging, a three-wavelength interference image is obtained. However, since the R, G, B spectral sensitivity curves of the camera overlap each other,

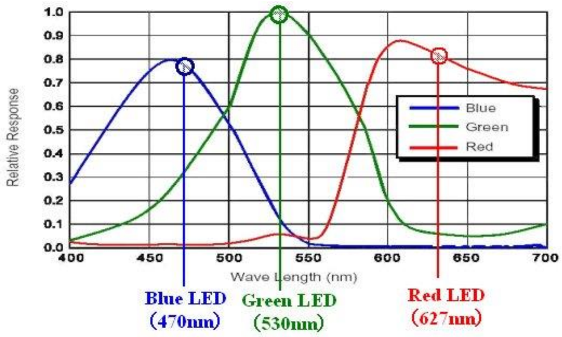

Fig. 3 Spectral sensitivity of the color CCD camera, with the peak wavelengths of three LEDs.

crosstalk occurs between each signal. In particular, the crosstalk from the B wavelength component to the G signal is estimated to be several tens of percent, and crosstalk compensation is necessary.

The author applied the concept of crosstalk compensation reported in the field of three-dimensional measurement by color projection method [12-16] to single-shot interferometry, and proposed the crosstalk compensation method[17] described below.

It is assumed that crosstalk is represented by the following linear model.

$$\begin{pmatrix} B' \\ G' \\ R' \end{pmatrix} = \begin{pmatrix} 1 & a & b \\ c & 1 & d \\ e & f & 1 \end{pmatrix} \begin{pmatrix} B \\ G \\ R \end{pmatrix} \quad (1)$$

where B', G', R' are the observed intensity values, B, G, R are the true values, and a, b, c, d, e, f are the coefficients representing the crosstalk. Then the true values can be calculated by the following equation.

$$\begin{pmatrix} B \\ G \\ R \end{pmatrix} = \begin{pmatrix} 1 & a & b \\ c & 1 & d \\ e & f & 1 \end{pmatrix}^{-1} \begin{pmatrix} B' \\ G' \\ R' \end{pmatrix} \quad (2)$$

For the above-mentioned crosstalk compensation, it is necessary to obtain the crosstalk coefficients in advance. However, the authors have used a method of obtaining the coefficients from three images obtained by individually turning on the illumination.[17] Let's call this method as the conventional method, or the individual lighting method. However, this method has some problems described in Section 2.3, and we have developed a new coefficient calculation method called the "all lamp lighting method".

In this paper, Section 2 describes the conventional method of calculating the crosstalk compensation coefficient, and Section 3 proposes a new method.

2. Conventional method

2.1 Algorithm

Three color images are captured separately by turning on the illumination of each wavelength individually. Then they are color-decomposed. By a regression analysis of the RGB values, we can obtain the crosstalk coefficients. The details of this method will be shown in the next section.

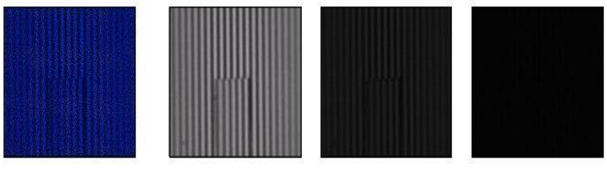

Fig. 4 Captured color image with B-LED on, and its decomposited B,G,R images.

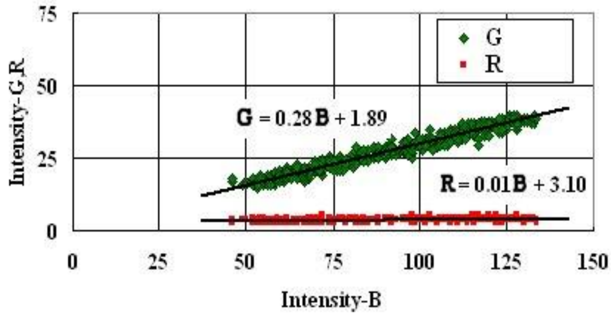

Fig. 5 Correlation among the RGB values.

2.2 Experimental results

Figure 4 shows a color image obtained by turning on the blue LED only with the 1μm standard step as the target surface and the BGR component images obtained by the color decomposition. From the R, B, and G values at each pixel on the y=120 line at this image (512 × 480 pixels), the correlation diagram of B, G, and R can be obtained as shown in **Fig. 5**. From the regression coefficient, we obtained c = 0.28 and e = 0.01 as the crosstalk coefficients. From similar experiments, by turning on the other LEDs, the coefficient matrix shown in Eq. (3) was obtained. This agrees with the value expected from the spectral characteristics in Fig. 3. In addition, we reported in the previous paper [17] that the crosstalk is effectively compensated using these coefficients.

$$\begin{pmatrix} 1 & a & b \\ c & 1 & d \\ e & f & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0.05 & 0.00 \\ 0.28 & 1 & 0.04 \\ 0.01 & 0.04 & 1 \end{pmatrix} \quad (3)$$

2.3 Problems of the conventional method

The conventional method has two problems. First, it is necessary to turn on the lights individually, capture three images, and perform a regression analysis of their intensity, which is troublesome. Second, it cannot be applied to an illumination system that cannot be individually lit, such as an illumination system [18] that uses a multi-wavelength band filter†1. In order to solve these problems, we use only a single color image obtained by turning on all the lights.

In the next section, we propose a method for collectively obtaining all crosstalk coefficients.

† 1 A multi-wavelength band-pass filter (Multi-Bandpass Filter) is commercially available. It uses multilayer thin-film interference, and can realize a multi-wavelength lighting system with a simple configuration, combined with one white lighting device such as a halogen light source.

3. New method

3.1 Algorithm

In a three-wavelength single-shot interferometer, all three illuminations are turned on, and a sample with a flat region is selected as the measurement target.[† 2] Then, it can be assumed that the DC component α, the interference amplitude γ, the phase ϕ, and the frequency f (these are called the waveform parameters) of the interference fringes are constant in the flat region, so the intensity $B(x)$, $G(x)$, and $R(x)$ at the point x on the line are represented by the following interference fringe model, assuming there is a carrier fringe in the x direction.

$$\begin{cases} B(x) = \alpha_B + \gamma_B \cos(\phi_B + 2\pi f_B x) \\ G(x) = \alpha_G + \gamma_G \cos(\phi_G + 2\pi f_G x) \\ R(x) = \alpha_R + \gamma_R \cos(\phi_R + 2\pi f_R x) \end{cases} \tag{4}$$

Substituting equation (4) into equation (1), the observed intensity at coordinate x is expressed by the following equation using the waveform parameters and crosstalk coefficients.

$$\begin{cases} B'(x) = \{\alpha_B + \gamma_B \cos(\phi_B + 2\pi f_B x)\} \\ \qquad + a\{\alpha_G + \gamma_G \cos(\phi_G + 2\pi f_G x)\} \\ \qquad + b\{\alpha_R + \gamma_R \cos(\phi_R + 2\pi f_R x)\} \\ G'(x) = c\{\alpha_B + \gamma_B \cos(\phi_B + 2\pi f_B x)\} \\ \qquad + \{\alpha_G + \gamma_G \cos(\phi_G + 2\pi f_G x)\} \\ \qquad + d\{\alpha_R + \gamma_R \cos(\phi_R + 2\pi f_R x)\} \\ R'(x) = e\{\alpha_B + \gamma_B \cos(\phi_B + 2\pi f_B x)\} \\ \qquad + f\{\alpha_G + \gamma_G \cos(\phi_G + 2\pi f_G x)\} \\ \qquad + \{\alpha_R + \gamma_R \cos(\phi_R + 2\pi f_R x)\} \end{cases} \tag{5}$$

The crosstalk coefficients can be obtained by fitting the observed intensity model and the measured data, that is, by solving the least squares problem with the following equation as the evaluation function.

$$J = \sum_{i=1}^{n} \left[\{B_i - B'(x_i)\}^2 + \{G_i - G'(x_i)\}^2 + \{R_i - R'(x_i)\}^2 \right] \tag{6}$$

where n is the number of data and B_i, G_i, R_i $(i = 1, n)$ is the observed intensity value at coordinate x_i. In addition, there are a total of 18 unknown parameters: the waveform parameters for each wavelength α_j, γ_j, ϕ_j, f_j (j = B,G,R) and the crosstalk coefficients $a, \ldots, f$. In order to obtain these 18 parameters, 18 or more observed intensity data are needed, which means that the number of data n must be 6 or more.

3.2 Experimental method and results

An attempt was made to calculate the crosstalk coefficients using an image (**Fig. 6**) obtained by three-wavelength single-shot imaging of a 1μm standard step sample. As the observed intensity values, the data of ±100 pixels (data number n = 201) in the center position on the y = 120 line was used.

The data are shown in **Fig. 7**. For the nonlinear least-squares fitting, the Solver, which is an optimization tool of Microsoft Excel 2003, was used. The initial values of the crosstalk coefficients were all zero, and the initial values of the waveform parameters were visually estimated from the waveform in Fig. 7.

Figure 8 shows the fitted values. There is a good agreement with the observed values (Fig. 7), indicating that the matching was performed correctly. the obtained crosstalk coefficients

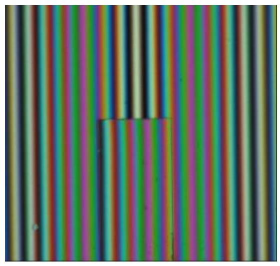

Fig. 6 Captured color image.

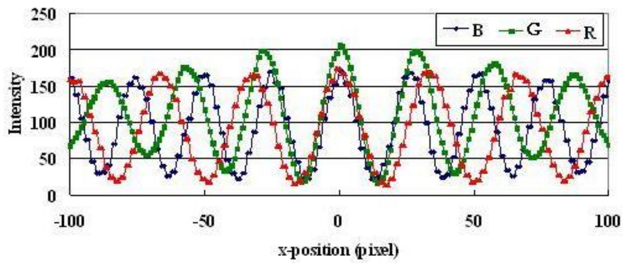

Fig. 7 Observed intensities.

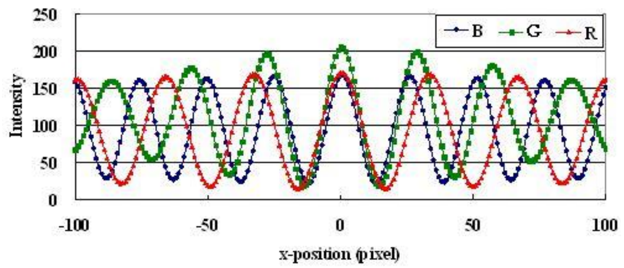

Fig. 8 Fitted values of intensities.

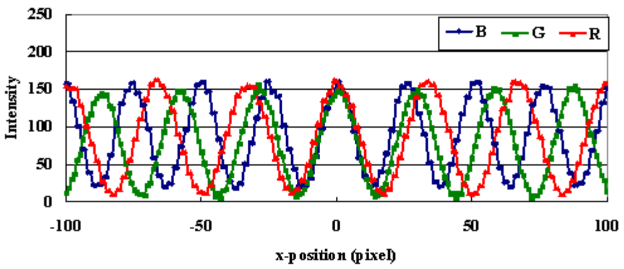

Fig. 9 Crosstalk-compensated intensities.

† 2 Crosstalk is a device constant that depends on the illumination and imaging system, and does not depend on the sample. Therefore, for estimating the coefficients, any sample can be selected.

$a,\ldots,f$ are shown in Eq. (7), and **Table 1** shows the obtained waveform parameters α_j, γ_j, ϕ_j, f_j (j = B,G,R).

$$\begin{pmatrix} 1 & a & b \\ c & 1 & d \\ e & f & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0.05 & 0.00 \\ 0.30 & 1 & 0.04 \\ 0.00 & 0.06 & 1 \end{pmatrix} \tag{7}$$

Table 1 Obtained waveform parameters.

	B	G	R
α	90	80	87
γ	69	71	74
ϕ	-0.15	-0.07	-0.09
f	0.0394	0.0344	0.0300

The obtained coefficients almost agree with the result of the single lighting method shown in Eq. (3), which shows the validity of the proposed method. **Figure 9** shows the corrected intensity (true intensity) obtained from Eq. (2). The intensity waveform of each wavelength is almost sinusoidal, and the effect of crosstalk compensation is apparent.

4. Summary

We proposed a new crosstalk coefficient estimation method for three-wavelength single-shot interferometry. This method estimates all crosstalk coefficients collectively by making a least squares fit of a model function derived from a crosstalk model and an interference model to the intensity data of one color image obtained by turning on the three wavelength light source. When it was applied to an imaging system with a 3-color LED lighting device and a color camera, good results were obtained and the validity of the proposed method was confirmed. Compared with the conventional method of turning on the light source individually, it is easy to operate and can be applied even to an illumination system that is difficult to turn on independently.

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