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Imaging rotational motion sensor for real-time multiple object observation

Hyo Bin Jeong[1], Jong-Kyu Park[1], Daewook Kim[2] and Ki-Nam Joo[1,#]

[1]*Department of Photonic Engineering, Chosun University, 309 Pilmun-daero, Dong-gu, Gwangju 61452, South Korea*
[2]*Wyant College of Optical Sciences, University of Arizona, 1630 E. University Blvd, Tucson, Arizona 85721, USA*

[#]*Corresponding author: knjoo@chosun.ac.kr*

Abstract
In this investigation, we propose an imaging sensor to monitor the rotational motions of several objects at once. This imaging sensor can interpret the polarized images by a polarization pixelated CMOS camera, and calculate the rotation angles. Based on the simple optical configuration using a polarization pixelated CMOS, the proposed sensor has the unique feature to monitor the rotational motions of several objects at once. In order to verify the performances, the rotation angles were measured and, the nonlinear errors were estimated less than ±0.02° with the compensation of the periodic errors. In addition, the proposed sensor was used for monitoring the clocking motions of several objects or segmented mirrors at once.

Keywords: Imaging rotational motion sensor, polarization pixelated camera, clocking motion

1. Introduction

The rotational motion metrology is very important to find out the rotational positions of the objects such as mechanically assembled components [1] and robotics [2]. Also, for the extremely large next-generation space telescope missions, off-axis segmented optical mirrors must maintain their clocking motion including translational motions [3].

Optical sensors are very useful to be applied for dynamic and static applications because they can precisely measure the rotational motions via non-contact approaches. Moreover, they are not sensitive to electromagnetic noise caused by the unit under test itself. As multiple measurement objects are added, however, the number of the sensor system should increase.

On the other hand, the polarization of the light is a very useful feature to divide, recognize and measure the light in optical system. One of the interesting phenomena is that the intensity of the light can be reduced by a polarizer.

In this investigation, we propose an instantaneous imaging sensor to monitor the rotational motions of several objects at once. This imaging sensor can obtain the polarized images by a polarization pixelated CMOS camera, and determine the clocking angles.

2. Principle

Figure 1 shows the optical layout of an imaging rotational motion sensor proposed in this investigation. A randomly polarized light from a LED is reflected off by a beam splitter (BS) after passing through a collimating lens (CL). The reflected light goes toward a linear polarizer (P) attached to a rotating object and reflected off by the P. In this case, the polarization status of the light is orthogonal to the transmission axis of the P and the light is captured by a polarization pixelated CMOS camera (PCMOS). In PCMOS, four kinds of polarizers with of the transmission axes of 0°, 45°, 90° and 135°, respectively, as an array format are located in front of an imaging sensor [4] as shown in the inset of Fig. 1.

The whole images obtained by the PCMOS can be divided into four images, and they are mathematically described as [5]

$$
\begin{aligned}
I_0 &= I_i cos^2(\varphi) = (I_i/2)[1 + cos\,(2\varphi)] \\
I_{45} &= I_i cos^2(45° - \varphi) = (I_i/2)[1 + sin\,(2\varphi)] \\
I_{90} &= I_i cos^2(90° - \varphi) = (I_i/2)[1 - cos(2\varphi)] \\
I_{135} &= I_i cos^2(45° + \varphi) = (I_i/2)[1 - sin\,(2\varphi)]
\end{aligned}
\qquad (1)
$$

where I_i and φ are the irradiance and the polarization angle of the light incident to the PCMOS, respectively. The polarization angle φ means the rotation of the P. I_0, I_{45}, I_{90}, and I_{135} are the irradiances of the light transmitted through four kinds of polarizers. From Eq. (1), φ can be calculated as

$$\varphi = tan^{-1}[(I_{45} - I_{135})/(I_0 - I_{90})]/2. \qquad (2)$$

In the imaging rotational motion sensor, the polarization angle of the P can be directly obtained by using Eq. (2) and is not affected by the optical power fluctuations of the optical source.

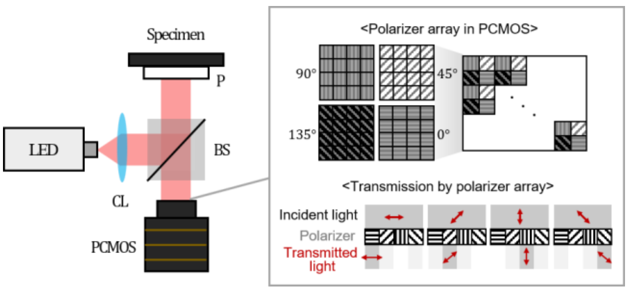
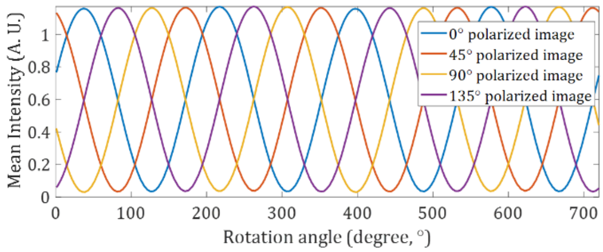


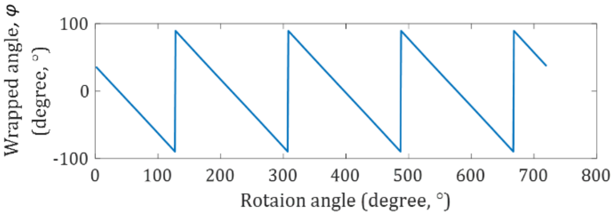
Figure 1. Optical layout of an imaging rotational motion sensor; CL, collimating lens; BS, beam splitter; P, linear polarizer; PCMOS, polarization pixelated CMOS camera. The inset describes an inner polarizer array of the PCMOS, and its transmission functionality.

3. Experimental results

To verify the performances of the sensor, feasibility tests were implemented. A white LED was used as an optical source, and a commercial PCMOS (PHX050S-PC, Lucid) with (2448 x 2048) pixels captured the whole image and divided it into four images. A linear polarizer was attached to stepping motorized rotary stage (K401-60M@Suruga Seiki) and rotated for 720° with 1° step. As shown in Fig. 2(a), the mean intensity variations of four polarized images are phase-shifted with π/2 as predicted in Eq. (1), and the rotation angles were calculated as shown in Fig. 2(b) by Eq. (2).



(a)



(b)

Figure 2. (a) Mean intensity variations of four polarized images along the rotation of the polarizer and (b) wrapped angle (φ).

As shown in Fig. 2(b), the wrapped angle had the period of 180°, which means the measurement resolution is twice better than the real rotation angle of the P as expected in Eq. (2). With the aid of phase-unwrapping, the measured rotation angles well agreed with those of the P, clockwisely rotated, as the linear slope of -1.00003. However, the measurement results contained a periodic errors caused by the unexpected reflections of light from the surfaces of optical components such as the BS and the P, which were not represent the rotational polarization of the light. This systematic errors were measured preliminary as shown in Fig. 3, and used for the compensation of the measurement result [5]. AS the result, the errors were less than ±0.02°, and their standard deviation was 0.006°.

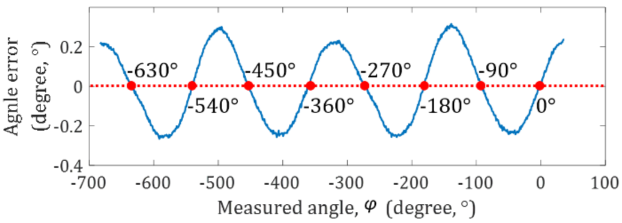


Figure 3. Periodic error versus measured rotation angle (ϕ) with zero crossing points.

The proposed sensor was used to confirm the rotational alignment status of several objects as an example of the segmented mirror alinment as shown in Fig. 4. The rotations of these several segments are not easy to be practically inspected or measured with the conventional techniques. However, our imaging rotational motion sensor has the capability to monitor the rotation of the segmented mirrors. A small piece of polarizing film was attached on the edge portion of each segmented mirror, and the PCMOS obtained the whole image of the mirrors, where the rotational angle of each mirror was caluculated. As the result, the mirrors were relatively rotated, and their relative rotation angles were also calculated as -11.4°, -21.1°, 17.8° and -12.3°, respectively. After adjustment of the rotations, the mirrors were able to be properly aligned within 0.1° as shown in Fig. 4(b).

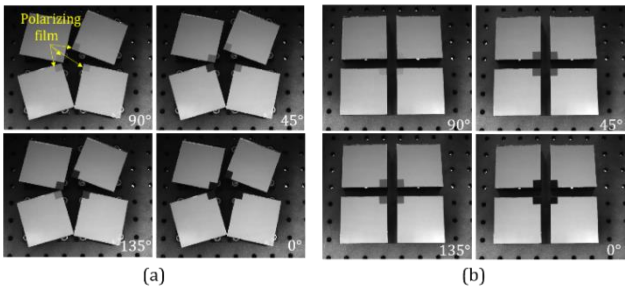


Figure 4. Four segmented mirrors with (a) the rotational misalignments and (b) the proper alignments.

As another application example, an arbitrary flow motion was monitored by the proposed sensor with small pieces of polarizing films on the water. In the typical image as shown in Fig. 5(a), the rotational motions of the film pieces were not easy to be monitored, but they were conveniently imaged by the proposed sensor, where the color indicated the rotation angles as shown in Fig. 5(b).

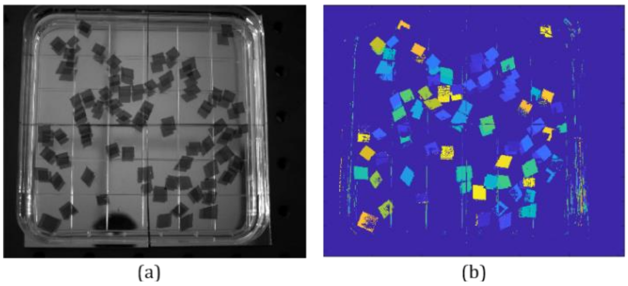


Figure 5. (a) Image and (b) rotational angle of polarizing film pieces by random water flow.

4. Conclusion

In conclusion, we proposed and experimentally verified an imaging rotation sensor. Based on the simple optical configuration using a polarization pixelated CMOS, the proposed sensor has the unique feature to monitor the rotational motions of several objects at once although small pieces of polarizer should be attached on the specimens. In order to verify the, the rotation angles were measured and, the application example were provided. With the aid of other 3D imaging techniques, it can be used for 3D rotational motion sensors because the proposed sensor is based on 2D polarized images. It will be further investigated as a combined measurement technique.

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