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Rapid underwater target enhancement method based on polarimetric imaging ☆

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ABSTRACT

Polarization-difference imaging (PDI) is an effective method for underwater image enhancement. Normally, the key factor of utilizing PDI is the choice of the optimal orthogonal transmission axes of analyzer. This limits the application range and implementation efficiency of PDI. Guided by the theory of PDI and the polarization component analysis of the veiling light, we simplified the implementation of PDI. In the modified method, without the analyzer rotation, the polarization-difference image could be obtained on the basis of the Stokes vector. The experimental results indicate that the contrast obtained by the method presented here is consistent with the contrast obtained by conventional PDI. Besides, the modified method could be beneficial to rapid imaging by combining with the imaging polarimetry.

1. Introduction

Underwater target detection is a challenging problem because of optical absorbing and scattering caused by suspended particles. Absorbing weakens the intensity of the object light reflected from the target. Meanwhile, scattering randomizes the phase and the propagation direction of the object light. In addition, the veiling light backscattered from the medium in front of the target plane superimposes on the object light, which usually results in diffusive background in the target image. All of these effects degrade the visibility of the image. Among them, scattering is the critical factor that limits the image quality. In order to enhance the image contrast, several imaging methods have been developed to mitigate the effects of scattering. Time gating [1,2], holographic imaging [3], frequency-domain amplitude modulation [4], and confocal detection technique [5] were usually used to discriminate the object information and obtain the high contrast images. Nevertheless, these techniques are more complex and difficult to implement generally. Therefore, the techniques that can be easily deployed have attracted increasing interest.

Recently, researchers have paid extensive attention to the fact that polarization imaging provides more information than intensity imaging [6,7]. Consequently, polarization imaging has been widely used to improve the underwater target detection performance due to simple operation, which is also used for enhancing degraded images resulted from the effects of haze [8–10]. Up to now, many efforts about polarization-based optical imaging have been done to enhance the target contrast. A series of polarization-based imaging methods were used to reduce the unwanted light and improve the image quality. Polarization gating imaging improves the contrast by selecting appropriate polarization state based on the difference in polarization of the object light and of the veiling light [11–15]. The image quality is seen to be much better in the co-polarized component for linearly polarized incident light and in the cross-polarized component for circularly polarized incident light. Polarization-degree imaging [16,17] takes advantage of the different polarization behaviors of the light undergoing different scattering processes. It can identify the image regions that have the same intensity distributions but different polarimetric properties. Mueller matrix imaging can be effectively used for target detection [18–20] because the Mueller matrix can describe the light scattering process and each element of the matrix represents the polarization characteristics of the target and the medium. Additionally, the physical model of underwater image formation has been proposed for target detection by use of polarization [21]. Based on the model, the method that takes into account the polarization of the veiling light and of the object light has been utilized to recover the object signal [22,23].

In particular, a typical imaging method is polarization-difference imaging (PDI) which captures images through a linear

☆ Fully documented templates are available in the elsarticle package on CTAN.

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analyzer at two orthogonal directions and calculates their difference [24]. In order to enhance the contrast, the optimal orthogonal transmission axes of the analyzer must be selected to make the projections of the veiling light onto the two orthogonal axis directions equal [25]. This operation can suppress the veiling light and reserve the object light. However, the selection of the optimal axes is time-consuming and inconvenient by rotating the analyzer mechanically. As a result, it is not suitable for rapid imaging and moving object detection in practical applications. In this paper, we optimize PDI and propose a modified polarization-difference imaging method (M-PDI) based on the polarization component analysis of the veiling light and the Stokes vector which can be easily obtained simultaneously in many ways [26–29]. This makes the implementation of PDI so convenient that rapid imaging could be realized. The theoretical analysis of M-PDI is detailedly presented in Section 2. The experimental setup is given in Section 3. The experimental results and discussion are presented in Section 4 while the conclusions are reported in Section 5.

2. Theoretical analysis

The light into a detector contains the veiling light and the object light. PDI makes use of the difference in the polarization orientation angles of these two kinds of light [25], as shown in Fig. 1. In order to obtain a clear image of the target, the two angles between the polarized direction of the veiling light and the optimal orthogonal transmission axis directions of the analyzer are 45°. Then, two intensity images emerging from the analyzer are registered. When the transmission axis is parallel to $\parallel$, the image intensity obtained is represented by $I_{\parallel}$. Correspondingly, when the transmission axis is parallel to $\perp$, the image intensity obtained is represented by $I_{\perp}$. Under this condition, the intensities of the components of the veiling light in the orthogonal axis directions ($I_{\parallel}(\mathrm{B})$ and $I_{\perp}(\mathrm{B})$) are nearly equal. Thus, the intensity of the veiling light obtained by PDI ($I_{pd}(\mathrm{B})$) is suppressed by subtracting $I_{\perp}(\mathrm{B})$ from $I_{\parallel}(\mathrm{B})$, which can be expressed as

$$I_{pd}(\mathrm{B}) = I_{\parallel}(\mathrm{B}) - I_{\perp}(\mathrm{B}) = 0. \tag{1}$$

Meanwhile, the object signal obtained by PDI ($I_{pd}(\mathrm{T})$) is shown as

$$I_{pd}(\mathrm{T}) = I_{\parallel}(\mathrm{T}) - I_{\perp}(\mathrm{T}) = I(\mathrm{T})\sin 2\beta, \tag{2}$$

where $I_{\parallel}(\mathrm{T})$ and $I_{\perp}(\mathrm{T})$ are the intensities of the components of the object light in the orthogonal axis directions, $I(\mathrm{T})$ is the total intensity of the object light, and β represents the difference between the orientation angles of the veiling light and the object light. Consequently, the image intensity obtained by PDI (I_{pd}) is expressed as

$$I_{pd} = I_{pd}(\mathrm{B}) + I_{pd}(\mathrm{T}) = I(\mathrm{T})\sin 2\beta. \tag{3}$$

The foregoing analysis yields that the implementation of PDI depends on the optimal transmission axes of the analyzer which are determinated by the polarized direction of the veiling light. However, it is impossible to estimate the direction before starting the experiment. Therefore, we usually have to rotate the analyzer mechanically until the optimal transmission axes are obtained in actual application. This is a brief review of the theory and the regular method for the implementation of PDI. Next, based on the theory of PDI, the principle of the modified method will be detailedly introduced.

It is known that any polarization state of light could be completely described by the Stokes vector and the interaction of an incident polarized beam with a polarizer that can change its polarization state is characterized by a Mueller matrix [30]. The Mueller matrixes for the linear analyzer with the transmission axis in the optimal orthogonal directions shown in Fig. 1 could be calculated respectively.

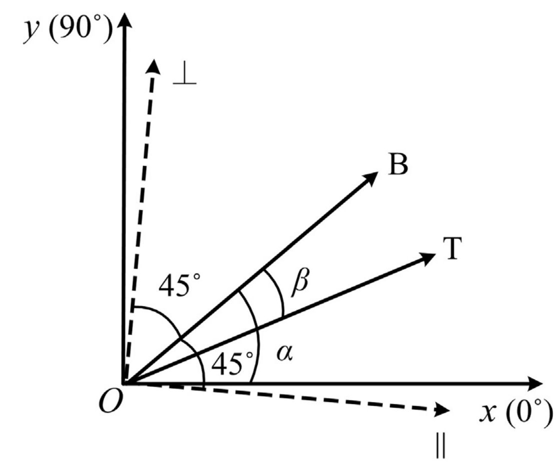

Fig. 1. Schematic diagram of polarization-difference imaging. T: the object light. B: the veiling light. $\parallel$ and $\perp$ represent the optimal orthogonal transmission axis directions of the analyzer. α: the polarization orientation angle of the veiling light. β: the difference between the polarization orientation angles of the veiling light and the object light. The directions of 0° and 90° are defined as the x axis and the y axis.

The Stokes vector of the object light is characterized by $S(\mathrm{T})$ = [$I(\mathrm{T})$ $Q(\mathrm{T})$ $U(\mathrm{T})$ $V(\mathrm{T})$] and that of the veiling light is represented as $S(\mathrm{B})$ = [$I(\mathrm{B})$ $Q(\mathrm{B})$ $U(\mathrm{B})$ $V(\mathrm{B})$]. Then the Stokes vectors are calculated respectively, which describe the object light and the veiling light emerging from the linear analyzer with the transmission axis along the optimal orthogonal directions. It is noted that we are interested in the first Stokes parameter that represents the total intensity of the light in PDI. Thus, the intensity projections of the veiling light onto the $\parallel$ and $\perp$ directions ($I_{\parallel}(\mathrm{B}), I_{\perp}(\mathrm{B})$) and the intensity projections of the object light ($I_{\parallel}(\mathrm{T}), I_{\perp}(\mathrm{T})$) are expressed as

$$I_{\parallel}(\mathrm{B}) = \frac{1}{2}(I(\mathrm{B}) + Q(\mathrm{B})\sin 2\alpha - U(\mathrm{B})\cos 2\alpha), \tag{4}$$

$$I_{\perp}(\mathrm{B}) = \frac{1}{2}(I(\mathrm{B}) - Q(\mathrm{B})\sin 2\alpha + U(\mathrm{B})\cos 2\alpha), \tag{5}$$

$$I_{\parallel}(\mathrm{T}) = \frac{1}{2}(I(\mathrm{T}) + Q(\mathrm{T})\sin 2\alpha - U(\mathrm{T})\cos 2\alpha), \tag{6}$$

$$I_{\perp}(\mathrm{T}) = \frac{1}{2}(I(\mathrm{T}) - Q(\mathrm{T})\sin 2\alpha + U(\mathrm{T})\cos 2\alpha). \tag{7}$$

Then the intensity of the veiling light obtained by PDI is given as

$$I_{pd}(\mathrm{B}) = I_{\parallel}(\mathrm{B}) - I_{\perp}(\mathrm{B}) = Q(\mathrm{B})\sin 2\alpha - U(\mathrm{B})\cos 2\alpha. \tag{8}$$

Using the expression of the orientation angle in terms of the Stokes parameters [30], we obtained that $\tan 2\alpha = U(\mathrm{B})/Q(\mathrm{B})$. It implies that the intensity of the veiling light expressed by Eq. (8) is 0. This is consistent with Eq. (1). As a result, I_{pd} is expressed as

$$I_{pd} = I_{\parallel}(\mathrm{T}) - I_{\perp}(\mathrm{T}) = Q\sin 2\alpha - U\cos 2\alpha, \tag{9}$$

where Q represents the sum of $Q(\mathrm{B})$ and $Q(\mathrm{T})$, and U represents the sum of $U(\mathrm{B})$ and $U(\mathrm{T})$. It means that I_{pd} could be obtained based on the orientation angle of the veiling light and the Stokes vector of the scene. Compared with previous PDI, the new imaging method is denoted by M-PDI.

Inspired by Ref. [31], the Stokes vector in the region without target may be used to directly estimate the orientation angle α. However, the estimated value is different from the actual value. Furthermore, the relationship between them could not be determined so that it is impossible to take the estimated value as the actual value by making corrections. Thus, how to estimate the accurate value of α from the Stokes vector of the scene with no