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Time-domain polarization difference imaging of objects in turbid water

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ABSTRACT

In this paper, we demonstrate time-domain polarization difference (TPD) imaging for target recognition in a turbid medium. The simulated results show that compared with conventional polarization difference (PD) imaging, when backscattered photons from the medium are polarization-preserving under polarized light illumination, higher image contrast and deeper detection range can be obtained by the TPD imaging method. For conventional PD imaging systems, backscattered light is imaged as noise to degrade the image. When TPD imaging is used, the effect of backscattered light can be effectively eliminated in time domain. This study opens interesting perspectives for the development of optical imaging in the turbid system.

1. Introduction

Optical imaging of objects in turbid conditions, such as rain, biological tissue, and turbid water, is a challenging problem due to light scattering and absorption caused by the medium attenuate valid signal [1–3]. The point of interest in this paper focuses on the turbid water environment. For situations where absorption dominates, enhancing intensity of the light source or increasing sensitivity of the detector can effectively improve the image quality. However, scattering light from the medium acts as noise to be imaged, which degrades the image contrast and resolution. Therefore, removing the effect of light scattering is one of the main tasks for optical imaging in turbid water.

Active optical polarization imaging technology is a promising method for imaging in scattering environments and a variety of investigations have been performed by researchers [4–6]. Since the principle of polarization discrimination is based on the difference in polarization properties between the backscatter and the target, different polarization imaging methods were proposed to detect different embedded objects in different turbid media [7–9]. When detecting depolarized objects in turbid water , orthogonal polarization imaging was introduced to suppress the most backscattered light from the medium. Gilbert and Pernicka investigated the effect of incidence polarization state on orthogonal imaging performance, and proved that better signal-to-noise ratio could be achieved using circular instead of linear polarization information [10]. Dubreuil et al. demonstrated that orthogonal polarization imaging could be improved by use of correlation technology [11]. Walker et al. further theoretically promoted orthogonal polarization imaging with a subtraction algorithm to enhance the visibility depth [12], which was experimentally verified by Miller and Dereniak [13]. Treibitz and Schechner performed image recovery in the underwater scattering environment [14] to solve the problem that orthogonal polarization imaging only obtains partial characteristics of the objects. When detecting polarized objects in turbid conditions , Kartazayeva et al. [15] and Nothdurft [16] exploited the helicity information of circularly polarized light to eliminate light scattering based on polarization memory effect. Huang et al. retrieved underwater polarized objects by estimating the polarized-difference signal of light field when both the object and the backscatter radiance contribute to the polarization [17]. When target recognition in turbid water was performed, polarization difference (PD) imaging was used to distinguish between polarized and depolarized objects relying on the depolarization [18,19]. However, depolarization property of backscattered light is closely related to the size parameter of particles contained in the turbid medium under polarized light illumination [15,20,21]. As a result, when backscattered photons from the medium are composed predominately of polarized light parallel to polarization illumination, conventional PD imaging performance is limited due to backscattered light acts as noise to degrade the image contrast.

To solve this problem, depolarization of both backscattered and forward transmitted light from the turbid media system is investigated based on Mueller matrix, and time-domain polarization difference (TPD) imaging method is introduced. On the basis of the Jaffe's underwater optical imaging model [22], the TPD imaging eliminates backscattering effect from the turbid medium with time gating, and discriminate target from the background with similar reflectivity by use of polarization information. It should be noted that the research in this

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paper is different from our previous work [23], which is aimed at removing the multiple backscattering components superimposed on the target signal in high turbidity levels. Furthermore, we apply the TPD imaging method to enhance target recognition performance in turbid conditions.

2. Theory

Under polarized light illumination, the concept of conventional PD imaging is defined as

$$I_{PD}(x, y) = I_{co}(x, y) - I_{cross}(x, y) \quad (1)$$

where $I_{co}(x, y)$ and $I_{cross}(x, y)$ indicate polarization images corresponding to the polarization detections that are parallel and orthogonal to the incident polarization, respectively, and (x, y) is the pixel position in the image.

For active optical imaging in turbid conditions, the influence of light scattering on the image quality can be described by the Jaffe's underwater imaging model [22].

$$I = I_T + I_{scatter1} + I_{scatter2} \quad (2)$$

where I is the total light intensity received by the detector, I_T is the target signal component, $I_{scatter1}$ is the backscattered light from the medium responsible for image contrast reduction, and $I_{scatter2}$ is the forward scattered light from the medium leading to image blurring.

The goal of this paper is to demonstrate that TPD imaging can enhance the image contrast between the target and the background in a scattering medium. Correspondingly, the forward scattered part of total signal that related to the image resolution is ignored. As a result, the object image obtained by conventional PD imaging system can be further expressed as

$$I_{PD}(x, y) = I_{\mathrm{PD}-T}(x, y) + I_{PD-scatter1}(x, y) \quad (3)$$

where $I_{PD\text{-}T}(x, y)$ and $I_{PD\text{-}scatter1}(x, y)$ correspond to the PD signal of target and backscatter, respectively.

It can be seen from Eq. (3) that, the performance of PD imaging is mainly determined by the amount of $I_{PD\text{-}scatter1}(x, y)$, which acts as noise to degrade the image. When the diameter d of particles contained in the medium is larger than the wavelength λ of incident light, conventional PD imaging is effective to remove the backscattered photons, which are depolarized under polarized illumination [19,21]. However, for the situations where $d < \lambda$, the image quality is seriously degraded because backscattered light from the medium is polarization-preserving with incident polarization [15,24]. To remove the backscattering effect, we introduce TPD imaging method that consists of three steps. Firstly, backscattered photons from the medium and object signal are separated from each other in time domain. Then, polarization images are obtained relying on mechanical orientation of the polarization analyzer's axis. At last, the acquired polarization images are processed with a polarization difference algorithm to reject the background from the target. It should be noted that the first and second steps in TPD imaging are operated at the same time.

3. Experimental method

Fig. 1(a) and (b) show setup for measuring depolarization property of polarized light propagating through a scattering medium in the backward and forward geometry, respectively. For the backscattering situation, smaller detection angle θ is useful to support remote sensing studies given that various systems measure at long ranges with adjacent generators and analyzers, and the value of θ is ~8° here. A He-Ne laser operating at the wavelength of 632.8 nm was used as the illumination source in the experiment. 10% Intralipid solution (Sino-Swed Pharmaceutical Corp. Ltd., China) contained in a 5 cm×5 cm×5 cm quartz cuvette was applied to simulate a scattering environment, which is diluted to different concentrations for different scattering coefficients. The particle size of the medium was 293 nm measured by the Malvern size analyzer, which satisfies with the relationship of $d < \lambda$ corresponding to the above mentioned problem. The polarization state generator (PSG) and the polarization state analyzer (PSA) ensure the wanted polarization illumination and polarization detection. The intensity of scattered light is recorded by a spectrometer (USB2000+, Ocean Optics, America). To avoid working saturation of the instrument, an optical attenuator (A) is placed behind the laser source to control the intensity of incident light.

The polarization state of light can be described by the Stokes vector $\boldsymbol{S}$, which consists of four parameters $[s_0, s_1, s_2, s_3]^T$. Here, s_0 is the total intensity of light, s_1 represents the difference between the 0° and 90° polarizations, s_2 indicates the difference between the 45° and 135° polarizations, s_3 is the difference between the right and left circular polarizations, T is the transpose symbol. When light interacts with the medium, the polarization state of scattered light is determined by the following relationship

$$S_{out} = M \cdot S_{in} \quad (4)$$

where S_{out} and S_{in} are the Stokes vectors of scattered light and incident light, respectively, M is the Mueller matrix of the medium with 16 elements.

In this paper, only the liner polarization information is considered, and a reduced 3×3 Mueller matrix [25] is computed based on Eq. (4).

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} = \begin{bmatrix} I_{HH} + I_{HV} + I_{VH} + I_{VV} & I_{HH} + I_{HV} - I_{VH} - I_{VV} & I_{PH} + I_{PV} - I_{MP} - I_{MM} \\ I_{HH} - I_{HV} + I_{VH} - I_{VV} & I_{HH} - I_{HV} - I_{VH} + I_{VV} & I_{PH} - I_{PV} - I_{MH} + I_{MV} \\ I_{HH} - I_{HV} + I_{VH} - I_{VV} & I_{HP} - I_{HM} - I_{VP} + I_{VM} & I_{PP} - I_{PM} - I_{MP} + I_{MM} \end{bmatrix} \quad (5)$$

where I_{ij} represents the intensity of detected light corresponding to the polarization illumination i and the polarization detection j, and H, P, V and M are 0°, 45°, 90° and 135° polarization components, respectively.

4. Experimental results

4.1. Depolarization of backscattered light

Table 1 gives original backscattered linear Mueller matrices of the medium that are normalized by $m_{\mathrm{ij}}/\mathrm{m}_{11}$ at different Intralipid concentrations, where m_{ij} is the matrix element. Mueller matrix of the medium can be used to quantify its polarization properties in terms of

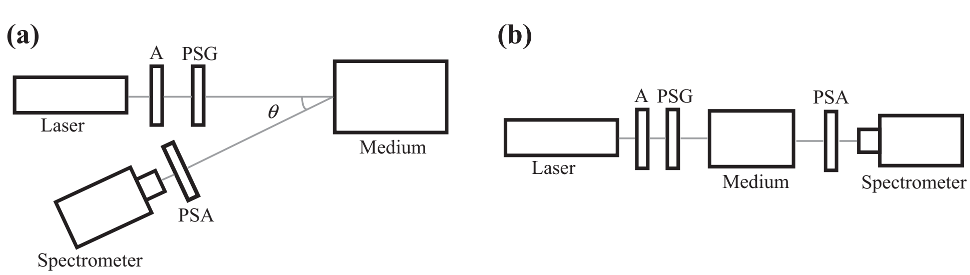

Fig. 1. Schematic experimental setup for depolarization measurement in the (a) backward and (b) forward geometry, respectively.