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Active imaging with the aids of polarization retrieve in turbid media system

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ABSTRACT

We propose a novel active imaging based on the polarization retrieve (PR) method in turbid media system. In our simulations, the Monte Carlo (MC) algorithm has been used to investigate the scattering process between the incident photons and the scattering particles, and the visually concordant object but with different polarization characteristics in different regions, has been selected as the original target that is placed in the turbid media. Under linearly and circularly polarized illuminations, the simulation results demonstrate that the corresponding polarization properties can provide additional information for the imaging, and the contrast of the polarization image can also be enhanced greatly compared to the simplex intensity image in the turbid media. Besides, the polarization image adjusted by the PR method can further enhance the visibility and contrast. In addition, by PR imaging method, with the increasing particles' size in Mie's scale, the visibility can be enhanced, because of the increased forward scattering effect. In general, in the same circumstance, the circular polarization images can offer a better contrast and visibility than that of linear ones. The results indicate that the PR imaging method is more applicable to the scattering media system with relatively larger particles such as aerosols, heavy fog, cumulus, and seawater, as well as to biological tissues and blood media.

1. Introduction

When the incident photons propagate through the turbid media systems, the processes of absorption and scattering effects caused by media system will weaken the intensity and randomize the initial polarization states, propagating directions and phases of the incident light. As a result, the visibility and contrast of object's images will be degraded seriously. In order to overcome this problem, there are many different techniques have been introduced, such as range-gated technology [1], active imaging techniques [2] and frequency-domain method [3]. However, most of above method are difficult to be applied in practical applications because of sophisticated mathematical problems or complicated experimental setups.

Recently, polarization imaging techniques have attracted more and more researching interests because its powerful ability of imaging an object hidden in a turbid media system, such as in the system of fog, cloud, underwater and biological tissue. Polarization is a fundamental property of light. Generally speaking, the polarization properties between the objects and the background, such as man-made objects and naturally occurring objects, are dissimilar due to the different materials or surface features, which can provide additional information in the detecting processes [4–7]. The polarization imaging technique [4–12] has been well developed and widely applied because it can improve the imaging contrast by selecting the polarization states of transmitted or backscattered lights. The polarization difference (PD) detection method has also been used in polarization imaging techniques for its superior detecting capabilities [10–12]. However, this method is still difficult to detect the objects when the objects are hidden in highly scattering media system, because this method can just reduce the influence of backscattering [13]. In this case, target detection suffers from reduced contrast because of the superposition of photons scattering caused by both object and scattering media. So we put forward an improved imaging technology based on polarization retrieve (PR) method in scattering medium to degrade the influence of scattering effect effectively.

In our previous study, PR method has been applied in the field of the influence of scattering process [14–17]. Here, by the MC simulation method which utilizes the random theory to obtain the photon's free path between two successive scattering events, we have established the model for simulating the concrete process of the light with linearly and circularly polarized states propagating in a scattering medium. Based on the MC algorithm and PR theory, we utilize the active polarization imaging technique to discriminate the object which is immersed in the turbid media. From

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the comparison of the intensity imaging, PD imaging and PR imaging, we can find that the imaging contrast can be significantly increased by PR imaging method. Moreover, the contrast of the image illuminated by circularly polarized light can be further improved than that of linearly polarized light. In addition, by changing the radius of particle in the medium and the immersed depth of the object, we also find that the depth of visibility can also be effectively extended by PR method when the medium is turbulent.

2. Theoretical background

When a polarized light passes through the scattering medium, the detecting image is composed of the object signals (target signals), the backscattered signals scattered by the medium, and the forward scattered signals scattered by the object and the medium [18]. Thus the measured Stokes vector of the image $S_{out}(x, y)$ can be defined as follows:

$$S_{out}(x, y) = S_T(x, y) + S_1(x, y) + S_2(x, y) \quad (1)$$

where $S_T(x, y)$, $S_1(x, y)$ and $S_2(x, y)$ are the Stokes vectors of the target signal, backscattered signal and forward scattered signal, respectively. In the previous study, the PD detection method is effective for removing the signal $S_1(x, y)$ which is scattered by the medium [13].

Because each transmitting lights can be represented by its four-component Stokes vector, $S=(I, Q, U, V)^T$, let S_i and S_o be the Stokes vectors of the incident laser light and the transmission light respectively. Therefore, the interaction between the light and the scattering medium can be described by the corresponding 4×4 Muller matrix [15], and the relationship between the incident Stokes vector and the output Stokes vector can be expressed as:

$$S_o = MS_i = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix} \quad (2)$$

This Mueller matrix of M can describe the optical properties of media system completely, and the information about particle size, particle shape, refractive index of the medium, scattering coefficient, anisotropy factor, the particle number density and so on, can be extracted from the four-by-four elements of the Mueller matrix for a highly scattering media system. Theoretically, the Mueller matrix is stable even if the state of incident light is variable. And the Mueller matrix can be obtained by solving Maxwell's equations with the corresponding boundary conditions. However it seems a computationally unrealistic task because of the complicated numerical calculations. Because a Mueller matrix has 16 independent elements, at least 16 independent measurements must be acquired to determine a full Mueller matrix. Here, in our simulations, the effective Mueller matrix (EMM) can be obtained by launching six different polarization states of photons as the incident lights, such as (1) Horizontal polarization, (2) Vertical polarization, (3) 45° polarization, (4) 135° polarization, (5) Right circular polarization, and (6) Left circular polarization. The corresponding effective Mueller matrix (EMM) can be expressed as [14,19]:

$$M = \begin{bmatrix} I_1 + I_2 & I_1 - I_2 & I_3 - I_4 & I_5 - I_6 \\ Q_1 + Q_2 & Q_1 - Q_2 & Q_3 - Q_4 & Q_5 - Q_6 \\ U_1 + U_2 & U_1 - U_2 & U_3 - U_4 & U_5 - U_6 \\ V_1 + V_2 & V_1 - V_2 & V_3 - V_4 & V_5 - V_6 \end{bmatrix} \quad (3)$$

where the subscripts indicate the scattered radiation associated with the aforementioned polarization states of the incident lights. Thus, the EMM for the single incident light can be obtained in this way. However, in our imaging simulations, we used a plane incident light, and the MC simulation need a very huge number of photons to gain reliable results, which results in a very low computational efficiency. To improve the computational efficiency, we introduce a method for obtaining the EMM for the plane incident light system by shifting position and superposition principle in the MC model. Firstly, the behaviors of the photons transmitted in the same length along the z axis but in different x and y positions are the same because of the symmetrical characteristics of the system (the transmission system is infinite in x and y directions). Therefore, the shifting position and superposition principle are suitable to the plane light transmission. Secondly, light transmission in the medium is a typical linear problem, and for any linear system, the principle of superposition is applicable. So the effective Mueller matrix of the plane incident light system can be defined as the superposition of the effective Mueller matrix (SEMM), which can be expressed as:

$$M_s(x, y) = \sum_{i=0}^{K} \sum_{j=0}^{N} M_{(i,j)}(x, y) \quad (4)$$

where the $M_S(x, y)$ is the SEMM, and $M_{(i,j)}(x, y)$ means the EMM in the position of (i, j); K and N are the maximum value for the positions of the incident light in the directions of x and y respectively. From above discussions, we know the $M_{(i,j)}(x, y)$ should be the same because of the symmetrical characteristics of the system. Therefore, if the media system is decided, we can obtain the SEMM ($M_{Smedium}$) uniquely by the Eqs. (3) and (4). Obviously, once we accurately obtain the SEMM in advance, the Stokes vector $S_r(x, y)$ of reflected photons from the target's surface can be retrieved by the inverse SEMM ($M_{S(medium)}$) and the received Stokes vector $S_{out}(x, y)$:

$$S_r(x, y) = M^{-1}_{S(medium)}(x, y) S_{\text{out}}(x, y) \quad (5)$$

Eq. (5) is the principle of our PR method, from which the degree of polarization (DOP) of the obtained PR imaging can also be calculated. Here the DOP of the PR imaging (DOP(PR)) and the PD imaging (DOP(PD)) can be expressed as:

$$\text{DOP(PR)} = \frac{\sqrt{Q_r^2 + U_r^2 + V_r^2}}{I_r} \quad (6)$$

$$\text{DOP(PD)} = \frac{|I_{co} - I_{cross}|}{I_{co} + I_{cross}} \quad (7)$$

where the I_r, Q_r, U_r and V_r are the retrieve received Stokes vectors by the PR method, and I_{co} and I_{cross} are the received optical intensities with the analyzer orienting parallel and perpendicular to the polarization of illumination [10–12].

3. System model and numerical scheme

The schematic of the system model where the monochromatic linearly and circularly polarized lights ($S=(1,1,0,0)^T$ and $S=(1,0,0,1)^T$) with the wavelength of $\lambda = 532$ nm diffuse through a homogeneous scattering media with a transmission distance of L, is shown in Fig. 1(a). The direction of incident light is parallel to the water level, and a detector is placed in the same side with the area of 1×1 cm^2. The scattering medium system is modeled as infinite in x and y directions, and containing randomly positioned non-absorbing spheres (Mie scatters) as shown in Fig. 1(a). The Mie particles are characterized by a size parameter ka ($k = 2\pi n_{med}/\lambda$ is the wave vector, where n_{med} is the refractive index of the medium, and a is the radius of the scattering particles). All