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Monte Carlo based angular distribution estimation method of multiply scattered photons for underwater imaging

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ABSTRACT

This paper proposes a Monte Carlo (MC) based angular distribution estimation method of multiply scattered photons for underwater imaging. This method targets on turbid waters. Our method is based on applying typical Monte Carlo ideas to the present problem by combining all the points on a spherical surface. The proposed method is validated with the numerical solution of the radiative transfer equation (RTE). The simulation results based on typical optical parameters of turbid waters show that the proposed method is effective in terms of computational speed and sensitivity.

1. Introduction

Multiple scattering is a well-known problem and attracts a considerable number of researchers who focus on turbid media, such as biological tissues [1–4]. It also plays an important role in underwater optical imaging [5–7]. Fig. 1 illustrates the principle of underwater optical imaging. Briefly, an underwater optical imaging system consists of a light source, a lens and a CCD [7,8]. Underwater optical imaging involves two steps: (1) illuminating an object with light emitted from the light source and (2) receiving an image of the object with the lens system.

Multiply scattered photons in the two steps may enter the imaging system and influence the image quality of the CCD. Considering that effective methods such as Laser Range Gate (LRG) have been proposed for rejecting the multiply scattered photons in the first step [9,10], this paper focuses on the multiply scattered photons in the second step. As shown in Fig. 1, some of them may enter the CCD and produce a scatter pattern and thus degrade the image quality.

To estimate the scatter pattern is the key point of scattering correction methods [11,12]. For an optical imaging system shown in Fig. 1, the scatter pattern on the CCD is determined by the angular distribution (AD) of multiply scattered photons at each point on the lens surface. Additionally, the AD is an important factor to be considered in designing an underwater optical imaging system [13]. This paper presents a method to estimate the AD for a point, such as the point P in Fig. 1.

Relatively little work has been done for estimating the AD of a point in turbid media. Andre Liemert and Alwin Kienle have been developed analytical solutions of the RTE for infinite and bounded media; they have obtained brilliant results [14–16]. However, their models were proposed to solve point spread functions (PSF). Thus, their models cannot be extended into the present problem. Xueqiang Sun et al. have developed a method for calculating the AD of multiply scattered photons through isotropic turbid slabs [17]. Their work targeted on an entire plane, and therefore cannot be used to calculate the AD for a point. Some other studies have tried to improve the image quality by use of PSF, such as Ref. [7], probably because it is not easy to obtain the AD in turbid waters.

In this paper, we propose a MC-based method to estimate the AD for a point, such as the point P in Fig. 1. MC has been widely investigated for turbid media due to its generality and being easy-to-implementation [3,18,19]. All these related studies targeted on the optical fluence in turbid media. It poses an obvious challenge to directly use these published methods to estimate the AD of the point P in Fig. 1. This paper proposes an efficient MC-based method that combines all the points on a spherical surface.

2. Methods

Our task is to obtain the AD of the point P in Fig. 1. This section briefly reviews typical MC ideas and then presents the proposed method. The flow chart of our method is given in Fig. 2. Our main contributions lie in the red parts of Fig. 2.

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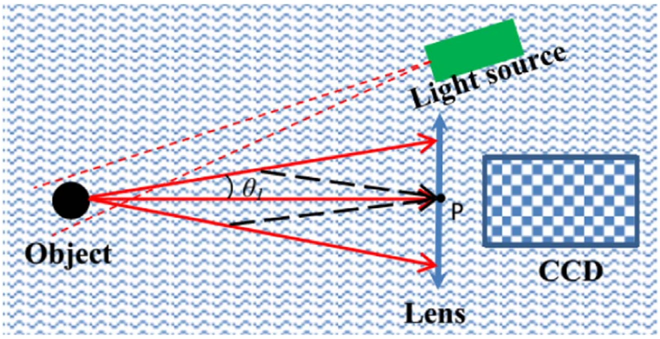

Fig. 1. Schematic of underwater optical imaging of an object in turbid waters.

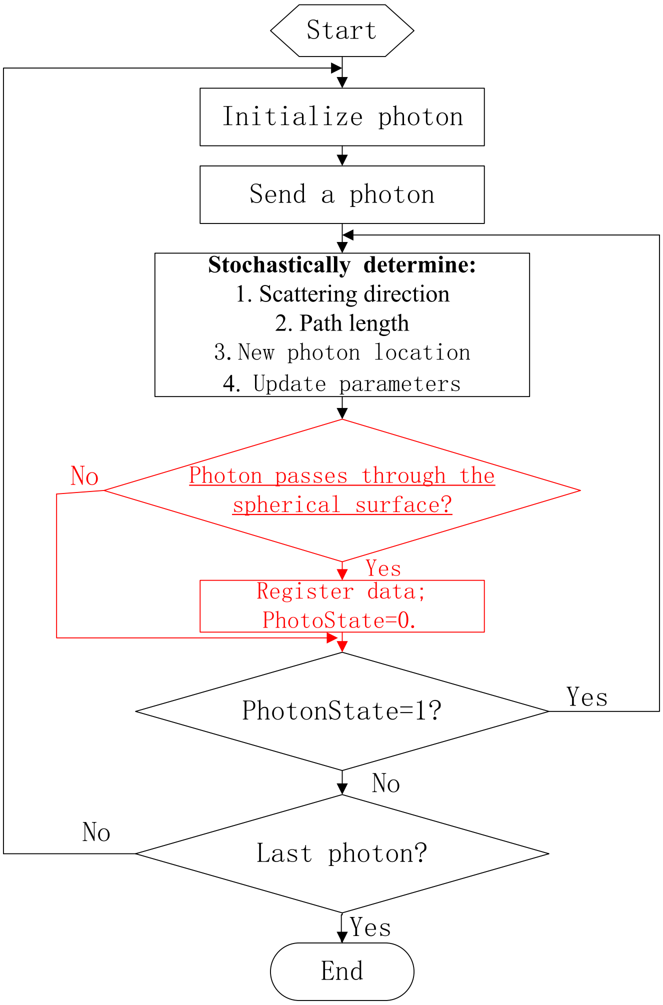

Fig. 2. Flow chart of the proposed method.

2.1. *Typical MC methods briefly sketched*

The frame of our MC model adopts a standard MC model as described in [19]. Mainly, this standard MC model consists of the following five steps: 1) it sends a photon, 2) it determines the scattering direction and pathlength of the photon stochastically to calculate the location of the photon after a scattering event, 3) it reduces the energy of the photon by taking into account attenuation due to absorption, 4) it repeats steps 2) and 3) until the energy is less than a threshold (the photon is dead, Photostate=0, see in Fig. 2), and 5) it repeats steps 1), 2), 3) and 4) until the number of photons meets the required precision. More detailed information can be found in Ref. [19]. and the black parts in Fig. 2.

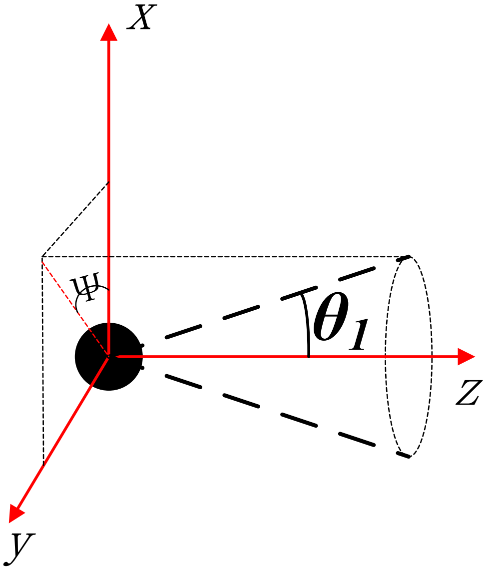

Fig. 3. The object in Fig. 1 scatters photons toward a cone with a cone angle of θ_1, Ψ represents azimuth angle.

To implement a simulation with MC, three parameters are required: (1) the absorption coefficient μ_a; (2) the scattering coefficient μ_s and (3) the anisotropy factor g which is from the volume scattering function [3,19].

2.2. *Initializing a photon*

It is assumed that the object in Fig. 1 scatters photons toward a cone with a cone angle of θ_1, as shown in Fig. 3. The initial direction of each photon is described using two angles, $\theta \in [0, \theta_1)$ and $\psi \in [0, 2\pi)$. As in Ref. [19], the initial direction is also specified by the directional cosines (μ_x, μ_y, μ_z), which are determined statistically as follows,

$$\mu_z = 2\xi_1 \cos\theta_1 - 1 \tag{1}$$

Next, the angle ψ is sampled as,

$$\psi = 2\pi\xi_2 \tag{2}$$

where, ξ_1 and ξ_2 are random numbers uniformly distributed over the interval [0,1]. Then μ_x, and μ_y can be expressed as,

$$\begin{aligned} \mu_x &= \sqrt{1-\mu_z^2}\cos\psi \\ \mu_y &= \sqrt{1-\mu_z^2}\sin\psi \end{aligned}. \tag{3}$$

The first step size s_1 is specified as,

$$s_1 = \frac{-\ln\xi}{\mu_t} \tag{4}$$

ξ is an uniformly distributed random number. After s_1, each photon is to be moved in turbid waters by a traditional Monte Carlo technique. Without loss of generality, θ_1 is to be taken as π in our following simulations, as in Refs. [5–7,14–16].

2.3. *Registering the AD*

In typical MC methods, the optical fluence at a point in turbid media is obtained by combining all the photons that pass through this point. In this paper, this idea is applied to the present problem. Considering $\theta_1 = \pi$ and that the object in Fig. 1 can be considered as an isotropic source, all the points on the spherical