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Deriving inherent optical properties from background color and underwater image enhancement

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ABSTRACT

The colors and quality of images acquired in underwater conditions can be very poor due to the specific propagation properties of light in water, and this degradation effect is relative to the optical properties of water. We find that the background color of underwater images has a relationship with the inherent optical properties of water medium. In this paper, we propose a method of deriving inherent optical properties of water from the background color of underwater images based on an underwater image formation model. Simulations and image enhancement results show that the proposed method can effectively estimate inherent optical properties and can be used for underwater image enhancement with good performance.

1. Introduction

In recent years, there is an increasing interest in ocean resources exploitation, ocean environmental protection and ocean military affairs. However, as the ocean water environment varies greatly with locations and seasons, measurement of ocean optical parameters remains difficult in practice. In the field of image acquisition and processing, underwater images are usually degraded by light absorption and scattering, which are caused by water molecules and suspended particles in the water medium (Schettini and Corchs, 2010). Lee et al. (2002) have proposed an algorithm to retrieve absorption and backscattering coefficients based on remote-sensing reflectance models derived from the radiative transfer equation. Inspired by this study, we develop an algorithm to estimate relevant attenuation and scattering coefficients of RGB channels. This algorithm is based on an underwater imaging model, especially the background light model of underwater imaging.

Underwater visibility is very important in underwater vision research and image processing. However, most underwater vision systems cannot guarantee satisfactory performance under poor water conditions. Due to its shortest wavelength and smallest attenuation coefficient, blue light travels the longest in ocean water. This is the reason why underwater images are usually dominated by blue color. Furthermore, ambient light is scattered into the line of camera's sight by suspended particles, which adds a layer of haze to the image and decreases the image contrast. As a result, underwater images usually have poor contrast and show bluish hues. Many methods of underwater image enhancement techniques have been proposed and demonstrated in the last few years. Methods based polarization (Schechner and Karpel, 2004), chromatism (Carlevaris-Bianco et al., 2010), quaternions (Petit et al., 2009), color model (Iqbal et al., 2007), wavelength compensation and image dehazing (WCID) (Chiang and Chen, 2012), model based image restoration (Stephan et al., 2013) and so on, have been proved to be effective for underwater image enhancement. However, strong hypothesis, optical properties given specifically or measured in situ, and two or more images were usually used during the process of these image enhancement.

In this paper, we propose a method to derive the inherent optical properties from background color of underwater images. The derivation is based on the fact that there is a relationship between background light and inherent optical properties in underwater imaging. An underwater imaging model under natural illumination is formed. We find that the global background light does not depend on the object–camera geometry, but on the inherent optical properties and camera properties. Based on the model of global background light, we can derive the inherent optical properties. Simulations and underwater image enhancement are made to demonstrate the effectiveness of our method.

2. Ocean optics

As light propagates in ocean water, it gets attenuated due to absorption and scattering caused by the water medium. Absorption

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causes energy loss of light while scattering changes the direction of light path. According to the Lambert–Beer empirical law (Gordon, 1989), light is exponentially attenuated as it travels in water. Assuming that the water medium is homogeneous, the transmission can be expressed as

$$t_\lambda(x)=\exp(-c_\lambda d(x)), \tag{1}$$

where c_λ is the attenuation coefficient and $d(x)$ is the distance between the camera and a point.

The light attenuation process is caused by absorption and scattering. Assuming that it is in an isotropic, homogeneous medium, the total attenuation coefficient c_λ can be decomposed as a sum of absorption coefficient a_λ and scattering coefficient b_λ, which can be expressed as $c_\lambda=a_\lambda+b_\lambda$. The scattering coefficient b_λ is the superposition of all scattering events at all angles. It is the integral of the volume scattering function $\beta_\lambda(\theta)$ over all solid angles (Spinrad et al., 1994)

$$b_\lambda=\int_0^\pi \beta_\lambda(\theta)d\omega=2\pi\int_0^\pi \beta_\lambda(\theta)\sin\theta d\theta, \tag{2}$$

The parameters c_λ, a_λ, b_λ and $\beta_\lambda(\theta)$ are the inherent optical properties of the medium. Unfortunately, the real-time and exact measurement of these parameters remains a very complex and cost-consuming task by far.

3. Underwater image formation model

On clear days, the image taken in air by a camera only consists of the scene radiance, which is the portion of light reflected into the camera by the object surface. However, underwater imaging conditions are more complex than that in the open air. First, absorption and scattering modify the spectral content of an underwater image, so the influence of the light spectrum changes on the color rendering must be considered (Boffety et al., 2012). Second, a portion of ambient light is scattered into the camera by suspended particles and water molecules, which is called the background light and adds a layer of haze to underwater images.

Following McGlamery's model (McGlamery, 1979), the irradiance components that are incident upon the camera plane contain three parts as is shown in Fig. 1: (1) background light, the irradiance due to scattering of ambient light; (2) direct attenuation, the irradiance due to non-scattered but attenuated light from the object; (3) forward scattering, the irradiance due to scattered light from the object. This formation can be expressed as

$$I_\lambda=B_\lambda+D_\lambda+F_\lambda, \tag{3}$$

where I, B, D and F are the total irradiance received by the camera, the background light, the direct attenuation component and forward scattering component, respectively. The subscript λ represents the wavelengths of light or color channels (R, G and B for an RGB image).

Jaffe (1990) has studied the formation of underwater images with artificial lighting based on McGlamery's theory. It should be noted that many underwater images are taken at the upper layer of water where no artificial light sources are needed. So it is necessary to study the situation of underwater imaging with natural illumination. In this paper, we model the formation of underwater images and focus on analyzing the relationship between the background light and the inherent optical properties under natural illumination.

3.1. Background light

Unlike direct attenuation and forward scattering components, the background light does not originate from the object. Instead, it is caused by the scattering of ambient light by suspended particles in the water from a large distribution of angles (Narasimhan and Nayar, 2002). Following McGlamery's (McGlamery, 1979) and Jaffe's (Jaffe, 1990) model, the three-dimensional cone along the camera's line of sight is sliced into planes of infinitesimal thickness. At first, the contribution of a plane at distance l and direction φ to the background light can be represented as

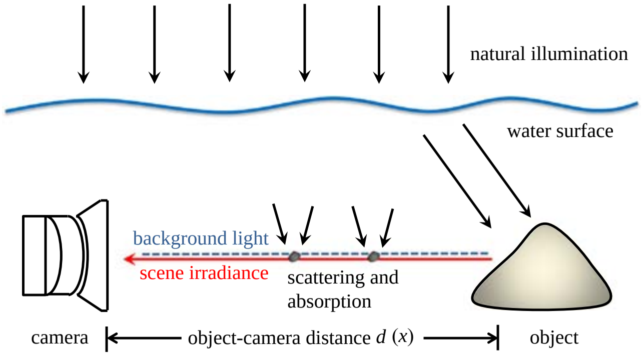

Fig. 1. *Imaging of an underwater object.* Light reflected from the object surface suffers scattering and absorption caused by water molecules and suspended particles. The irradiance received by the camera is a sum of the attenuated and scattered scene irradiance and the background light.

$$dB_\lambda(l,\varphi)=\beta_\lambda(\varphi)E_\lambda(l,\varphi)\exp(-c_\lambda l)\times\frac{\pi}{4F_n^2}T_l\left[1-\frac{F_l}{l}\right]^2 dl, \tag{4}$$

where φ is the angle relative to the direction of the incident light and line of camera's sight, $E_\lambda(l,\varphi)$ is the intensity of the ambient light. In McGlamery and Jaffe's model, both the attenuation and forward scattering effects of the single volume's scatter light are considered. However, only attenuation is considered in many other studies (Schechner and Karpel, 2004, 2005) for simplification. We have reason to believe that the latter is a reasonable assumption for not very turbid waters (case 1 and case 2 waters for instance).

In the situation of natural illumination without artificial light sources, it's convenient to assume that the underwater ambient light is approximately uniform, since light intensity varies slightly among several meters below the water surface (Warrant and Locket, 2004). Here, it is simplified to a constant E_a for convenience. The camera system is characterized by three parameters, F_n (F number of the camera), T_l (lens transmittance) and F_l (focal length).

Typically, F_l is very small compared to the object–camera distance l and $F_l \ll l$ (Schechner and Karpel, 2004), which leads to $1-(F_l/l)\approx 1$. Then we can make the simplification of Eq. (4) as

$$dB_\lambda(l,\varphi)=\beta_\lambda(\varphi)E_a\exp(-c_\lambda l)\kappa_l dl, \tag{5}$$

where κ_l is a constant within a single image, and represents the camera system's properties.

The total background light of the pathlength d from the object to the camera can be obtained by integrating the right hand side of Eq. (5) from distance $l=0$ to $l=d$ and casting up all scattering components at all directions (since ambient light incident on the scattering volumes from all directions) as

$$B_\lambda(d)=\int_0^d\int_\Theta \beta_\lambda(\varphi)E_a\exp(-c_\lambda l)\kappa_l dl d\varphi=B_{\lambda,\infty}(1-\exp(-c_\lambda d)), \tag{6}$$

where Θ represents all possible scattering angles for a certain scattering volume and

$$B_{\lambda,\infty}=\frac{\kappa_l E_a}{c_\lambda}\int_\Theta \beta_\lambda(\varphi)d\varphi \tag{7}$$

is the background light from the infinity distance to the camera, or global background light.