J. Vis. Commun. Image R. 38 (2016) 504–516

Contents lists available at ScienceDirect

J. Vis. Commun. Image R.

journal homepage: www.elsevier.com/locate/jvci

Underwater image enhancement method using weighted guided trigonometric filtering and artificial light correction ☆

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ARTICLE INFO

Article history:
Received 4 June 2014
Revised 9 June 2015
Accepted 30 March 2016
Available online 1 April 2016

Keywords:
Deep-sea imaging
Inherent optical property
Image enhancement

ABSTRACT

This paper describes a novel method for enhancing optical images using a weighted guided trigonometric filter and the camera's spectral properties in turbid water. Absorption, scattering, and artificial lighting are three major distortion issues in underwater optical imaging. Absorption permanently removes photons from the imaging path. Scattering is caused by large suspended particles found in turbid water, which redirect the angle of the photon path. Artificial lighting results in footprint effects, which cause vignetting distortion in the captured image. Our contributions include a novel deep-sea imaging method that compensates for the attenuation discrepancy along the propagation path, and an effective underwater scene enhancement scheme. The recovered images are characterized by a reduced noise level, better exposure of dark regions, and improved global contrast such that the finest details and edges are significantly enhanced. Our experiments showed that the average Peak Signal to Noise Ratio (PSNR) improved by at least 1 dB when compared with state-of-the-art-methods.

1. Introduction

There have been increased developments in deep-sea exploration using autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs). However, the contrast of underwater images is still a major issue for application. It is difficult to acquire clear underwater images around underwater vehicles. Since the 1960s, sonar sensors have been extensively used to detect and recognize objects in oceans. Due to the principles of acoustic imaging, sonar-imaged images have many shortcomings such as a low signal to noise ratio and a low resolution. Consequently, vision sensors must be used for short-range identification because sonars yield to low-quality images [1].

In contrast to natural images, underwater images suffer from poor visibility. Firstly, Light is absorbed when sunlight is reflected by a water surface. Additionally, absorption substantially reduces the ambient light energy. Random attenuation and scattering degrade the contrast of the scene. Objects at a distance of more than 10 m are almost indistinguishable, because the colors are faded [2]. Furthermore, artificial lighting can cause a distinctive footprint on the seafloor.

Over the past two decades, researchers have been focusing on improving the quality of underwater images. Recent research on underwater image enhancement can be classified into two major categories according to input types: multiple or single inputs. For multiple inputs, Schechner et al. used a polarization imaging method to compensate for visibility degradation [3]. Treibitz et al. proposed a multi-directional illumination fusion method for turbid scene enhancement [4]. Ouyang et al. proposed a multiple laser lighting and bilateral filtering-based image deconvolution method for underwater image enhancement [5].

For single-input image methods, Ancuti et al. proposed a Laplacian fusion method that reconstructs a clear image in turbid water [6]. Fattal et al. first used the underwater dehazing method for underwater image enhancement [7]. This technique estimates the scene radiance and derives the transmission map using a single image. However, it cannot sufficiently process images with heavy haze and colors can be distorted. Lu et al. [8] proposed a dehazing

☆ This paper has been recommended for acceptance by Zhao Vicky.

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http://dx.doi.org/10.1016/j.jvcir.2016.03.029
1047-3203/

and color correction method for recovering underwater scenes. He et al. [9] proposed a scene depth information-based dark channel priors dehazing algorithm using a matting Laplacian. However, this algorithm requires significant computation time. To overcome this disadvantage, they also proposed a guided image filter [10] with the foggy image used as a reference image. However, this method leads to incomplete haze removal.

Although these approaches can enhance the image contrast, there are several drawbacks that reduce their practical applicability. First, the imaging equipment is difficult to use in practice (e.g., a range-gated laser imaging system is rarely applied in practice [5]). Second, multiple input images are difficult to obtain [3,4]. Third, these methods cannot sufficiently alleviate color distortions [6–9].

As noted in previous publications [6,9], it is impossible to capture the same scene at the same time in turbid water. Consequently, single-image enhancement methods can achieve better results. Single underwater-image enhancement is a challenging, but ill-posed problem. In underwater imaging, the captured images are significantly influenced by absorption, scattering, and inhomogeneous illumination. In this paper, we introduce a novel scheme that enhances underwater images using a single image as input. The proposed method overcomes the previously mentioned drawbacks of conventional methods. The organization of this paper is as follows. Section 2 explains the ocean imaging model. Section 3 describes the method for underwater image enhancement and proposes our weighted guided trigonometric filter. Section 4 applies the proposed method to underwater optical images. Finally, Section 5 concludes this paper.

2. Ocean imaging model

Artificial light and ambient light traveling through the water is the source of illumination in an ocean environment. Suppose that the amount of light radiation (W) formed after wavelength attenuation can be derived using the energy attenuation model as

$$E_c^W(x) = E_c^A(x) \cdot Nrer(c)^{D(x)} + E_c^I(x) \cdot Nrer(c)^{L(x)}, \quad c \in \{r, g, b\}. \tag{1}$$

where $E_c^W(x)$ is the amount of illumination at the scene point, $E_c^A(x)$ is the amount of illumination from ambient light at the scene point, $E_c^I(x)$ is the illumination from artificial light, and *Nrer* is the normalized residual energy ratio. In this imaging model, artificial light is reflected at a distance $L(x)$ from the camera. $D(x)$ is the underwater scene depth. Absorption and scattering occurs in this process. Suppose that the attenuation rate is $\rho_c(x)$, then the illumination of ambient light is

$$E_c^{\omega}(x) = \left(E_c^A(x) \cdot Nrer(c)^{D(x)} + E_c^I(x) \cdot Nrer(c)^{L(x)}\right) \cdot \rho_c(x), \quad c \in \{r, g, b\}. \tag{2}$$

Following the Nayar–Narasimhan dehazing model [11], the captured image $I_c(x)$ formed at the camera plane can be formulated as

$$I_c(x) = \left(E_c^A(x) \cdot Nrer(c)^{D(x)} + E_c^I(x) \cdot Nrer(c)^{L(x)}\right) \cdot \rho_c(x) \cdot t_c(x) + (1 - t_c(x)) \cdot A_c, \quad c \in \{r, g, b\}. \tag{3}$$

where the background A_c represents the light reflected by the object. $t_c(x)$ can be represented in terms of a light beam of wavelength λ over a distance $d(x)$ within the water, that is,

$$t_c(x) = \frac{E_\lambda^{residual}(x)}{E_\lambda^{initial}(x)} = 10^{-\beta_\lambda d(x)} = Nrer(c)^{d(x)}, \tag{4}$$

where β_λ is the extinction coefficient of the medium. *Nrer* is the normalized residual energy ratio [14]; in the Ocean Type I, it satisfies

$$Nrer(c) = \begin{cases} 0.8 - 0.85 & \text{if } \lambda = 650 - 750\ \mu\text{m (red)} \\ 0.93 - 0.97 & \text{if } \lambda = 490 - 550\ \mu\text{m (green)} \\ 0.95 - 0.99 & \text{if } \lambda = 400 - 490\ \mu\text{m (blue)} \end{cases}. \tag{5}$$

Consequently, substituting Eq. (4) into Eq. (3) we can obtain

$$I_c(x) = \left[\left(E_c^A(x) \cdot Nrer(c)^{D(x)} + E_c^I(x) \cdot Nrer(c)^{L(x)}\right) \cdot \rho_c(x)\right] \cdot Nrer(c)^{d(x)} + (1 - Nrer(c)^{d(x)}) \cdot A_c, \quad c \in \{r, g, b\}. \tag{6}$$

The above equation incorporates the light scattering during the course of propagation from object to the camera, and the wavelength attenuation along the object-light and water depth. When the object-light distance $L(x)$, scene depth $D(x)$, and camera-object transmission map $d(x)$ are known, we can recover the final clean image.

Fig. 1 shows the diagrammatic sketch of the proposed model. To improve the image quality, we use the process shown in Fig. 2. In the first stage, we determine the artificial light (if it exists) and remove the footprint or vignetting. In the next stage, we calculate the transmission map of the scene using dual-channels priors, refine the transmission map using a weighted guided trigonometric filter, and remove the scatters using the dehazing method. Finally, we recover the scene color using the camera's spectral properties.

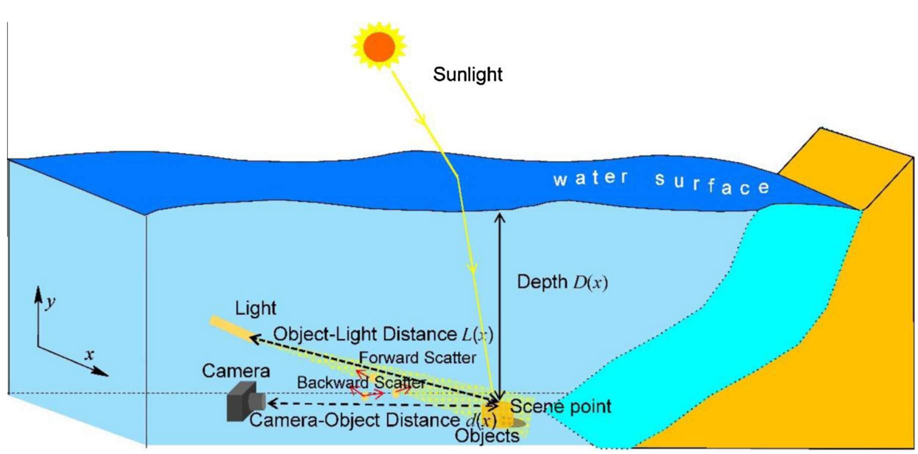

Fig. 1. Schematic of ocean optical imaging model.