Underwater images enhancement by light propagation model inversion

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Abstract

In this paper, a supervised enhancement method dedicated to underwater images is presented. It is well-known that the water alters the light propagation. Underwater images often present low contrast and luminosity. The aim of the proposed method is to correct the effects of the light propagation in the water. This method is based on the physical properties of the light. The originality of this processing is to work without any a priori information about the scene or about the water composition. Experiments show that this method increases the contrast and the color dynamic of underwater images while preserving a good color rendering. In addition, the analysis of the experimental results, conducts a relation between optical parameters and colorimetric attributes.

Introduction

Underwater imagery is recognized as a useful tool for objects detection, objects recognition or for studies of sea life-form populations and oceanic resources. However, underwater scenes are usually veiled by the light interaction with the medium: images present low contrast and luminosity, and visibility is reduced. Two phenomenons, absorption and scattering, affects the way the light is propagated into the water. Moreover the color perception is affected and the turbidity due to suspended matter causes scattered illumination, termed *in-scattering*. Enhancement of image quality is then useful before any underwater images analysis or processing.

Today, enhancement methods already exist. Color constancy algorithms improve the dynamic range compression and the color rendition. Among them, Multi-Scale Retinex (MSR) [3] can be particularly noticed. These algorithms require no special knowledge about acquisition conditions. However, perturbations (haze) due to the in-scattering phenomenon make them unable to reach a sufficient correction.

Other algorithms directly deal with light interaction on water and propose underwater images preprocessing by mean of an inversion of the light propagation model [2]. They provide a compensation of the light attenuation by the seawater. However, light propagation is governed by the physical properties of the media (Inherent Optical Properties : IOP). From the available literature, there is no color correction using in-scattering directly with scattering coefficient and functions. Some methods restrict the problem to the attenuation phenomenon only [1]. Several ways have been explored to estimate and compensate effects of attenuation on a scene but a calibration, by *a priori* measurements or from using known references like a grey object, is needed [1]. In [8], MRF-approaches are used with reference images and knowledge about the expected result in order to compensate attenuation. In [4], a couple of images taken through a polarizer at different orientations gives good results in dehazing.

The aim of this study is to extend the physical model approach using it without any knowledge about the conditions and the environment to enhance underwater images. Our supervised algorithm is correcting images without any initial information by reversing the radiative transfer equation. The radiative transfer equation requires to know or to estimate the optical properties of the medium characterized by the attenuation and scattering coefficients. The optical properties are estimated by our algorithm. Depending on its biochemical constitution, the medium, here the natural waters, can take different aspects going from blue to green, or yellow. Pure water attenuation coefficients are known [5]. Visual aspect of images, in term of colors, is depending on the concentration of materials suspended and/or dissolved into the water. In [5],[6],[7], a bio-optical model of attenuation which is linking concentrations to IOP, is described.

In this paper, a correction method based on the physical properties of the light and light inversion model, is proposed. The originality of this process is to work without any *a priori* information about the scene or about the water composition. Using the model inversion, the best concentrations, in-scattering coefficients and illumination are estimated manually until obtaining the best visual correction. This method produces enhanced underwater images and constitutes the first part of this work. In a second time, the link between the colorimetric attributes of corrected images and the estimated parameters, is studied.

This paper is organized as follows. First, the light propagation in seawater is briefly described. Then, the underwater image enhancement method is explained and some results are presented. Next, the link between colorimetric attributes of the images and the chlorophyll concentration, is considered. Finally perspectives of this work are drawn.

Light propagation in seawater

Radiative general transfer equation

The light variation along an optical path is defined by the radiative general transfer defined by the equation 1:

$$\frac{dL_\lambda(P,\theta)}{dP} = - c_\lambda.L_\lambda(P,\theta) + k_\lambda.L^e_\lambda(P,\theta) + b_\lambda.\int_\Omega L^i_\lambda(P,\theta').\varphi(\theta,\theta')d\theta' \quad (1)$$

where $-c_\lambda.L_\lambda(P,\theta)$ represents the light attenuation coming from the direction θ at a given wavelength λ along a path P, $k_\lambda.L^e_\lambda(P,\theta)$ is the self-illumination by the medium and the sum is the scattering of the incident light L^i_λ. The term $\varphi(\theta,\theta')$ is a phase function described below. This equation expresses the light variation within a medium. But, the terms of this relation are governed by the attenuation coefficient c_λ and the scattering coefficients b_λ characterizing the interaction between light and medium as explained here after.

Light-medium interaction

When passing through a medium composed of molecules and particles, the light interacts with the constituent matter of this medium. When the light reaches a particle, a part of its energy is absorbed and the remaining energy is scattered all around the particles following a spatial distribution specific for each type of particles. The amount of absorbed energy and the amount of scattered energy are described by the efficient section of absorption α and efficient section of scattering σ, given in m^{-2}. The medium is characterized by both the absorption coefficient a_λ and scattering coefficient b_λ, directly linked to α_λ and σ_λ by their products with the density ρ, expressed in number of particles by volume unit. These coefficients all depend on the wavelength λ of the light (equation 2). Thus, coefficients a_λ and b_λ can be written as :

$$a_\lambda = \rho\alpha_\lambda \quad b_\lambda = \rho\sigma_\lambda \tag{2}$$

Light scattering by particles is described by their phase functions $\varphi(\theta,\theta')$ which give the amount of light coming from a direction specified by θ scattered towards the one specified by θ'. For a given particle, this function is comparable to the bidirectional reflectance distribution function for a surface. The percentage of the total scattered energy emitted in a given direction is expressed by a phase function.

Several kinds of phase functions previously established give the different types of interaction of the light with particles [9]. The figure 1 illustrates two classical phase functions: the Rayleigh and the Mie phase function representations. The Rayleigh scattering is typically the scattering of light by particles much smaller than the wavelength of the light (water molecules). When this size is equal or greater than the wavelength, the scattering around the particles is really more complex. Mie propose an analytical solution of Maxwell equations for the scattering by spherical particles. This theory gives rise to an approximation of the scattering by that kind of particles (suspended matter within the water or microscopic living organism)

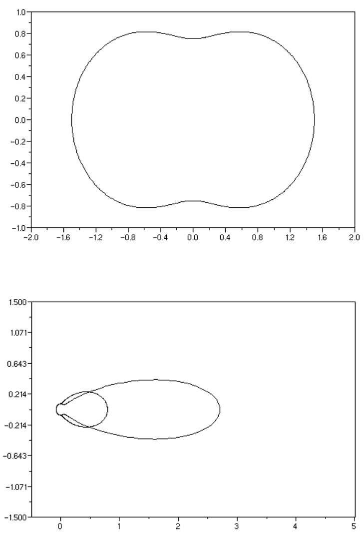

__Figure 1.__ Polar representation of (top) Rayleigh phase function and (bottom) Mie phase function

Light propagation

The part of the light absorbed by the medium and the part of the light scattered into all directions different of the observer one is represented by the light attenuation. The spectral attenuation coefficient c_λ is thus simply defined as the sum of the two absorption and scattering coefficients a_λ and b_λ, which depends on the wavelength (equation 3):

$$c_\lambda = a_\lambda + b_\lambda \tag{3}$$

The quantity of light traveling through an optical path from a point P_0 to a point P without suffering the influence of attenuation is defined by the Beer-Lambert law [9]:

$$L_\lambda(P) = L_\lambda(P_0).e^{\int_{P_0}^{P} -c_\lambda \, dP'} \tag{4}$$

The incident light is also interacting with the medium. A part of this light is scattered by the particles all along the optical path between an object and the observer. This light, which is also attenuated between the interacting point and the observer, is added to the light coming from the objects and thus veiling the scene giving a feeling of haze. Then, the quantity of light perceived by the observer is the sum of the incident light scattered on each point of the path and attenuated between the interaction point and the observer:

$$L(P) = \int_{P_0}^{P} \left[e^{\int_{P'}^{P} -c_\lambda dP''} b_\lambda \int_\Omega L^i_\lambda(P',\theta)\varphi(\widehat{PP_0},\theta)d\theta \right] dP' \tag{5}$$

These phenomenons depend on the bio-chemical nature of the medium. Scattering and absorption are linked to the density of particles, hence linked to the medium opacity, but also to the nature of the particles. Each type of particles is not affecting the light spectra in the same way.

Bio-optical properties of natural waters

The light-medium interaction has been described in the previous section in the general case, for any medium. Let now see the definition of the attenuation in the case of natural waters. The first component of natural waters is the water itself. When clear water mainly scatters blue light, waters containing more organic matter scatter more green and yellow light. Many measurements has been done, and a model linking chemical properties and attenuation has been established [5],[6],[7]. The quantities a, b and c depend only on the constituents of the medium and are known as the inherent optical properties (IOPs). They are all linearly additive over the constituents, i.e. if c^w_λ is the specific attenuation coefficient of the pure water and c^i_λ the specific coefficient of the ith constituent,

$$c_\lambda = c^w_\lambda + \sum_i c^i_\lambda \tag{6}$$

The individual IOPs are directly proportional to the concentration of the constituents. Clear water component is known and based on an accurate and consistent set of data [5],[6],[7]. Usually, the partition can be reduced to three components, the pure water c^w_λ, a chlorophyll component c^c_λ accounting for all "chlorophyll-like" pigments, the dissolved organic matter c^d_λ accounting for the remaining absorption, and thus c_λ can be written as:

$$c_\lambda = c^w_\lambda + c^c_\lambda + c^d_\lambda \tag{7}$$

Note that, of course, specific coefficient depend also on the wavelength λ of the light. In [5], more details are given about this model. Each component equation is a function of the respective concentration of the concerned constituent.

Underwater image enhancement method

The proposed method

The proposed enhanced method is based on the light propagation model in the water. It consists of an incremental algorithm as described on figure 3. After extracting the IOP from colorimetric attributes of the images, the process starts using these parameters and using a fixed distance defined by users. This process, which is descibed in the next section, consists in the light model inversion. Actually, we consider the image to enhance as the result of the light propagation in the water on a scene. Our purpose is then to remove from this image the effects induced by the light propagation. The distance decreases progressively until reaching a good visual quality. The complete model of propagation is used, including in-scattering. Actually, the correction can be reduced to the attenuation only in the case of clear waters (DOM component negligible). But in turbid waters, when the in-scattering becomes substantial and inducing a veiling of the scene, it becomes essential to take account of this effect into the correction process in order to remove the additional light due to scattered illumination.

Model inversion

Some hypothesis have been done in order to simplify the radiative transfer equation. First, the incident underwater light L_i coming from the sun light can be considered as homogeneous and white. Assuming that the image acquisition direction is horizontal, the incident light is perpendicular to the optical path $P_O P$ from an object placed in P_0 to the observer or the sensor placed in P. Note that, in the case of artificial illumination such as a spot placed over the acquisiton system, in-scattering can be easily expressed by simply multiplying the attenuation distance two times. The scattering is considered as isotropic and then the phase function is given by the constant $\frac{1}{4\pi}$ for any values of θ and θ'. There is no self-illumination (no fluorescence or any other phenomenon). The equation (1) becomes:

$$L(P) = L_\lambda(P_0).e^{\int_{P_0}^{P} -c_\lambda .dP'} + \int_{P_0}^{P} b_\lambda L_i \frac{1}{4\pi} e^{\int_{P'}^{P} -c_\lambda dP"} .dP' \qquad (8)$$

by inversing, the light emmited from the point P_0 is expressed by the following function of the perceived light in P :

$$L_\lambda(P_0) = \frac{L_\lambda(P) - \int_{P_0}^{P} b_\lambda L_i \frac{1}{4\pi} e^{\int_{P'}^{P} -c_\lambda dP"} .dP'}{e^{\int_{P_0}^{P} -c_\lambda .dP'}} \qquad (9)$$

if we define $x = d(P, P_0)$, by integration the relation becomes:

$$L_\lambda(P_0) = e^{c_\lambda x} \times \left[L_\lambda(P) - \frac{L_i}{4\pi} . \frac{b_\lambda}{c_\lambda} . (1 - e^{-c_\lambda x}) \right] \qquad (10)$$

This inverse model is then applied to each pixel on each channel of the images by using the respective spectral attenuation coefficients at the wavelengths corresponding to each channel, respectively 435nm for the blue, 545nm for the green and 700nm for the red.

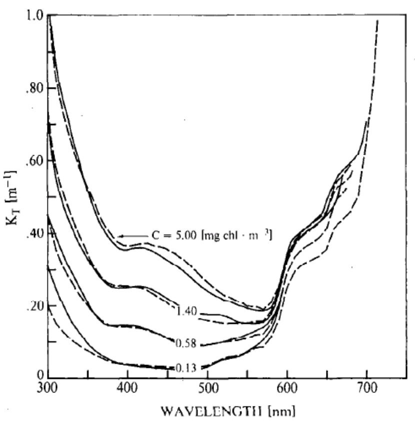

Figure 2. Spectral attenuation coefficient vs. wavelength

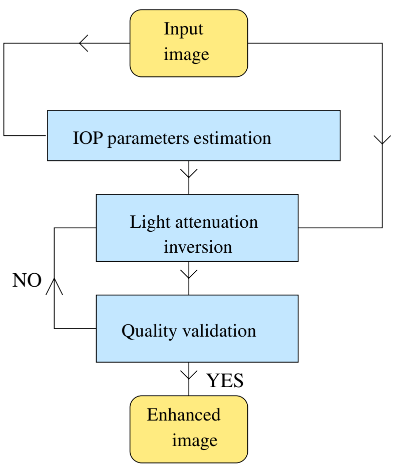

Figure 3. Schematic of incremental algorithm

First results: manual correction

Several tests of the proposed method have been carried out on a set of diving images available on the web. Figure 4 shows the restoration of an oceanic scene. Color balance is getting closer from what it can be expected without water. Objects contrast and visibility are significantly improved. For example, some background objects, hardly visible before the processing, become visible. Haze due to in-scattering is also well removed.

The MSR is a human perception-based image processing algorithm which provides color constancy and dynamic range compression. Comparison with the MSR algorithm [3] shows that MSR provides very good results in term of contrast and visibility, but color rendering is not as good as that provided by the present method. Actually, MSR computes only a partial compensation of light attenuation by removing illumination differences on each channels. When an image is bluish or greenish, colors are partially restored, but the aspect of the images still remains blue or green.

However, after MSR computation, background contrast and lightness are better enhanced because this algorithm does not take account of the distance. Actually, the method performs a global enhancement at a given average distance. However, it is obvious that all objects of the scene are not standing at the same distance from the observer. A local processing, accounting for distance differences between the area of the scene, would provide most accurate results in terms of contrast improvement.

Colorimetric attributes and chlorophyll concentration

Manual corrections were applied to a set of about 50 images. Some examples are presented on figure 5. The user defines the concentration, the distance and the scattering parameters. Adjustment have been done until obtaining the best correction according to the user. These images constitute a training set for our correction algorithm. In order to obtain one semi-supervised or unsupervised algorithm, relationship between the estimated parameters and the colorimetric properties of our training set, were determined. This study is described here after.

Colorimetric attributes in different color spaces (*RGB*, *Lab*, YIQ, YUV, $I_1I_2I_3$, XYZ, *HSI*) have been calculated on our training set. A study of the data shows that the data obtained in the common RGB space, and then colorimetric properties of the images in this space, are linked to the estimated parameters variations: data analysis shows a correlation between the chlorophyll concentration C and the logarithm of the difference between the mean intensity on blue channel and the mean intensity on red channel $log(\overline{I}_B - \overline{I}_R)$ as shown in figure 6. This correlation, about 90%, results from the influence of concentration on spectral attenuation coefficient. Indeed, studies on bio-optical model [6],[7] have directly linked the chloropyll concentration C to attenuation parameters such as described by the following equations:

$$\begin{aligned} c^c_\lambda &= c_1(\lambda) \times C, C < 1 \\ c^c_\lambda &= c_{x2}(\lambda) + c_2(\lambda) \times C, C > 1 \\ c^c_\lambda &= c_{x2}(\lambda) + c_2(\lambda), C = 1 \end{aligned} \quad (11)$$

The parameters $c_1(\lambda)$, $c_2(\lambda)$ and $c_{x2}(\lambda)$ are specific coefficients computed from experimental measured data given in [6].

Figure 4. *(left) Original image (center) Image corrected with our method (right) Image corrected with Multi-Scale Retinex*

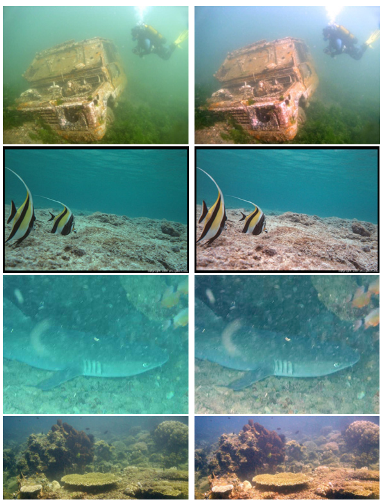

Figure 5. *(left) Original image (right) Corrected image*

These equations show the attenuation is strictly raising for each wavelength when the concentration is increased. However, the relative attenuation of colors is modified. In a pure water, blue radiations are very slightly attenuated unlike the red radiations. The higher is the chlorophyll concentration, the higher is the blue radiations attenuation whereas the red radiations attenuation is almost stable (figure 2). For values of concentrations higher than $13 mg.m^3$ the blue radiations are more attenuated than the red ones. However, the values of the mean intensity on the chromatic channels are strongly linked to the nature of the image content. Given the curve of the figure 6, the regression of the data provides a mathematical model which links colorimetric parameters of the corrected images to the Chlorophyll concentration :

$$C = 11 \times e^{-6.33 \times (\overline{I}_B - \overline{I}_R)} - 0.12 \quad (12)$$

Thus, the equations 11 link colorimetric parameters to the attenuation parameters. Given these parameters, the distance still remains the last parameter to be estimated in order to apply a complete model inversion. Currently, the distance is directly fixed by the user before the process. A data analysis gives a relation between optical parameters and colorimetric attributes, allowing to perform automatically an estimation of the attenuation parameters needed by the model which is then reversed. Moreover, extension of this work will give rise to a fully automatic method for underwater images enhancement by estimating the distance, illumination and in-scattering parameters.

Conclusion

The method presented in this paper opens a new approach for improving contrast and color dynamic on underwater images. The proposed method, based on the physical properties of the light, works without any *a priori* information about the media. The obtained results show that final color rendering produced by this algorithm is better than an often-used color constancy computation, especially when overall haziness is substantial. Next to these accurate enhancement results, a data analysis shows a correlation between colorimetric attributes and chemical properties of the water. The obtained model allows to define attenuation coefficient without any knowledge about the medium and the acquisition conditions. On going works will be conducted on a criteria allowing to automatically fix the distance and get with a much better accuracy scattering parameters by mean of fitting methods.

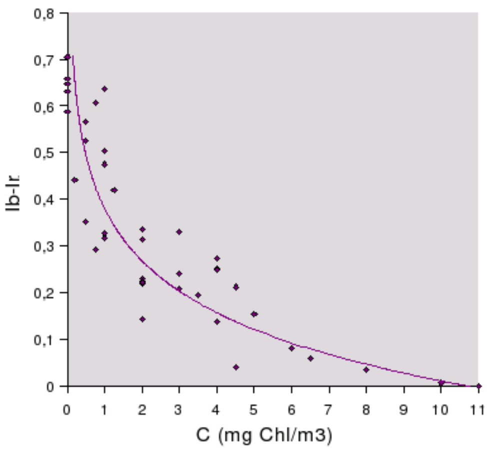

Figure 6. *Blue/red intensity difference $\overline{I}_B - \overline{I}_R$ vs. chlorophyll concentration C*

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