A RETINEX-BASED ENHANCING APPROACH FOR SINGLE UNDERWATER IMAGE

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ABSTRACT

Since the light is absorbed and scattered while traveling in water, color distortion, under-exposure and fuzz are three major problems of underwater imaging. In this paper, a novel retinex-based enhancing approach is proposed to enhance single underwater image. The proposed approach has mainly three steps to solve the problems mentioned above. First, a simple but effective color correction strategy is adopted to address the color distortion. Second, a variational framework for retinex is proposed to decompose the reflectance and the illumination, which represent the detail and brightness respectively, from single underwater image. An effective alternating direction optimization strategy is adopted to solve the proposed model. Third, the reflectance and the illumination are enhanced by different strategies to address the under-exposure and fuzz problem. The final enhanced image is obtained by combining use the enhanced reflectance and illumination. The enhanced result is improved by color correction, lightens dark regions, naturalness preservation, and well enhanced edges and details. Moreover, the proposed approach is a general method that can enhance other kinds of degraded image, such as sandstorm image.

Index Terms— Underwater image, retinex, image enhancement, variational framework, alternating direction optimization

1. INTRODUCTION

Since oceans, rivers and lakes contain abundant resources, underwater imaging has become an important researching filed and received much attention recently. While due to the absorption and scattering when light is traveling in water, there are three major problems of underwater imaging: color distortion, under-exposure and fuzz. This degradation is mainly caused by the physical properties of the medium [1]. First, the color of underwater images is usually distortion due to different light wavelengths. The red light is firstly absorbed and disappears in the water since it has the longest wavelength, in other words the energy of red light is minimum, while the green light has the opposite property [2]. This property makes the underwater images become blue or green. Second, under-exposure is mainly due to the absorption of light energy. This causes the attenuation of brightness and the objects which more than 10 meters from the camera are almost invisibility [3]. Third, two reasons lead to the fuzz of underwater images displayed on the screen. One is due to the abundant particles suspending in sea water, the light is scattering and the propagating direction is shift. Another is that both water and suspended particles reflect light to the camera which affects the objects' reflected light in the water. Meanwhile, a portion of the light scattered back from particles which reduce the scene contrast.

Many approaches are proposed to enhance this special degraded images and can be classified into two categories. One is based on image enhancement method. In [4], the polarization imaging is used to enhance the visibility of underwater images. This method requires different degrees of polarization images and is impractical for application. A similar approach is introduced in [5] which use multiple images to restore the contrast. Methods in [3][6] are based on image fusion and blends different filters to reconstruct a clear image. Literature [2] utilizes the haze removal algorithm [7] to restore the clear image since the underwater imaging is similar to hazy image formation model. However, this method fails when the color distortion is severe. Another kind of approaches is based on the image restoration method. In [8], a point spread function and a modulation transfer function are combined to suppress the blurring effect. Recently, an image restoration approach [9], which based on the radiation transfer function, is adopted to restore the visibility of degraded underwater images.

The variation of underwater environment can be seen as the change of illumination, since the scattering in water has the property of a uniform distribution [10]. This property makes it possible to use retinex method to enhance the un-

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derwater image. In this paper, a novel retinex-based enhancing approach is proposed to enhance single underwater image. There are mainly three steps to enhance an underwater image. First, a simple but effective color correction strategy based on a statistical approach is adopted to address the color distortion. Then a variational retinex model is built to decompose the reflectance and the illumination from the luminance of the color correction image. Third, since the reflectance and the illumination represent the detail and brightness respectively, two methods based on histogram are used to enhance the reflectance and the illumination. This post-processing can address the problem of fuzz and under-exposure. Since the proposed approach is based on single image, other information about the underwater environment or scene condition is not required.

Unlike existing methods, the proposed approach first decomposes the reflectance and illumination from single underwater image. The enhanced image is obtained by combining use the enhanced reflectance and the enhanced illumination. This processing mechanism is more consistent to the objective fact and subjective perception than other methods. Another contribution is that a novel variational retinex model is proposed to compute the reflectance and the illumination effectively. In addition, our approach can enhance other kinds of degraded image, such as sandstorm image, which is shown in the experimental results.

2. THE PROPOSED NEW ENHANCING APPROACH

The proposed strategy consists of mainly three steps: color correction of the input underwater image, decomposing the reflectance and the illumination (from the color corrected input) and post-processing for fuzz and under-exposure. Fig. 1 is the flow chart of the proposed algorithm.

2.1. Color correction

Since the green light travels the longest distance through water for its shortest wavelength, most underwater images appear green or blue. To address the color cast, a color correction based on statistical method is adopted. We define S as the observed underwater image. The operation process is as follows. First, the mean value and the mean square error are computed in RGB (red, green and blue) channels of S respectively. Second, the maximum and minimum of each channel is calculated by

$$\begin{aligned} S^c_{\max} &= S^c_{\text{mean}} + \mu S^c_{\text{var}} \\ S^c_{\min} &= S^c_{\text{mean}} - \mu S^c_{\text{var}} \end{aligned} \tag{1}$$

where $c \in \{R, G, B\}$, S^c_{mean} and S^c_{var} are the mean value and the mean square error (MSE) in the c channel, respectively; μ is a parameter to control the image dynamic; $S^c_{\max}$ and $S^c_{\min}$ are the maximum and the minimum of the c channel. Finally, the color corrected image is obtained by

$$S^c_{CR} = \frac{S^c - S^c_{\min}}{S^c_{\max} - S^c_{\min}} \times 255 \tag{2}$$

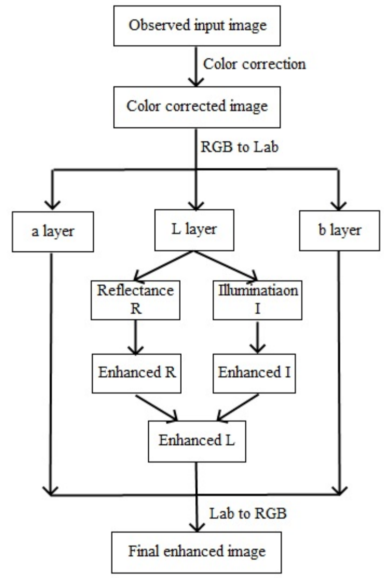


Fig. 1. The flow chart of the proposed algorithm.

where S_{CR} is color corrected image.

2.2. Decomposing the reflectance and the illumination

Since the variation of underwater environment is similar to the change of illumination, retinex method can be used to overcome the problem of under-exposure and fuzz. The retinex theory demonstrates that the human visual system can deal with illumination that changes both brightness and color adaptively [11][12]. In this paper, we use this theory to decompose the reflectance and the illumination from luminance layer of S_{CR} to address under-exposure and fuzz. In the following, a novel variational retinex model is presented, and then an alternating direction optimization strategy is adopted to solve the model.

Since S_{CR} is color corrected, the proposed variational retinex model is established on the luminance layer of Lab color space based on a large amount of psychophysical data concerning color-matching experiments performed by human observers [13][14]. The formula of retinex is $S = R{\cdot}I$, where S is the observed image, R is the reflectance and I is illumination. It is an ill-posed problem to compute R and I by using one observed image S, so other constraints should be used. The proposed model is based on the following known information, 1) illumination is piece-wise smooth; 2) reflectance is piece-wise constant and contains edges and details information; 3) the value of R is from 0 to 1, which means $I \geq S$.

First, the color corrected image S_{CR} is mapped into Lab color space and then the luminance layer L is used to build the proposed model

$$\begin{aligned} \arg\min_{R,I} \|R \cdot I - L\|_2^2 + \alpha \|DI\|_2^2 + \beta \|DR\|_1 \\ + \gamma \|I - I_0\|_2^2 \;\; s.t. \;\; L \leq I \end{aligned} \tag{3}$$

where α, β, and γ are free positive parameters, D is the difference operator at both in horizontal and vertical direction. The first penalty term ($\|R \cdot I - L\|_2^2$) constrains proximity between $(R \cdot I)$ and L. The second penalty term ($\|DI\|_2^2$) constrains spatial smoothness on the illumination, therefore the regularization term is given by L2-norm. The third penalty term ($|DR|_1$) constrains piece-wise constant on the reflectance and total variation (TV) is used as the regularization term. The forth term ($\|I - I_0\|_2^2$) which weighted by γ, is used for a theoretical setting. In this paper, we simply use the Gaussian low-pass filtering of L as I_0 to avoid illumination intensity varies too quickly. Moreover, according to the prior, the value of R is from 0 to 1, the equation should subject to: $L \leq I$.

Since there are two unknown variables in model (3), traditional gradient decent or other discrete optimization methods are not usable. An alternating direction optimization algorithm is introduced to calculate R and I iteratively. An auxiliary variable d is introduced to solve the TV term. Model(3) is rewritten as

$$\arg\min_{R,I,d} \|R \cdot I - L\|_2^2 + \alpha \|DI\|_2^2 + \beta\{\|d\|_1 + \lambda \|DR - d\|_2^2\} + \gamma \|I - I_0\|_2^2 \quad s.t. \; L \leq I \tag{4}$$

The computing procedure is presented is as following. First, an initialization for the alternating optimization is made. In this paper, the Gaussian low-pass filtered image of L is employed as the initialization of I and set $R = 0$.

After the initialization, for a given R, d is updated by using shrinkage operator

$$d_x = shrink(D_x R, \frac{1}{2\lambda})$$
$$d_y = shrink(D_y R, \frac{1}{2\lambda}) \tag{5}$$

where $shrink(x, \varepsilon) = \frac{x}{|x|} * \max(|x| - \varepsilon, 0)$, x and y are the horizontal and vertical directions respectively.

Given d and I , update R by using

$$R = \mathcal{F}^{-1}\left(\frac{(1+\beta\lambda)\mathcal{F}(L/I)}{\mathcal{F}(1)+\beta\lambda(\mathcal{F}(D_x)^*\mathcal{F}(D_x) + \mathcal{F}(D_y)^*\mathcal{F}(D_y))}\right) \tag{6}$$

where $\mathcal{F}$ is the Fast Fourier Transform (FFT) operator and $\mathcal{F}()^*$ is the complex conjugate. The FFT diagonalizes derivative operators and this operation avoids very-large-matrix inversion in order to acceleration. All calculations are component-wise operators.

Given R, update I by using

$$I = \mathcal{F}^{-1}\left(\frac{\mathcal{F}(\gamma I_0 + L/R)}{\mathcal{F}(1+\gamma)+\alpha(\mathcal{F}(\mathrm{D}_x)^*\mathcal{F}(D_x) + \mathcal{F}(D_y)^*\mathcal{F}(D_y))}\right) \tag{7}$$

According to the prior knowledge: $L \leq I$, we simply make a correction of I after calculation: $I = \max(I, L)$.

2.3. Post-processing for fuzz and under-exposure

After computing R and I with a few iterations, a post-processing based on histogram is adopted to address the fuzz and under-exposure problem. Since the reflectance R, which contains details and edges information, is fuzzed and attenuated by suspended particles' affection in the water, contrast limited adaptive histogram equalization (CLAHE) [15] is adopted to obtain the enhanced reflectance $R_{enhanced}$. This operation can enhance details and edges effectively meanwhile avoids noise amplification. To address the problem of under-exposure, a slight improved histogram specification is worked on the illumination I. The enhanced illumination should be bright enough to improve exposure and lighten dark regions; meanwhile the lightness order and naturalness should be preserved. According to the experimental results, the shape of arc tangent performs well: $I' = \arctan(I)$.

Inspired by the Bi-log Transformation [16], the number of the gray intensity is utilized as a weight to generate a weighted histogram. This operation takes both the numbers of pixels and gray values into consideration and can well preserve the naturalness. According to the definition of the Cumulative Density Functions (CDF) [17][18], the CDF of I' is:

$$C(z) = \frac{\sum_{i=0}^{z} I'(i) \cdot n(i)}{\sum_{i=0}^{\max(z)} I'(i) \cdot n(i)} \tag{8}$$

where z is the zth gray level of I, $\max(z)$ is the maximum gray level of I, n is the number of the zth gray level. In order to lighten dark regions and preserve naturalness to avoid over-enhancement, we constrain the region of specified histogram in $[15, 230]$. The CDF of the specified histogram is defined:

$$Cf(t) = \frac{\sum_{i=0}^{t} s(i)}{\sum_{i=0}^{230} s(i)} \tag{9}$$

where $s(t) = \arctan(t - 15), t \in [0, 230]$. The enhanced illumination $I_{enahnced}$ can be obtained by $I_{enhanced} = Cf^{-1}(C(I))$.

Finally, we combine the enhanced R and I together to obtain the enhanced L layer: $L_{enahnced} = R_{enahnced} \cdot I_{enahnced}$. Then the new Lab color space is transformed into RGB to acquire the final enhanced color image.

3. EXPERIMENTAL RESULTS AND ANALYSIS

Experimental results are presented to demonstrate the effectiveness of the proposed approach in this section. The simulation tool is Matlab R2012a on a PC with a 2.60GHz Intel Pentium Dual Core Processor. The parameters μ, α, β, γ, and λ are fixed as 2.3, 100, 0.1, 1 and 10 respectively in our experiments and 4-6 iterations are generally performed. It

(a) (b)

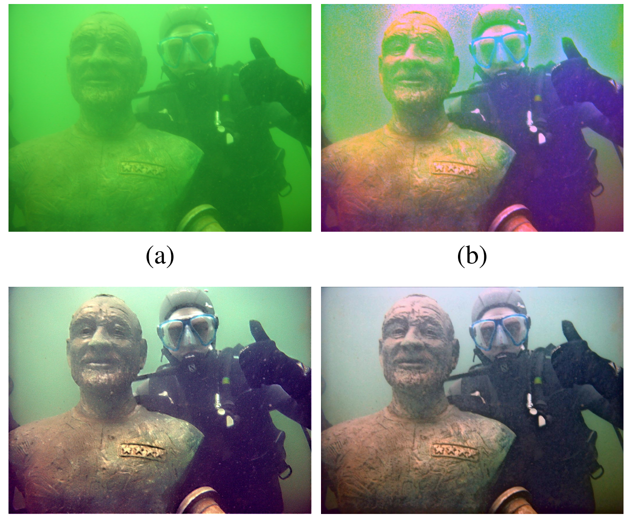
Fig. 2. (a) the observed image. (b) the enhanced image by proposed approach.

takes about 5 seconds to process one color image with size of 950×720. More experimental results can be found on our website: http://smartdsp.xmu.edu.cn/underwater.html.

Fig. 2 shows one of experimental results. As shown in Fig. 2 (a), the observed underwater image is color distortion, fuzz and under-exposure due to the absorption and scattering. Comparing with the original image, the enhanced one shown in Fig. 2 (b) has a significant improvement by color correction, lightening dark regions, naturalness preservation, and enhanced edges and details.

In this test, two up-to-date approaches [2][3] are referenced to make a comparison. It is obviously that method [2] fails to process the observed image as shown in Fig. 3 (b). Since method [2] uses the dark channel prior and haze removal algorithm [7] to restore the degraded image, while in some extremely conditions, such as serious color distortion and ambient light is very dark, this algorithm does not work well. Method [3] uses image fusion technology to enhance underwater images and obtain a good result as shown in Fig. 3 (c). While in some regions has a slight over-enhancement, such as the five-pointed star on the statue. This due to the method [3] blends different filters to enhance corresponding details which not consider the balance of objective facts and subjective perception. The enhanced result, which shown in Fig. 3 (d), has a similar visual quality with [3] meanwhile the global naturalness is preserved better. This is because the proposed method, which based on the human vision system, not only enhances details but also adjusts the illumination to make subjective visual perception more comfortable.

In addition, the proposed approach can enhance other kinds of degraded image, such as sandstorm image. Since the sandstorm has the similar environment with underwater: both of them have suspended particles in the medium, light is absorbed and scattered, images appear color distortion and fuzz. Fig. 4 shows the experimental result of a sandstorm image. In Fig. 4 (b) the color is well corrected, meanwhile edges, details and visibility of distant view are enhanced by the proposed approach. This result demonstrates the specific application capability of our method.



(a) (b)

(c) (d)

Fig. 3. (a) the observed image. (b) the enhanced image by [2]. (c) the enhanced image by [3]. (d) the enhanced image by proposed approach.

(a) (b)

Fig. 4. (a) the observed sandstorm image. (b) the enhanced image by proposed approach.

4. CONCLUSIONS

A new retinex-based enhancing approach for single underwater image is proposed in this paper. Reflectance and illumination from single color corrected underwater image are decomposed to address the fuzz and under-exposure. A novel variational retinex model is built and an alternating direction optimization algorithm is introduced to make the decomposition. A simple and yet effective post-processing is adopted to enhance degraded images after decomposing. Experimental results demonstrate that enhanced images have the property of color correction, brightness, naturalness preservation and well sharpness. Moreover, it is shown that the proposed new approach can enhance other kinds of degraded image.

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