Single Underwater Image Enhancement with a New Optical Model

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***Abstract*— As light is attenuated when disseminating in water, the clarity of images or videos captured under water is usually degraded to varying degrees. By exploring the difference in light attenuation between in atmosphere and in water, we derive a new underwater optical model to describe the formation of an underwater image in the true physical process, and then propose an effective enhancement algorithm with the derived optical model to improve the perception of underwater images or video frames. In our algorithm, a new underwater dark channel is derived to estimate the scattering rate, and an effective method is also presented to estimate the background light in the underwater optical model. Experimental results show that our algorithm can well handle underwater images, especially for deep-sea images and those captured from turbid waters.**

I. Introduction

For an underwater image, the radiance of the scene point attenuates exponentially with the propagating distance, according to Beer–Lambert law. The light attenuation in water is caused mainly by absorption and scattering. From red to violet, the wavelength becomes shorter gradually. According to the selective absorption of water, visible light is absorbed at the longest wavelength first. So red light is much easier to be absorbed than shorter wavelengths such as the blue and green. On the other hand, based on Rayleigh scattering theory, scattering intensity is inversely proportional to the fourth power of wavelength, so that shorter wavelengths of violet and blue light will scatter much more than the longer wavelengths of yellow and especially red light. We can conclude that water absorbs the longer wavelength of red and scatters the blue and violet when visible light disseminates in it. The wavelength of green light is between the wavelength of red and blue light, but much closer to the latter. Thus, we can also assume that the attenuation of green light only results from scattering. All of the above constitutes the theoretical basis of our work. It should be noted that for an outdoor haze image, the major factor resulting in light attenuation is scattering due to suspended particles [1]. Clearly, there are significant difference between underwater images and outdoor haze images in physical process.

Recently, several techniques have been proposed to handle single underwater image [5, 7, 8]. In [7, 8], the authors directly applied the dark channel prior [4] in underwater conditions. However, as we will specify in Section III, the traditional dark channel prior is not applicable for underwater images. Carlevaris-Bianco et al. [5] proposed a prior that exploits the strong difference in attenuation between the three image color channels to estimate the depth of the scene and then used the depth map to reduce the effect of water. In [3], Fattal presented a method for single image dehazing, but he also provided results for underwater images. Among these methods, the authors all built their underwater image enhancement work on the atmospheric scattering model. However, due to the distinction between atmosphere and water, it is not appropriate to use the atmospheric scattering model for underwater images.

In this paper, we propose a new underwater optical model to describe the formation of underwater images and present an effective underwater image enhancement method based on this model. Fig. 1 shows the flow of our method. We use underwater dark channel prior to estimate the scattering rate and the transmission of blue and green light. We also employ a novel and effective *light attenuation difference* based method to estimate the background light of an underwater scene. The details of our algorithm will be presented in Section IV.

II. Underwater Optical Model

In [2, 4], the model used to describe the formation of a haze image is:

$$I(x) = J(x) \cdot t(x) + A(1 - t(x)), \qquad (1)$$

where I is the observed intensity, J is the scene radiance, A is the global atmospheric light, and t is the transmission map. This model is also used in [5, 7, 8] for underwater image enhancement. To some degree, an underwater image is similar to a haze image. Both of them are degraded by the turbid medium, and the captured intensity can be modeled as being composed of two components: the direct transmission of light from the scene and the transmission due to scattering by the particles of the medium. But due to the difference in attenuation between in atmosphere and in water, we should not equate the underwater optical model to its atmospheric version. That is, for underwater images, we should consider both the effect of absorption and scattering on light attenuation. What's more, the extent of the attenuation is not exactly the same for different wavelengths of light. Consequently, we should employ different transmissions for different color channels.

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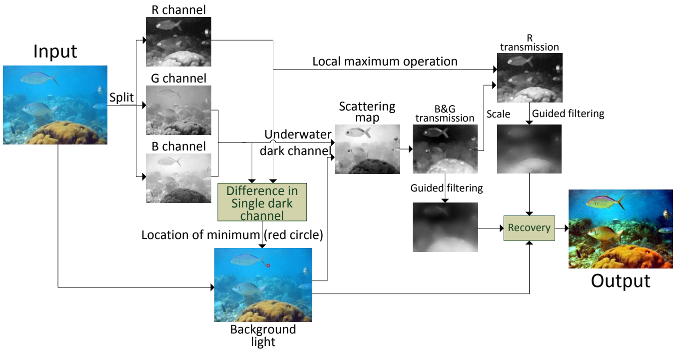


Fig. 1. Frame diagram of our method.

Instead, our model can be described mathematically as:

$$I^c(x) = J^c(x) \cdot t^c_\beta(x) + B^c \cdot t_\alpha(x), \tag{2}$$

where I is the observed intensity, J is the true scene radiance, c is a color channel which can be red, green or blue, B is the scattering light from the medium, which can be called as background light, and t_β is the transmission which represents the percentage of the scene radiance reaching the camera, and t_α is the scattering rate. Note that t_β includes the effect of both absorption and scattering.

III. Underwater Dark Channel Prior

The traditional dark channel prior is based on the following observation on haze-free outdoor images: in most of the non-sky patches, at least one color channel has very low intensity at some pixels. It can be defined as:

$$J^{dark}(x) = \min_{c\in\{r,g,b\}} (\min_{y\in\Omega(x)} (J^c(y))), \tag{3}$$

where J^c is a color channel of J and $\Omega(x)$ is a local patch centered at x. According to the dark channel prior, except for the sky region, the intensity of the dark channel is low and tends to be zero. Next, we will illustrate why the above dark channel prior does not apply to underwater images. According to He et al.'s theory, the intensity of the dark channel of a haze image is a rough approximation of the thickness of the haze. Its the key to haze removal. But for underwater images, the traditional dark channel prior may fail at many cases. In order to facilitate the description, we define *the single dark channel* as:

$$I^{dark(c)}(x) = \min_{y\in\Omega(x)} (I^c(y)), \tag{4}$$

and the dark channel of I can be written as:

$$I^{dark}(x) = \min_{c\in\{r,g,b\}} (I^{dark(c)}(x)). \tag{5}$$

We find that for an image captured around deep-water area or under muddy water, due to the energy of red light being absorbed largely, the intensity of $I^{dark(r)}(x)$ is very low and tends to be zero, which causes the dark channel of the input underwater image to be prone to a zero map (Fig. 2 middle). Consequently, the dark channel of these underwater images cannot provide information about the thickness of the water (i.e. the distance between the scene and the camera).

Fig. 2. Comparison with traditional dark channel. Left: input image. Middle: He's dark channel. Right: underwater dark channel.

As light attenuation in atmosphere and the attenuation of blue and green light in water almost share the same principle—scattering, we could consider only the blue and green channels and redefine a new dark channel that fits the underwater image:

$$J^{uwdark}(x) = \min_{c\in\{g,b\}} (\min_{y\in\Omega(x)} (J^c(y))). \tag{6}$$

We call it *the underwater dark channel* of J. Similarly to the traditional dark channel prior, the intensity of the underwater dark channel should be low and tend to be zero. Empirically, the backgrounds of underwater scenes tend to be blue (for seas and oceans) or green (for lakes). Due to the color shift caused by the background light, the intensities of blue or green channels of a captured underwater image should be larger than their true radiances. And the underwater dark channel of an underwater image will have higher intensity in regions farther from the camera. Consequently, the underwater dark channel can qualitatively reflect the underwater distance between the scene point and the camera. In the following section, we will use it to estimate the scattering rate.

IV. Underwater Visibility Enhancement

From (2), we can derive:

$$J^c(x) = \frac{I^c(x) - B^c \cdot t_\alpha(x)}{t^c_\beta(x)}. \tag{7}$$

In order to recover the true radiance J of an underwater scene, we need to estimate B, $t_\alpha(x)$ and $t^c_\beta(x)$ to calculate $J^c(x)$.

A. Background Light Estimation

In [2, 3], the atmospheric light is estimated from the most haze-opaque pixel. In [4], He et al. pick the top 0.1% pixels in the dark channel instead of the brightest pixel. Atmospheric light found in these ways tends to be white, while it is empirically true that the background of an underwater scene tends to be blue or green. So the methods used to estimate atmospheric light is ill-suited for underwater images.

Due to the severe attenuation of red light, the intensity of the red channel of the background is very low, but that of the blue or green channel is relatively high due to the addition of scattering light. Then the background light can be estimated as follows:

$$p = \arg \min_x (I^{dark(r)}(x) - \max(I^{dark(b)}(x), I^{dark(g)}(x))), \tag{8}$$

where $p = (i, j)$ is the pixel location where we get the background light from the input image. As shown in Fig. 6, the background light pixel locates in the center of the red circle of each input image.

B. Scattering Rate Estimation

Since the attenuating principle of blue and green light are much the same in water, we assume the transmissions of blue and green color channels are identical in this paper. We further assume the transmission and the scattering rate in a local patch $\Omega(x)$ is constant here and we denote the patch's transmission and the scattering rate as $\tilde{t}_\beta$ and $\tilde{t}_\alpha$. Taking the min operation in the local patch then among the color channels on (2), we have:

$$\min_c(\min_{y\in\Omega(x)}(\frac{I^c(y)}{B^c})) = \tilde{t}_\beta(x)\min_c(\min_{y\in\Omega(x)}(\frac{J^c(y)}{B^c})) + \tilde{t}_\alpha(x), \tag{9}$$

where $c \in \{b, g\}$. Similarly to the dark channel theory [4], the first term on the right side of the above equation should tend to be zero. So we can estimate the scattering rate as:

$$\tilde{t}_\alpha(x) = \min_{c\in\{b,g\}}(\min_{y\in\Omega(x)}(\frac{I^c(y)}{B^c})). \tag{10}$$

In fact, $\min_{c\in\{b,g\}}(\min_{y\in\Omega(x)}(\frac{I^c(y)}{B^c}))$ is the underwater dark channel of the normalized underwater image $\frac{I(y)}{B}$.

C. Transmission Estimation

Since the attenuation of both blue and green light results from scattering, it is easy and immediate to estimate their transmission as:

$$\tilde{t}^b_\beta(x) = \tilde{t}^g_\beta(x) = 1 - \tilde{t}_\alpha(x). \tag{11}$$

Next, we will estimate the transmission of the red channel of an input image. For a scene point under water, the farther it is from the camera, the more energy of red light is absorbed, and accordingly the smaller the transmission of the red channel will be. Moreover, there is few red component in the ambient light which is reflected into the propagating line by water molecules and other particles. We intuitively presume that the foreground's intensity of the red color channel should be larger than the background's. And for objects with similar color, the one closer to the camera has larger intensity of the red color channel than the others. So the red channel of an underwater image can qualitatively reflect the transmission rate of the red channel. We can directly calculate the transmission map of the red color channel as follows:

$$\tilde{t}^r_\beta(x) = \tau \cdot \max_{y\in\Omega(x)} I^r(y), \tag{12}$$

where τ is a scale parameter used to amend the transmission map of the red color channel. It can be a default constant. In this paper, we choose it as:

$$\tau = \frac{avg(\tilde{t}^b_\beta(x))}{avg(\max_{y\in\Omega(x)} I^r(y))}. \tag{13}$$

Just like other dehazing methods, we place one lower boundary on each estimated transmission to avoid accentuating noise in regions with very bad visibility. The lower boundary in our experiments is from 0.3 to 0.5 for a 600×400 image. For transmission maps estimated in (11) and (12), we assume that the transmission in a local patch $\Omega(x)$ is constant, which will introduce some block effect. Then we apply the guided filter proposed in [6] to refine $\tilde{t}^b_\beta(x)$ and $\tilde{t}^r_\beta(x)$.

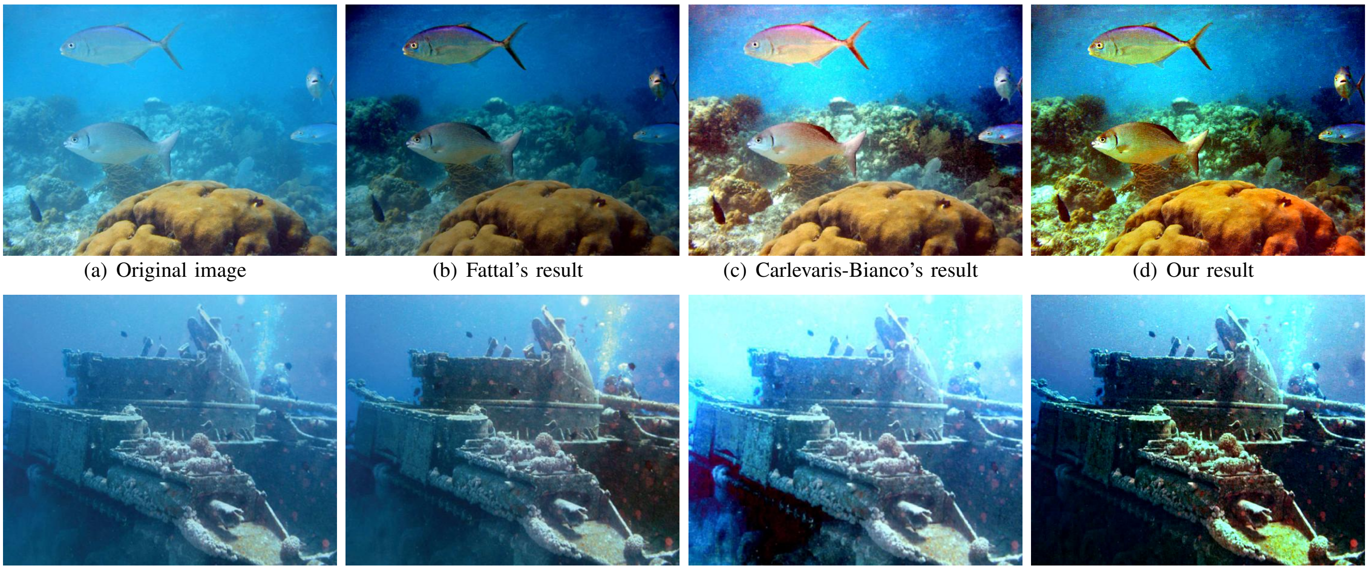
Fig. 3. Comparison with He's work. Left: input image. Middle: result of He's method. Right: our result.

Fig. 5. Enhancement results. Top: input underwater images. Bottom: our results.

V. Results

Fig. 3 shows comparison between the result of our implementation for He's algorithm and our result. It can be seen that He's work has little or no effect on this kind of deep-sea image due to the failure of the traditional dark channel prior. Our result has apparent effect for revealing distant details. In Fig. 4 we simultaneously compare our results with those provided by Fattal [3] and Carlevaris-Bianco [5]. For the image with fish, our result provides better enhancement for distant objects and background than Fattal's result; Carlevaris-Bianco's result well handles distant objects, but there are more red components in their result, especially in the background. Possibly our result is more visually pleasuring. For the image with ship, Fattal's result unveils the details only in the regions above the main diagonal of the image and do nothing below the diagonal; Carlevaris-Bianco's result provides no significant effect for dehazing and contains evident color distortions in the lower left area; instead, our result provides good dehazing effect in the whole image and unveils more details than Fattal's result.

Fig. 5 and 6 show more results of our method. We can see that our method can expose the details and recover vivid color information even in very turbid regions. For instance, the left-hand-most pair of images in Fig. 6 show almost perfect recovery. In the top row of Fig. 6, the center of the red circle of each input image represents the location of the background light pixel found by our method. Clearly, our method can find the precise background light of scenes.



(a) Original image (b) Fattal's result (c) Carlevaris-Bianco's result (d) Our result

(e) Original image (f) Fattal's result (g) Carlevaris-Bianco's result (h) Our result

Fig. 4. Comparison with Fattal's and Carlevaris-Bianco's work.

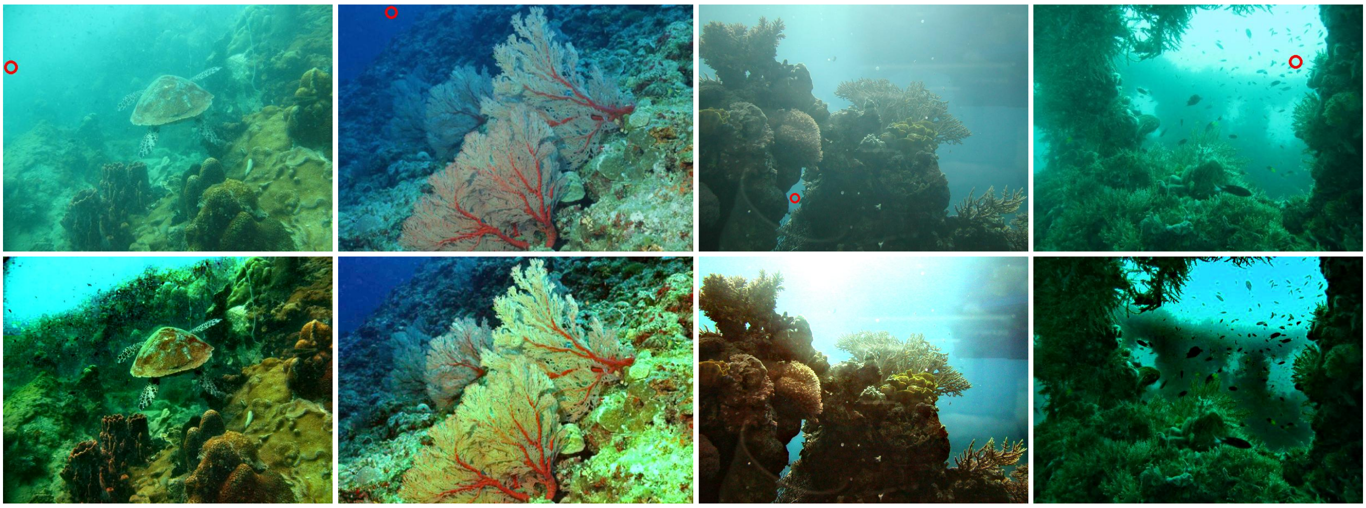


Fig. 6. More enhancement results. Top: input underwater images. Bottom: our results. The red circle in each input image tells the location of the background light pixel.

VI. Conclusions

In this paper, we derive a new underwater optical model to describe the formation of an underwater image, and then propose an effective underwater image enhancement algorithm with this model. Our algorithm is effective and physical valid, and can well handle deep-sea images and images captured from turbid waters. In future work, we will further improve the adaptability and flexibility of our algorithm.

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