# A Review on Intelligence Dehazing and Color Restoration for Underwater Images

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***Abstract*—Underwater image processing is an intelligence research field that has great potential to help developers better explore the underwater environment. Underwater image processing has been used in a wide variety of fields, such as underwater microscopic detection, terrain scanning, mine detection, telecommunication cables, and autonomous underwater vehicles. However, underwater imagery suffers from strong absorption, scattering, color distortion, and noise from the artificial light sources, causing image blur, haziness, and a bluish or greenish tone. Therefore, the enhancement of underwater imagery can be divided into two methods: 1) underwater image dehazing and 2) underwater image color restoration. This paper presents the reason for underwater image degradation, surveys the state-of-the-art intelligence algorithms like deep learning methods in underwater image dehazing and restoration, demonstrates the performance of underwater image dehazing and color restoration with different methods, introduces an underwater image color evaluation metric, and provides an overview of the major underwater image applications. Finally, we summarize the application of underwater image processing.**

***Index Terms*—Color restoration, image dehazing, image enhancement, underwater image processing.**

## I. Introduction

In RECENT years, with the growing shortage of resources and the continuous development of the global economy and international relations, the underwater environment has gradually become a novel center of the world. The underwater environment, which contains numerous biological resources and energy, is one of the central components necessary to maintain the sustainable development of human beings. People often use video or images to obtain valuable information when studying the underwater environment. However, the acquisition of underwater optical imaging faces more challenges than that in the atmosphere, whereby degradation is usually caused by strong absorption and scattering. This image degradation seriously affects exploration of the underwater environment. Therefore, the research on underwater optics [1], [2], underwater imaging technology [3]–[6], and underwater target detection technology [7]–[10] has a wide range of applications from underwater resources exploration [11], underwater environmental protection [12] to underwater military affairs [13].

Common underwater optical imaging cannot guarantee satisfactory performance, because light propagating underwater suffers from strong absorption, scattering, color distortion, and noise from the artificial light source [3], [14], [15]. The particles of the water absorb the vast majority of light energy, resulting in dim and blurry images. The scattering process consists of a series of direction changes of light after collision with particles in the water, such as sand and plankton, causing a hazy image [16]–[18]. This situation is similar to the effect of hazy weather on outdoor vision.

The camera received light generated by three components: 1) the direct component is that light reflects from the objects to the camera directly; 2) the forward component is that light deviates on its way from the original directions and randomly reflects to the camera; 3) the back scattering component is that light encounters particles before reflects to the camera, and these particles in turn scatter the light. The multiscattering process along the course of propagation further disperses the beam into homogeneous background light. Because of the wavelength dependence of light attenuation, the shorter wavelengths (green and blue colors), can reach greater depths under the water than the longer wave-lengths (red color) which vanish rapidly after 4–5 m, leading to images with a typical bluish or greenish tone. Owing to the turbidity and the suspended particles of the water, it is a huge challenge to restore the image; the performance of algorithms has a strong correlation with water conditions which vary greatly with the location and season.

Usually, in order to increase the visibility under the water, an artificial light source is added to the camera device [19]–[21], but the artificial light sources bring some problems as well: the high power cost of illuminating an underwater scene is too expensive for long-term continuous use, it also reduces the portability and flexibility of the device; moreover, the illumination brings inhomogeneous characteristics and there occurs a bright area in the central area of the image, the overall image brightness distribution is uneven, degrading the image quality. Fig. 1 shows the underwater optical imaging model summarized above.

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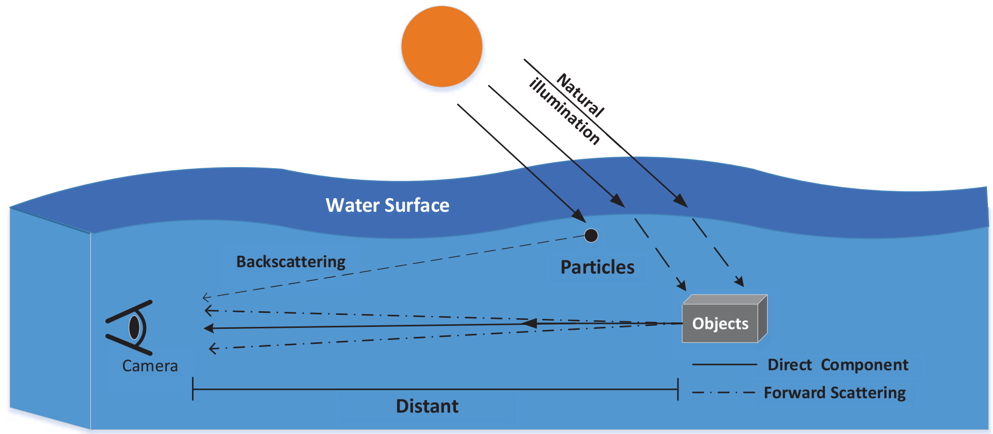


Fig. 1. Underwater optical imaging model.

Usually, underwater image visibility decreases fast after a distance of 4–5 m under the water. Researchers have designed numerous hardware platforms and cameras in order to increase the visibility under the water over the past years [22], [23], which have already been applied in a wide range of fields. In these applications, hardware platforms include range-gated imaging [24], [25], fluorescence imaging [26], and stereo imaging [27]; the cameras include an underwater video camera [22], drifting underwater camera system [28], two-view camera [29], and underwater three-dimensional scanner [30]. All these researches have been utilized in various fields, including underwater microscopic detection [31], terrain scanning, mine detection, telecommunication cables, autonomous underwater vehicle (AUV) [32], pipelines [33], nuclear reactors, and columns of offshore platforms.

Many scholars have published literature reviews about underwater imaging, which tightly integrated the development of underwater imaging [34]–[38]. Lu *et al.* [39] surveyed underwater optical imagery captured from AUVs. Mallet and Pelletier [40] focused on a review of underwater video techniques for observing coastal marine biodiversity developed in the last 60 years. Tan *et al.* [41] analyzed the advances in the field of underwater localization. Chu *et al.* [42] reviewed biomimetic underwater robots using smart actuators. Moreover, Partan *et al.* [43] discussed underwater sensor networks. Unlike other literature reviews, which only concentrate on certain aspects of underwater imaging, we offer scholars a comprehensive understanding of underwater image processing. For example, Erol-Kantarci *et al.* [44] mainly focused on discussing underwater acoustic signal processing broadly; Sahu *et al.* [45] only introduced a series of underwater image enhancement methods; and Kaeli *et al.* [46] merely outlined a set of algorithms for underwater image color correction improvement.

In this review, we investigate the advances of underwater imaging, the current challenges and applications. Our major contributions may be described as follows.

We summarize a comprehensive review on the current research. We introduce typical underwater image degradation types such as absorption, scattering, color distortion, and artificial light source disturbance in details.

We outline the-state-of-the-art underwater image intelligence dehazing and color restoration algorithms like deep learning methods which can help scholars better comprehend the concept of underwater image processing.

We analyze the application of underwater image in various fields, including underwater target detection, underwater navigation, and AUVs.

The rest of this paper is organized as follows. In Section II, we introduce the current challenge and research advances in reducing haze from underwater imagery. We summarize the-state-of-the-art algorithms on underwater color distortion and the color evaluation metric in Section III. In Section IV, we outline the applications of underwater image processing. Finally, we conclude this review in Section V.

## II. Underwater Image Dehazing

Although the development of underwater cameras can promote image quality to a certain extent, digital image processing is much easier and cheaper to implement in software than the high cost of imaging system devices. Since the conception of digital image processing was proposed, the research of underwater image processing has been greatly developed [47]–[49]. We have counted the proportion of the research hotspots of underwater imaging in the engineering village database. Underwater image restoration and underwater image enhancement are the dominate fields as shown in Fig. 2. We have also calculated the number of underwater image papers in the Web of Science database from 2010 to 2016, as shown in Fig. 3. It can be seen that the number of works related to underwater imaging has continuously increasing.

Now we concentrate on the propagation characteristics of light in water. In an underwater scene, the light accepted through a camera mainly has three components: 1) light that reflects from the object is called a direct component; 2) forward-scattering makes light deviate on its way from the original directions and randomly reflects to the camera; and 3) back-scattering is caused by suspended particles reflecting light to the camera before it actually contacts the object [28]. An underwater image can be described as a linear superposition of these three components [50]. Both the

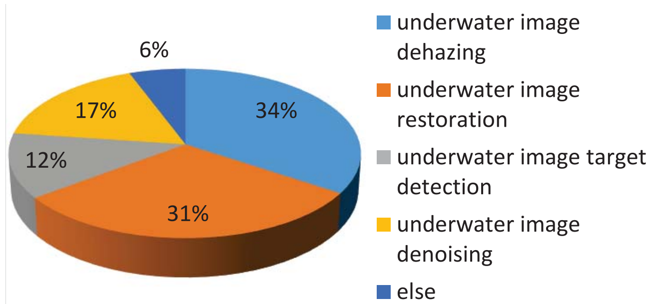


Fig. 2. Underwater image research hotpots in the engineering village database.

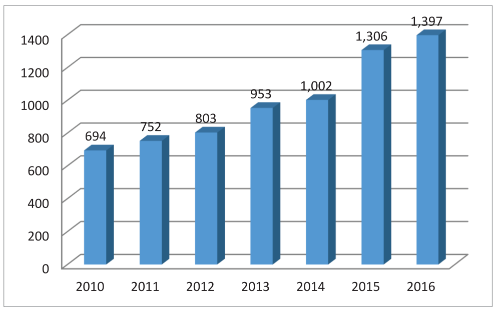


Fig. 3. Number of underwater image papers in the Web of Science database.

forward-scattering and back-scattering cause image blurring and hazing.

Underwater image processing includes image enhancement and image dehazing, enhancement methods make underwater image have better contrast and dehazing methods make underwater image have better visibility.

In recent years, researchers have proposed numerous image enhancement and dehazing algorithms [51], [52]. Pizer *et al.* [53] presented the adaptive histogram equalization (AHE) method; the AHE transformed each pixel with a transformation function derived from a neighborhood region. The method was used to enhance the local contrast of the image. Kim [54] proposed the brightness preserving bihistogram equalization (BBHE) method, which first decomposed the image, then equalized the decomposed image components to each other around the input mean. This method could effectively conserve the mean brightness of the image. Reza [55] developed the contrast limited AHE (CLAHE) in order to prevent the overamplification of noise by contrast limiting, which AHE had a tendency to do. Demirel and Anbarjafari [56] demonstrated the inverse discrete wavelet decomposition (IDWT) method, which decomposed an image by DWT to get several subbands images, and then interpolated the high-frequency sub-band and the raw image; the coefficients obtained by interpolating the high-frequency sub-band image were amended by a stationary wavelet transform. Finally, all these images were combined together to produce an enhanced image. Deng [57] proposed the generalized unsharp masking (GUM) method to improve the sharpness by employing an exploratory data model as a framework. This method enhanced contrast and sharpness simultaneously, and could also eliminate the halo effect. A probability-based method (PB) [58] for enhancement with illumination and reflectance evaluation in the linear domain was presented by Fu *et al.* As shown in Table I, we compare the different image enhancement algorithms described above. However, classic image enhancement algorithms cannot deal with the degradation of underwater images effectively. The reason mainly is that applying classic image enhancement algorithms directly to the degraded underwater images usually neglects the fact that the extent of underwater image degradation varies with the distance of the camera.

In order to deal with hazy weather, researchers have proposed many single-image dehazing algorithms or matrixes. Fattal [59] exploited a method for estimating the optical transmission in foggy scenes based on minimal input; it could fail when the signal-to-noise ratio was inadequate or the multiplicative variation in the core area of the image was insufficient. Moreover, Fattal [60] proposed a novel single-image dehazing algorithm using color-lines pixel regularity. Furthermore, for the purpose of solving the transmission in isolated pixels, Fattal presented an augmented Gauss-Markov random field model. He *et al.* [61] demonstrated a useful and effective single-image dehazing method named the dark channel prior, because the method was based on statistics and thus could fail at some certain physically invalid scene such as where the brightness of objects was similar to that of the background. Tan [62] proposed a method to enhance the visibility in bad weather or turbid underwater circumstances based on single images, without requiring the geometrical structure nor any user interactions. Gao *et al.* [63] and Wang *et al.* [64] extended and improved He's method, and achieved impressive results. Ancuti and Ancuti [65] employed a single-image multiscale per-pixel fusion method to enhance the visibility of foggy images taken in bad weather.

Recently, the deep learning approach has become the state-of-the-art solution in many fields, and shows great performance. Ling *et al.* [66] first proposed a deep learning network for single-image dehazing. The method deals with RGB channels and local detail information simultaneously by a deep transmission network (DTN). The DTN could detect and process haze-relevant features automatically. Meanwhile, they claimed the information of RGB channels was more useful than haze estimation. Cai *et al.* [67] implemented an end-to-end system for medium transmission estimation named DehazeNet, which used a convolutional neural network to output a medium transmission map to dehaze a single image, and got excellent performance. We sort the literature strategies discussed above in Table II. The single-image dehazing methods described above have shown some advantages in terrestrial images. However, there are still some limitations when these methods are used in underwater scenes. Commonly, using methods to enhance and restore underwater images shows less effect owing to the different properties of underwater imaging and lighting conditions with respect to terrestrial imaging. For underwater scenarios, the assumptions and prior matrix used in these single dehazing methods may easily fail.

Owing to the limitations of single-image dehazing techniques, researchers began to focus on the specialized underwater image enhancement and restoration methods in

TABLE I
OVERVIEW OF CLASSIC IMAGE ENHANCEMENT METHODS

| Method | Advantages | Disadvantages |
|---|---|---|
| AHE [53] | A fairly straightforward technique and an invertible operator | The overenhancement of noise in relatively homogeneous regions of an image |
| BBHE [54] | Good consequence for mean brightness preserving while enhancing the contrast | Requires more complicated hardware than the typical histogram equalization |
| CLAHE [55] | Low computational complexity ($o(N)$), prevent overamplification of the noise | Pixel mapping has some limitations in corner regions and boarder regions |
| IDWT [56] | Keep sharper edges than other interpolating methods | Restrictions on some certain conditions |
| GUM [57] | Solving the range problem and halo effect, promotion the contrast and sharpness, eliminating the rescaling process | Poor edge preserving, only useful at atmospheric condition |
| PB [58] | Good computational efficiency by using the FFT to avoid large-matrix inversion, the convergence is guaranteed | Do not stretch the dynamic range to increase the contrast |

TABLE II
OVERVIEW OF SINGLE-IMAGE DEHAZING METHODS

| Author | Advantages | Disadvantages |
|---|---|---|
| Fattal [59] | Locally uncorrelated, good robustness | Easy to fail when signal-to-noise ratio is inadequate or multiplicative variation in the core area of the image is insufficient |
| Fattal [60] | High overall accuracy, long-range coupling | Having the treatment, the sky receives effect, showing limitation when the atmospheric light is close to sky color |
| He et al. [61] | Simple model because the method is based on statistics | May fail at some certain physically invalid scene |
| Tan et al. [62] | Without requiring the geometrical structure nor any user interactions | Halo effects, sometimes cannot guarantee the global optimum |
| Ancuti et al. [65] | Low complexity because of using an effective per-pixel computation, good accuracy | Having limitation when process color images |

recent years. Chiang and Chen [68] enhanced underwater images by joining a dehazing method with wavelength compensation (WCID). This method could deal with dehazing and color restoration simultaneously. The method can get more accurate estimation of the scene depth than the dark channel prior method. According to estimation of the wavelength attenuation, a reverse compensation was conducted to restore the color distortion. However, the salinity and the suspended particles in the ocean decreased the accuracy of light energy loss estimation, affecting the effectiveness of the method.

Zhao *et al.* [6] presented a method to calculate the inherent optical properties of an underwater scene from the background color and restored underwater images based on real-time and precise measurements. Serikawa and Lu [69] implemented a joint trilateral filter to eliminate scattering and color distortion in underwater images by compensating the wavelength attenuation along the propagation path. However, the method did not consider the influence of an artificial lighting source. Ancuti *et al.* [70] exploited a new method to restore the visual quality of underwater images and videos based on the fusion principle. The method showed good dehazing performance but still suffered from an artificial lighting source. Carlevaris-Bianco *et al.* [71] presented a simple prior that utilizing the significant difference in RGB color wavelength attenuation to estimate the depth of a scene, and then used the depth information to enhance haze in underwater images. Lu *et al.* [72] investigated a physical underwater dark channel prior method, developed a color-lines-based ambient light estimator and a weighted guided domain filter to compensate underwater images. Li *et al.* [47] proposed a method to get higher contrast of the underwater image based on a minimum information loss and histogram distribution prior.

With its continuous development [73], the deep learning approach has been used in the underwater image dehazing field. Li *et al.* [49] first attempted to use deep neural network to dehaze an underwater image. The method combined a normalized image and physical spectral characteristics correction to enhance the visibility in the high-turbidity underwater image and achieved an excellent performance. Meanwhile, because the method considered lighting characteristics, it could restore the color distortion simultaneously. However, the method had poor performance for images captured under low-light conditions; moreover, the method cannot totally remove noise. As shown in Table III, we compare the different algorithms described above. We exhibit some dehazing enhancement results of underwater images to offer scholars a comprehensive understanding of underwater image dehazing methods' performance which we discussed above [47]. The comparison results can be seen in Fig. 4. It can be seen from Fig. 4, He's method [61] and Li's method [47] improve the visibility in the turbid scene, WCID method [68] and Li's [47] method get better visual performance in underwater scene.

Furthermore, some researchers use multiple-image dehazing methods [74], [75] or specialized hardware devices [76], [77] to enhance the contrast of underwater images. Although these methods have some effectiveness for underwater image enhancement, there still remain problems to be solved, which may potentially decrease the practical applicability. For example, the underwater camera used in the methods mentioned above may be extremely expensive and complex. In another instance, the methods of using multiple images may present a great challenge to acquire multiple images of the same scenarios.

TABLE III
OVERVIEW OF UNDERWATER IMAGE DEHAZING METHODS

| Author | Advantages | Disadvantages |
|---|---|---|
| Chiang et al. [68] | Dealing with dehazing and color restoration simultaneously, great enhancement and restoration effect | Accuracy decreases at high-salinity and turbid scenes |
| Serikawa et al. [69] | Good edge preservation with a narrow spatial window, suitable for real-time underwater imaging system | Ignorance of artificial lighting source |
| Ancuti et al. [70] | Good dehazing performance | Ignorance of artificial lighting source |
| Carlevaris et al. [71] | Reveal greater image detail and can estimate the depth of a scene | May produces an overly-bright background and ignorance of artificial lighting source |
| Lu et al. [72] | Low computational complexity the use of Laplacian matting, good edge preservation, and noise removal | May result in the inability with the increase of turbidity sediment and remove only haze-like scatter |
| Li et al. [47] | High image contrast, dehazing and contrast enhancement synchronous | Poor performance in low-light conditions, cannot totally remove noise |

## III. UNDERWATER IMAGE COLOR CORRECTION AND QUALITY EVALUATION METRIC

In this section, we concentrate on the special transmission properties of light in water. Underwater image color correction is a novel research hotpot because of the physical wavelength attenuation [78], [79]. Fig. 5 shows an illustration of underwater color attenuation. First, the red color dies away quickly after 4–5 m. Then, most of the orange color vanishes approximately at the depth of 5 m. The yellow color disappears totally at the depth of 10 m and the green color disappears at the depth of approximately 20 m. Finally, the blue color dies away at over 50 m. The color of the water represents which wavelength travels further. The blue wavelength propagates better in the sea, however, the green wavelength travels further at coastal water. Therefore, underwater images usually are dominated essentially by a bluish or greenish tone. Valuable detailed information from the underwater image is lost.

### A. Underwater Image Color Correction

The enhancement of underwater image contrast is a widely used technique for color correction. The development of contrast enhancement has attracted much attention in recent years. Many scholars have proposed numerous methods to enhance the quality of underwater images and recover as much valuable detailed information as possible from the degraded images. Schechner and Karpel [80] advanced an image color correction method in view of a couple of images taken at different orientations with a polarizer to enhance the visibility of the degraded images. Rizzi *et al.* [81] presented a method to use unsupervised image color equalization with simultaneous global and partial effects to recover the color distortion. Trucco and Olmos-Antillon [82] devised a special image enhancement filter, which can automatically simplify the underwater imaging matrix proposed by Jaffe [15] and McGlamery [28]. However, the methods described above have high computational complexity.

Iqbal *et al.* [83] implemented an integrated color model (ICM), of which the output image in the RGB channel was spread into the whole dynamic range. The image was transformed to the HueSaturation-Intensity (HSI) color model. Moreover, Iqbal *et al.* [84] demonstrated an unsupervised color correction method (UCM) to acquire a restored underwater image based on RGB and HSI color balance and histogram stretching. The results showed efficiency in bluish tone removal and the red color channel improvement. The main problem was that the ICM and UCM models could produce extra noise. Ghani and Isa [85] modified and extended the ICM and UCM method based on the Rayleigh distribution. The method improved the contrast and minimized the under-enhanced and over-enhanced areas. Galdran *et al.* [86] proposed an extension of the dark channel prior method, where red color with short wavelengths was restored, which led to a contrast improvement. Naim and Isa [87] proposed a novel method named pixel distribution shifting color correction for color-distorted images to correct the white balance and preserve the achromatic. The method recovered the color channel to make the image look more normal. The method recovered the image saturation simultaneously; however, the method could not enhance the image contrast apparently.

Hitam *et al.* [88] advanced an algorithm called mixture contrast limited AHE specialized for underwater images. This algorithm could effectively denoise the noise introduced by CLAHE to reduce the subsequent processing of underwater images. He *et al.* [89], [90] designed a new filter that exhibited a nice property of edge-preserving smoothing, and showed low computational complexity. Gastal and Oliveira [91] proposed a method showing excellent edge-preserving filtering of images. The filters had low computational complexity, flexibility and could yield high-quality images, but the rotationally invariant that overly depended on matching result may cause some difficulties. Tarel and Hautière [92] demonstrated a method to increase the visibility from a single image without using any extra information as a particular filtering problem based on a median filter. It has high computational complexity and good edge preservation.

As shown in Table IV, we compare different algorithms described above. We exhibit some color restoration results of underwater images to show scholars a comprehensive understanding of underwater image color restoration methods' performance which we discussed above [48]. The compared results can be seen in Fig. 6. It can be seen in Fig. 6, Ancuti method [65] has better visual performance.

### B. Underwater Image Color Evaluation Metric

Now, we focus on building an effective and objective underwater degradation image quality evaluation (IQE) metric,

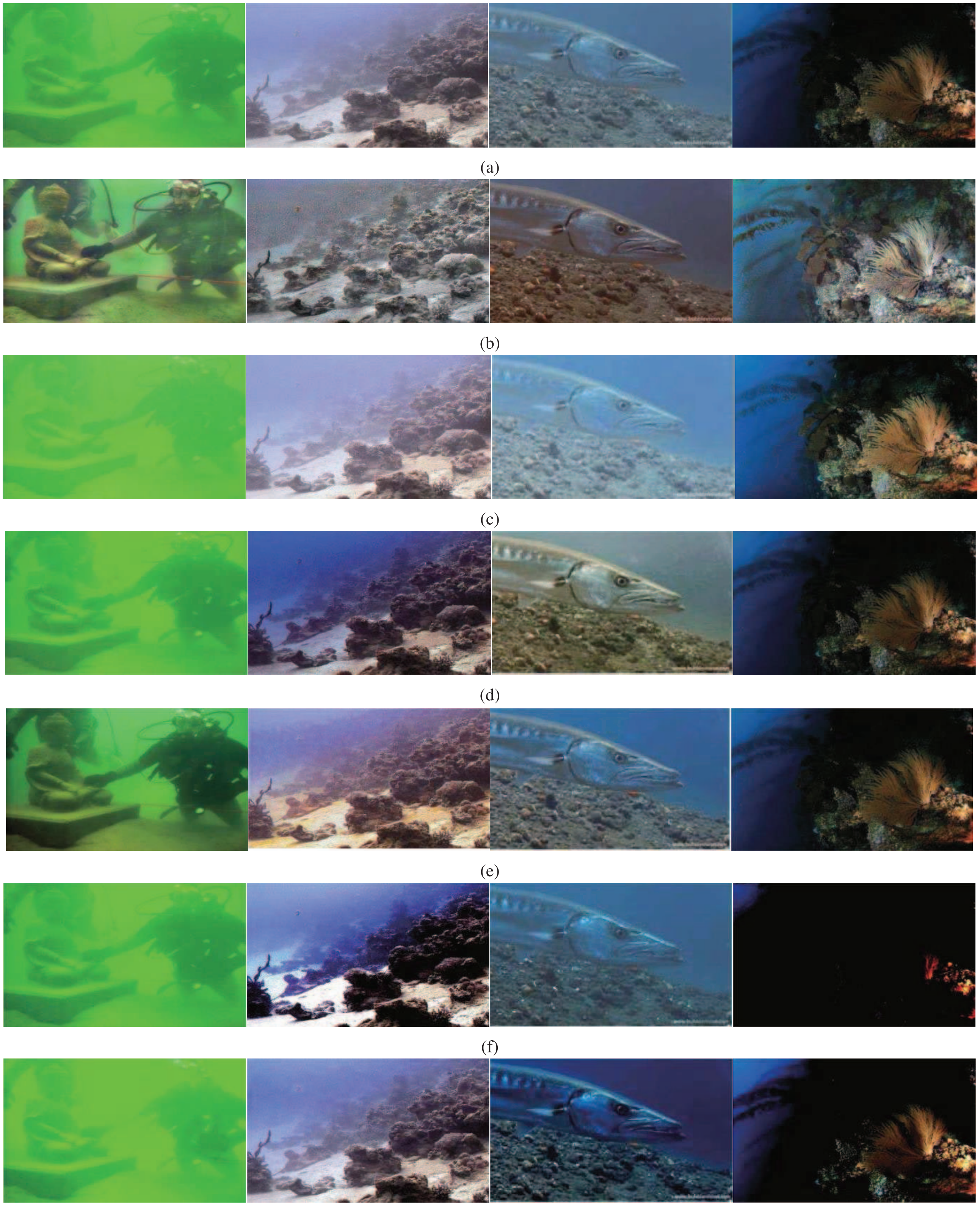

Fig. 4. Comparison of underwater image dehazing methods discussed above. (a) Underwater images from left to right: turbid and hazy scene, deep water scene, artificial lighting scene, low-light scene; (b) He method [61]; (c) PB method [58]; (d) WCID method [68]; (e) Li method [47]; (f) SID method [59]; and (g) CB method [71].

in order to enable processing, classification, and analysis of underwater images [93]–[95], especially in underwater environmental monitoring and target detection. Subjective evaluation metrics are usually known to show the most reliable standard; however, it costs a long time and is unachievable for real-time application and integrated systems. People usually

TABLE IV
OVERVIEW OF UNDERWATER IMAGE COLOR CORRECTION METHODS

| Author | Advantages | Disadvantages |
|---|---|---|
| Iqbal et al. [83] | Enhances the color contrast in the image and also solves the problem of lighting | May produce amount of noise |
| He et al. [89] | Exhibits the nice property of edge-preserving smoothing and good computes efficiently ($o(N)$) and non-approximately | Ignorance of artificial lighting source |
| Trucco et al. [82] | Simplifies the underwater imaging matrix automatically | Low computational efficiency because the method needs tracking parameter values |
| Gastal et al. [91] | Show excellent edge-preserving filtering of images, has flexibility and high-quality of images | Depends on matching, the rotationally invariant may lead to difficulties |
| Naim et al. [87] | Good efficiency in the white balance correction and the achromatic preservation | Cannot enhance the image contrast apparently |

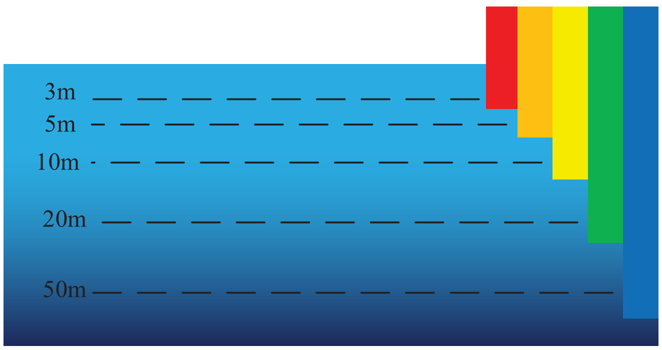


Fig. 5. Blue color has shortest wavelength so that it travels the longest in the water. Therefore, the underwater images always are dominated essentially by bluish-greenish tone.

classify the objective IQE metric by whether it has a reference image. The evaluation metrics are usually classified into three types: 1) the full-reference (FR) image quality assessment; 2) the reduced-reference (RR) quality assessment; and 3) the no-reference quality assessment (NR). FR means a reference image is established. RR presumes that partial detail about the reference is achievable and can be used for quality assessment. NR means none of the detail about the reference is acquirable. Obviously, in most cases, underwater images present huge difficulties to obtain the reference. Therefore, an NR objective IQE metric is needed to evaluate underwater image quality. The evaluation metric for underwater images should have the following characteristics: identify the degradation images; correlate with human vision; trusted reference standard image; helpful in selecting the optimal variable; low computational complexity and suitable for most of the underwater image dehazing and color restoration algorithms. Although many quality metrics for atmospheric images are available [96]–[100], they are not suitable for underwater images owing to the special transmission properties of light in water.

Many NR image quality assessments have been established for evaluating gray scale images, of which the main reasons for distortions are blurring and fogginess. Kanaev *et al.* [101] presented structure tensor oriented image quality metric in underwater image quality for gray scale images. The metric can afford high resolution and low noise estimate of image sharpness. The widely available gray scale image quality metrics measure contrast [102], [103] and edge sharpness [104]. Evaluating the quality of color images often presents many challenges, because of the highly complicated human vision for different colors. Some color image quality metrics extend from gray scale image quality metrics in most scenes. Some color images metrics still utilize gray scale assessments by transforming the color image into a gray scale image [96] or by evaluating the quality in each RGB color channel individually and integrating the assessment parameters with different weights [105]. The problem with this is that the color to gray scale transformation procedure is lossy. Some color image quality metrics only concentrate on one characteristic of the IQE such as contrast, entropy [97], [98], brightness [99], [106], [107], and sharpness [108], [109]. Hasler and Suesstrunk [110] proposed a method to assess the colorfulness in atmospheric images. The method establishes the red-color, green-color, blue-color channel, and then acquires a colorfulness metric based on mean values and standard deviations of the RGB channels.

Panetta *et al.* [100] presented a color image quality assessment evaluating the image through colorfulness, sharpness, and contrast, named color quality enhancement (CQE). The CQE method exploits the contrast assessment relationships of the RGB channels and advances a color root mean enhancement (CRME) to evaluate the correlation between the color image center area and its neighbors. The metrics described above were proposed for atmospheric color images. However, there are huge differences between atmospheric color images and underwater color images. The types of degradation in underwater images are not only due to blurring and low contrast which are the most common reasons for atmospheric images but also fogginess and color distortion due to absorption and scattering which are caused by the spectrally nonuniform attenuation and the distribution of the light spectrum.

Several underwater image assessment metrics have been proposed to evaluate the algorithm performance for underwater gray scale images dehazing and restoration. Schechner and Karpel [1] set up a measure to evaluate the underwater image quality by using global contrast. Hou *et al.* [111] presented an evaluation metric to assess restored underwater images based on the weighted gray scale angle. Arnold-Bos *et al.* [112] presented an assessment metric extended by Pratt [113]. However, the quantitative evaluation of the underwater color image enhancement and restoration results for different algorithms has many challenges; thus, it is meaningful to set up an integrated evaluation metric

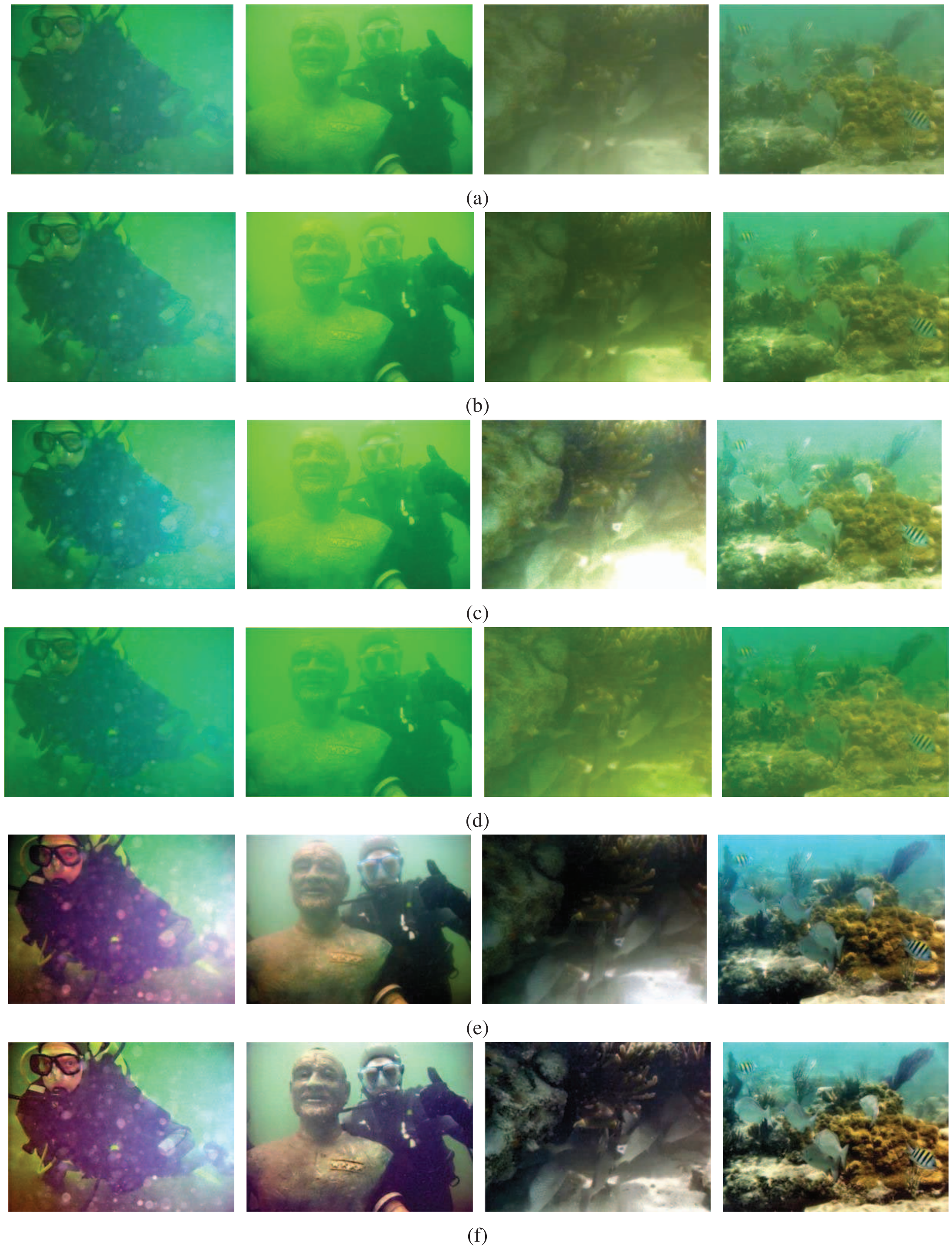

Fig. 6. Comparison on underwater image color restoration method discussed above. (a) Raw image, (b) He method [89], (c) Fattal method [59], (d) Tarel method [92], (e) Iqbal method [83], and (f) Ancuti method [65].

dealing with automatic and real-time underwater processing. Therefore, an effective underwater color image quality metric is a major goal of the underwater research community. Yang and Sowmya [48], [114] proposed a synthetic gray scale and color image evaluation metric for predicting the objective quality named underwater color IQE (UCIQE). The metric is much useful in assessing different dehazing and color restoration algorithms in underwater degradation images. We compare different quality evaluation metrics among the enhancement methods listed in Fig. 6, the comparison results are shown in Table V. The data indicate the coherence of each evaluation metrics with the subjective perspective.

## IV. Application of Underwater Image Processing

According to domestic and international data, getting a clear underwater image has played an important role in many oceanic fields such as assessing biological environments

TABLE V
COMPARISON OF EVALUATION METRICS ON IMAGES SHOWN IN FIG. 6

| | Metric | Image1 | Image2 | Image3 |
|---|---|---|---|---|
| Raw image | CQE | -0.0465 | -0.0427 | -0.0377 |
| | CRME | 2.9922 | 3.0253 | 3.0457 |
| | UCIQE | 0.5400 | 0.3930 | 0.5009 |
| Fattal method [60] | CQE | -0.0418 | -0.0274 | -0.0211 |
| | CRME | 2.9527 | 2.8858 | 3.0473 |
| | UCIQE | 0.6448 | 0.6158 | 0.6503 |
| Ancuti method [65] | CQE | -0.0280 | -0.0345 | -0.0465 |
| | CRME | 2.8670 | 2.6644 | 2.7973 |
| | UCIQE | 0.8937 | 0.7441 | 0.8814 |
| Tarel method [92] | CQE | -0.0690 | -0.0538 | -0.0438 |
| | CRME | 3.0489 | 3.1884 | 3.1535 |
| | UCIQE | 0.5821 | 0.5308 | 0.5828 |
| Iqbal method [83] | CQE | -0.0403 | -0.0734 | -0.0405 |
| | CRME | 2.8687 | 2.6302 | 2.7417 |
| | UCIQE | 0.7684 | 0.5919 | 0.7507 |
| HE method [89] | CQE | -0.0421 | -0.0390 | -0.0346 |
| | CRME | 3.0217 | 3.1244 | 3.1131 |
| | UCIQE | 0.5874 | 0.4818 | 0.5631 |

and monitoring underwater environments, in the meantime, intelligence underwater image processing has been greatly developed. It can be predicted that more and more oceanic fields will embrace underwater image processing in the future. For example, image color correlation can be used in real time to identify an underwater object. Image registration techniques can be applied to clarify the underwater object whether in gray scale or in a colored image. Furthermore, the applications of underwater image processing appear in diverse fields such as underwater navigation, underwater resources exploration, underwater environmental protection, and underwater military affairs. Within these fields, a variety of devices and algorithms are presented. The intelligence dehazing and color restoration methods improve the visibility and color balance of underwater images to help researchers better explore underwater environments. In the following, we review underwater image processing applications according to their use in underwater navigation and underwater target detection.

### A. *Underwater Navigation*

The autonomous navigation of underwater vehicles is becoming a growing research field in order to more effectively explore the underwater resources [115]–[117]. The main reason for this is the increasing desire for underwater data collection such as environmental monitoring and mine detection. A part of the research hotspots of underwater vehicles has been concentrated on the development of underwater images, data acquisition and vehicle navigation [118], [119]. Enhanced underwater images are useful to realizing operations such as path planning and obstacle avoidance. With the increasing quality of underwater images, the operating costs of underwater vehicles can be reduced. The drivers' main tasks will be to define the primitive mission to be carried out and to acquire higher-level control.

Underwater imaging devices are broadly used in observing the sea floor. Therefore, the enhancement and restoration degree of images are the core questions about observing. Underwater imaging devices are usually installed in autonomous underwater vehicles (AUVs), and *in situ* ocean sensor networks. There are many research hotspots related to underwater imaging devices. For example, visual navigation is the key technology for AUVs navigating close to the sea floor. High-quality underwater images are required to be automatically built and used as a representation of the sea bottom [120]. Enhanced underwater images will enable missions in which an AUV required to map a field and then to navigate through it [121], [122]. For building the video, the quality constraints of underwater images are very strict, because global navigation is mostly based on the enhanced underwater images. Therefore, highly accurate and clear underwater images are strongly needed.

During navigation, underwater vehicle performance strongly depends on the clarity of the underwater video or image to locate the previously constructed map. Two significant demands are the limitations of localization and real-time position estimates: 1) image registration and 2) interimage motion estimation.

When the underwater vehicle is navigating, localization information can be represented straightly by an image frame or transformation an explicit position. A trajectory-generation module is carried out to avoid when path matching has too difficulties to driving in the area. The module provides a series of path points between the current location and destination, which searches a short path to keep away from the boundaries.

### B. *Underwater Target Detection*

Underwater environment monitoring, which has been used in recent decades, depends on ocean geographic data collection systems by exploiting underwater equipment [123]–[125]. In a common scenario, the equipment acquires data from the underwater surroundings and sends these data to an on-shore station or a vessel though satellite or underwater cables. In monitoring systems, the equipment (usually sensors) collects several indicators, such as salinity, temperature, pressure, and underwater images. The underwater sensor nodes are networked via acoustics.

It is effective to use image color detailed information acquired by an underwater imaging device or sensors for underwater detection of objects [126]. The Beer-Lambert law states that the RGB color attenuation coefficients under the water depend on the observation distance and illumination. The underwater target detection method identifies a mission object in underwater circumstances [127]. In many cases, the proposed method of detecting targets such as [128] requires *a priori* color experience of the underwater object and allows several objects with having different colors. Additionally, owing to the degradation of the underwater image, the detecting algorithm often has large computational complexity and costs much time.

Many underwater imaging systems were proposed to help people detecting objects such as range-gating, laser line scanning, modulation techniques, multiple-perspective image construction, and polarization discrimination, which have attracted much attention [129]. Polarization filtering is one of the adapted methods to detecting and identifying underwater targets. Usually, the enhancement methods of underwater images for detection and identification have the following characteristics.

1) It is easy to achieve.
2) It is required to carry out detection and identification of target simultaneously.

A basis issue of underwater target detection is considered about the development trend, low power consumption, and high-speed underwater identification. Optical correlation methods are required to identify underwater target automatically. The method enhances the underwater image visibility by the generation of a large reference database of targets. However, there still remain some limitations of target recognition. Thus, developing image dehazing and color restoration is essential for improved underwater target detection. The enhancement image methods have several requirements: easy to use, low consumption, real-time detection, and identification. The enhancement image methods increase the contrast of the underwater images and decrease underwater color distortion and backscattering degradation.

## V. Conclusion

Intelligence dehazing and color restoration methods for underwater images are novel research fields that have great potential to help developers better explore the underwater environment. These methods used to deal with the degradation like strong absorption, scattering, color distortion, and noise from the artificial light source to improve the visibility and color balance. With the rapid development of image processing, underwater image processing opens up many new research directions.

In this survey, we summarize a comprehensive review of the current research. We first introduce typical underwater image degradation types such as absorption, scattering, color distortion, and artificial light source disturbance in detail. Subsequently, we outline dehazing and restoration algorithms for underwater images, which helps scholars better comprehend underwater image processing. According to this paper, we envision the intelligence dehazing and restoration methods like deep learning will be hot research topics in research of underwater image processing. Then, we review underwater image processing applications according to their use in underwater navigation and underwater target detection. We hope that this review will be useful for researchers and developers to understand the significance and enormous applications in underwater image processing. We predict that the intelligence underwater image processing will provide a great contribution to help researchers better explore underwater environments in the future.

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