Underwater Image Enhancement Using Color Compensation and Multi-Scale Fusion with Quality Evaluation Metrics

SHAKHAMURI KARTHIK[1], SURYADEVARA PAVAN[2], PATHIGULLA SRI HARI[3], MAKKENA PARDHU VISHNU VARDHAN[4], DR. A. YASWANTH KUMAR[5]

[1, 2, 3, 4, 5]*Information Technology, R.V.R & J.C College of Engineering*

Abstract- *Images acquired underwater are often characterized by poor contrast, visibility, and color information due to the absorption and scattering of light within the underwater environment. This affects the overall performance of underwater images, particularly in underwater exploration and robot navigation. This paper proposes an improved underwater image enhancement approach using color compensation and multi-scale fusion techniques. Initially, the red channel and white balancing are performed to compensate for the color information loss. Two improved images are formed using the gamma correction and detail enhancement approaches. Weight maps are calculated to focus on the salient features of the underwater images using the Laplacian contrast, saliency, and saturation features. Finally, the images are fused using the multi-scale approach based on the Gaussian and Laplacian pyramid operations. Post-processing operations are performed to enhance the overall visibility of the underwater images using CLAHE, contrast stretching, and saturation enhancement techniques.*

Indexed Terms- Underwater Image Enhancement, Color Compensation, Multi-Scale Fusion, Image Quality Metrics, Underwater Image Processing.

I. INTRODUCTION

Underwater imaging is a critical component in marine exploration, underwater archaeology, environmental monitoring, and underwater robotics. Unfortunately, images acquired underwater are highly degraded by the absorption and scattering of light in water. Physical phenomena affect the image acquired underwater and cause color distortion, low contrast, blurring, and low visibility in images acquired underwater. In water, red light is absorbed first, followed by orange and yellow light. This causes images acquired underwater to appear bluish or greenish in tone [1]. In addition, the suspended particles floating in water cause light to scatter, leading to image degradation with the appearance of haziness and loss of contrast in images acquired underwater [12], [13].

Conventional image enhancement techniques like histogram equalization and gamma correction have been used to enhance underwater images. However, the effectiveness of these techniques is limited in handling the degradations of underwater images since the techniques do not take into account the physical properties of the underwater environment [8]. Recent studies have proposed the development of more advanced image processing algorithms for underwater image restoration and enhancement. In the proposed study, an advanced image enhancement technique for underwater images is implemented based on color compensation and fusion.

1.1 Applications of Underwater Images

Underwater image enhancement techniques have many important practical applications. Some of the most important applications include underwater infrastructure inspections, where techniques for monitoring underwater pipelines, underwater cables, etc., are needed [2], [3]. Underwater image enhancement techniques also find many practical applications in underwater biological research for analyzing underwater species [6]. Additionally, underwater imaging techniques find many practical applications in underwater archaeological research for the exploration of underwater shipwrecks and artifacts [7]. Enhanced underwater images also find many practical applications for the improvement of various computer vision techniques for object detection, segmentation, etc., used in underwater robots or AUVs [5].

1.2 Literature Survey

Several techniques have been proposed to improve the quality of images degraded by scattering, color

distortion, and low contrast in underwater images. Some of these techniques include using hardware systems such as underwater laser imaging and optical sensing systems [10]. Other techniques include using polarization to reduce back-scattering in images by capturing images with different polarization states [11]. Some techniques also include using model-based techniques such as Dark Channel Prior (DCP) to estimate images and improve their transmission maps [19][26]. Some techniques also include using UDCP, which improves images using blue

and green channel images [28]. Other techniques include using Red Channel Prior techniques, which improve images using red channel attenuation [29]. Other techniques include using fusion techniques to improve images using weighted fusion techniques [23][35].

1.3 Motivation

In the underwater image, there are effects of color attenuation, poor illumination, and scattering because of the interaction of water particles with the light. In the image, the long wavelengths of the light get absorbed very fast, and only shades of blue or green are visible [1]. The presence of particles causes haze and contrast degradation because of forward and backward scattering of light [12], [13]. There are many image enhancement techniques that make use of complex models or multiple images or special hardware [10], [11]. Dark channel prior is a model-based approach that may not work well in underwater images [19], [28]. Fusion-based techniques improve contrast, color balance, and clarity by fusing multiple enhanced images [23], [35].

1.4 Objectives of the Project

The main goals and objectives of this work are to improve images acquired in an underwater environment with low contrast and distorted colors because of light absorption and scattering in water [1]. The main goals of this study are to apply techniques in color compensation and white balancing to improve the natural colors in images acquired in an underwater environment [35]. In addition, gamma correction and enhancement techniques are applied to improve the visualization of images acquired in an underwater environment [23]. Furthermore, this approach also makes use of multi- scale fusion techniques to improve

images acquired in an underwater environment [23], [35]. Finally, this enhancement algorithm is evaluated using various quality metrics such as UIQM, UCIQE, and PCQI to improve images acquired in an underwater environment [65], [66].

1.5 Scope of the Work

The research of this work is to improve the degraded images obtained underwater using conventional cameras. The method uses image processing techniques such as color compensation, white balancing, gamma correction, and fusion to improve the images. Improved images are obtained, which can be used for underwater exploration, inspection, computer vision, segmentation, feature matching, etc. [5], [7]. The method is based on a single image, and there is no need for prior information regarding the environment. [23], [35].

1.6 Input Images

The input to the suggested system is an image obtained from an underwater camera. The input image may experience distortion in terms of color, poor visibility, and contrast because of the environmental conditions of the underwater world. The first step involves color compensation to improve the attenuation of color information. After that, an enhanced version of the input image is obtained through gamma correction and detail enhancement techniques. These images are fused using a multi-scale fusion framework to obtain an enhanced image of the underwater world.

1.7 Contributions of the Proposed Work

The Contribution of the fusion-based underwater image enhancement framework, where color compensation and multi-scale fusion techniques have been utilized for the improvement of underwater images. The proposed method also includes additional post-processing techniques such as CLAHE, contrast stretching, and saturation boosting for better improvement of the visual quality of underwater images. The Shades of Grey white balancing technique has also been utilized for better improvement of the color constancy of underwater images. The proposed method has been extensively tested using various underwater image quality assessment metrics such as UIQM, UCIQE, and PCQI.

II. VARIANTS OF UNDERWATER ENHANCEMENT METHODS

2.1 Underwater Dark Channel Prior (UDCP)

2.1.1 Introduction

Underwater imaging plays a major role in various fields such as marine biology, underwater infrastructure inspection, underwater archaeology, and autonomous underwater vehicle navigation [1], [2], [3], [5], [6], [7]. However, the quality of underwater images deteriorates due to poor visibility resulting from the absorption of light in the water containing suspended particles [12], [13]. During this absorption, long wavelengths such as red are strongly absorbed, while shorter wavelengths such as blue and green penetrate deeper. This results in underwater images having a blue or green hue and losing valuable information [12], [13]. However, the conventional dehazing techniques assume that the attenuation of light in the images occurs equally in all the color channels. This assumption does not hold true in the underwater imaging environment, as the attenuation of light occurs depending on the wavelengths of the light [8]. For this problem, the Underwater Dark Channel Prior (UDCP) method was proposed as a variant of the Dark Channel Prior method [19], [26]. This method improves the visibility of the underwater images using a single image, neglecting the red channel that gets highly attenuated.

2.1.2 Methodology

The UDCP algorithm processes an underwater RGB image that is affected by absorption and scattering during light transmission through water [12], [13]. As the red channel is highly attenuated in this case, it computes the dark channel using only the blue and green channels. It represents the minimum intensity in a local area in an image, called the dark channel, and is useful in estimating haze in an underwater image [28]. It estimates background light using the brightest pixels in the dark channel and computes an initial transmission map, which represents radiance in the image. It also uses edge-preserving filtering to refine this transmission map and then computes scene radiance using this transmission map and background light, thereby enhancing the image with better visibility. However, UDCP also fails to restore natural colors in images properly because of attenuation in different wavelengths.

$$I(x) = J(x)t(x) + B(1 - t(x))$$

where I(x) is the observed underwater image, J(x) is the true scene radiance, t(x) is the transmission map indicating the amount of light that has reached the camera and B is the background light produced by scattering within the water medium.

2.2 Polarization-Based Underwater Enhancement

2.2.1 Introduction

Polarization-based underwater image enhancement is a multi-image restoration approach that uses the polarization property of the scattered light to enhance the underwater images. When light propagates through the underwater channels, the suspended particles scatter the light in different directions, producing a veiling effect called backscatter, which reduces the contrast of the images [12], [13]. The polarization filters are designed to separate the scattered light and the radiance of the images by capturing the images at different polarization angles and estimating the scattered light component to restore the images of the scenes [11]. However, the limitation of this approach lies in the requirement to capture multiple images, and hence it cannot be used for real-time applications and underwater scenes. However, this approach is useful to study the light propagation and image restoration techniques in underwater channels [8].

2.2.2 Methodology

The enhancement process commences with a color compensation operation that restores the red channel with the green channel information due to the lesser effect of underwater attenuation on the green channel [1]. Then, the Gray-World white balancing algorithm is applied to the image to remove the color cast from the image and to balance the color channels by assuming that the average color of a natural image should be gray [41]. Following this, two enhanced versions of the white-balanced image are obtained by applying the gamma correction to enhance the global contrast of the image and the normalized unsharp masking to enhance the edges of the image that were attenuated due to underwater scattering [1]. Then, the images are combined by applying the Laplacian contrast, saliency,

and saturation weight maps. Finally, the enhanced image with improved visibility and contrast is obtained by applying the multi-scale pyramid fusion.

$$t(x) = 1 - \frac{A(x)}{A_\infty}$$

where t(x) represents the transmission at a given pixel location x, A(x) represents the estimated air light component at the given pixel location, and A∞ represents the global air light value that corresponds to the maximum level of scattered light.

III.   PROPOSED METHODOLOGY

3. Color Compensation and Multi-Scale Fusion
3.1   Introduction
Underwater images experience low visibility, color distortion, and contrast reduction caused by the absorption and scattering of light in water. With increased depth, the absorption of longer wavelengths like red is more prominent, causing images to turn bluish or greenish in color [1]. In addition, water particles cause the scattering of light, resulting in hazy images with low clarity [12], [13]. Researchers have proposed several techniques to restore underwater images. Model-based image restoration techniques involve estimating the image transmission maps to enhance image clarity [19], [26]. Other techniques involve using multiple images or equipment, making the system more complex [10], [11]. Fusion-based image enhancement techniques address these problems by using multiple images or equipment and improving image clarity using weighted fusion techniques [23], [35]. In this paper, an image enhancement technique using color compensation and multi-scale fusion is proposed to enhance the clarity of underwater images.

3.2   Methodology
The process of the suggested method of improving the quality of the underwater image involves several steps including color compensation, white balancing, input image creation, weight map creation, multi-scale fusion, and post-processing. In the first place, the quality of the underwater image is affected by the attenuation of the red channel of the image because the water absorbs red light very quickly. In order to

compensate for the loss of the red channel, information from the green channel is used to compensate the red channel as follows:

$$I_{rc}(x) = I(x) + \alpha(\bar{I}_G - \bar{I})(1 - I(x))I_g(x),$$

where (I) and (Ig) represent the red and green channels of the image, while $(\bar{I})$ and $(\bar{Ig})$ denote their mean values. The value of the parameter (α) is usually set to 1 [35].

After compensation, a white balancing technique is applied to correct color cast in the underwater image. For this work, Shades of Grey is employed to estimate the illuminant and normalize the color channels to obtain a natural color appearance in underwater images [41].

Next, two enhanced inputs are derived from the white-balanced image to acquire additional information about the images' appearance. One input is derived through gamma correction, which enhances the global contrast and brightness distribution of the images. Another input is derived through detail enhancement using the unsharp masking technique to enhance the image's edges and structures. The sharpened image is calculated as:

$$S = I + \beta(I - G \cdot I)$$

where (I) represents the input image, $(G * I)$ denotes the Gaussian blurred image, and (β) controls the sharpening intensity [23].

For the proper combination of the improved inputs, weight maps are determined on the basis of three measures of visual quality: Laplacian contrast, saliency, and saturation. The weight map for the Laplacian contrast emphasizes the edges and textured areas, the saliency weight emphasizes the salient areas of the image, and the saturation weight emphasizes the areas with higher saturation.

Both the enhanced inputs are then combined using a multi-scale pyramid fusion technique. Laplacian pyramids are formed for the input images, and Gaussian pyramids are formed for the corresponding

weight maps. At each level of the pyramid, the images are combined using weighted blending given by:

$$R(x) = \sum_{k=1}^{K} W_k(x)\, I_k(x)$$

where (Ik) represents the input images and (Wk) denotes their normalized weight maps [23], [35].

Finally, the post-processing operations like Contrast Limited Adaptive Histogram Equalization (CLAHE), Contrast Stretching, and Saturation Boosting are performed to enhance the quality of the images. The performance of the proposed image enhancement technique is validated using the conventional underwater image quality assessment metrics like Underwater Image Quality Measure (UIQM), Underwater Color Image Quality Evaluation (UCIQE), and Patch-based Contrast Quality Index (PCQI), which measure the colorfulness, contrast, and overall perceptual quality of underwater images [65, 66].

Block Diagram
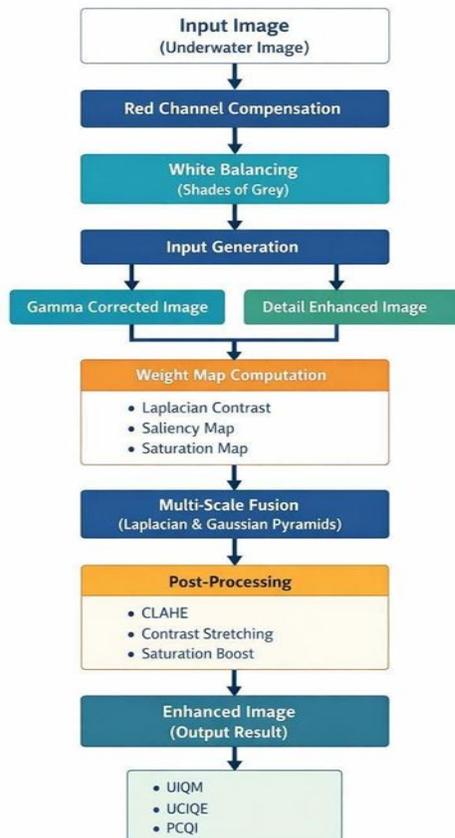
IV. RESULTS AND DISCUSSION

4.1 Experimental Setup

The proposed algorithm for image enhancement in the underwater environment has been implemented using the Python programming language with the help of the OpenCV and NumPy libraries. The experiment has been performed on a system with an Intel Core processor and 8 GB RAM. A number of underwater images were taken in different environments with varying depths, lighting conditions, and turbidity levels. These images contain various underwater effects like low contrast, color distortion, and haziness due to the absorption and scattering of light in the underwater environment [1], [12]. The proposed algorithm enhances the quality of a single underwater image using various techniques like color compensation, white balancing, and contrast enhancement. Initially, the attenuation of the red channel is corrected, followed by the generation of two enhanced images using gamma correction and detail enhancement techniques. These two images are fused using the multi- scale image fusion framework based on the Laplacian and Gaussian pyramids [23], [35]. At last, post- processing techniques like CLAHE, contrast stretching, and saturation enhancement are performed for better image enhancement.

4.2 Evaluation Metrics

To quantitatively assess the performance of the suggested approach, three most commonly used image quality measures for underwater images are utilized: Underwater Image Quality Measure (UIQM), Underwater Color Image Quality Evaluation (UCIQE), and Patch-based Contrast Quality Index (PCQI). The UIQM assesses the quality of the underwater images using colorfulness, sharpness, and contrast. The higher the value, the higher the visual quality and clarity of the image [66]. The UCIQE measures the quality of the image using chroma variance, luminance contrast, and saturation distribution. The higher the value, the higher the quality of the image [65]. The PCQI measures the contrast quality of the image using the structural similarity of the patches between the original and enhanced images.

4.3 Experimental Results

The proposed method has been tested on several underwater images, and the results show significant improvements in the enhancement of the images. The red channel compensation provides the corrected colors, and the fusion-based framework provides the enhanced edges and details. The fusion of the images at different scales provides the enhanced image. After the fusion, the post-processing steps provide the enhanced image. Figure X shows the results of the enhancement of the underwater image. In the original image, the underwater scene is blurred and has bluish colors because of the attenuation of the wavelength. After applying the proposed method, the enhanced image shows the improved contrast and details.

Input   Output

4.4 Quantitative Analysis

	PCQI	UCIQE	UIQM
Initial Image	0.735	0.498	3.636
Fish	0.846	0.504	3.421
Reef 2	0.847	0.523	3.672
Reef 3	0.775	0.509	3.631
Ancuti 3	0.758	0.512	3.626
Galdran 2	0.753	0.499	3.628
Ancuti 1	0.811	0.498	3.608
Average	0.789	0.506	3.603

From the results, it is clear that the proposed method improves the quality of underwater images considerably. It is clear from the UIQM values that the proposed method improves the colorfulness and sharpness of the underwater image. Also, the high scores of the UCIQE confirm that the proposed method improves the contrast and color distribution in the underwater image. Moreover, the proposed method improves the contrast quality of the underwater image,.

4.5 Discussion

The research confirm that the proposed underwater image enhancement method effectively addresses common degradation issues such as color distortion, low contrast, and poor visibility. The color compensation technique restores the attenuated red channel, improving overall color balance, while the fusion-based framework enhances contrast and structural details by combining multiple enhanced inputs. Compared to traditional techniques such as histogram equalization and gamma correction, the proposed method achieves better visual quality and

improved objective metrics. The multi-scale fusion strategy also reduces artifacts and halo effects often observed in single-scale enhancement methods . Overall, the proposed approach provides a simple yet effective solution for improving visibility, restoring color information, and enhancing structural details in underwater images for applications such as marine exploration and underwater monitoring.

V. CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this paper, a novel approach to improving the quality of underwater images through color compensation and multiscale fusion techniques has been discussed. This approach can be used to improve the quality of underwater images that are degraded due to various factors such as low contrast, poor visibility, and color distortion. The approach to improving the quality of underwater images through red channel compensation and white balancing techniques has been discussed. The red channel compensation technique improves the quality of underwater images by correcting the color distortion. White balancing techniques improve the quality of underwater images. Two enhanced images are formed through gamma correction and detail enhancement techniques. The multiscale fusion technique improves the quality of the underwater images. The multiscale fusion technique improves the contrast of the underwater images. The post-processing techniques such as CLAHE, contrast stretching, and saturation enhancement improve the quality of the underwater images. The performance of the proposed approach to improving the quality of underwater images has been evaluated through various image quality metrics such as UIQM, UCIQE, and PCQI.

5.2 Future Scope

Future research can be extended by the addition of deep learning techniques for better performance of the image enhancement. Future work may be focused on the real- time implementation of the method for underwater robotics and autonomous vehicles. Moreover, the method may be adapted for underwater video image enhancement.

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