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Study on Underwater Image Enhancement Techniques and Their Evaluation Metrics

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ABSTRACT

Underwater imaging poses unique challenges due to the adverse optical properties of water, leading to significant degradation in image quality. In this research paper, present a comprehensive study of underwater image enhancement techniques aimed at mitigating the detrimental effects of the underwater environment. We analyze and compare various traditional and state-of-the-art machine learning-based algorithms, discussing their strengths, limitations, and performance in different underwater imaging scenarios. Additionally, we explore evaluation metrics commonly used to assess the quality of enhanced underwater images and identify the remaining challenges in the field. This study serves as a valuable resource for researchers and practitioners interested in developing effective underwater image enhancement methods and advancing the field.

1. INTRODUCTION

Underwater environments present unique challenges for imaging systems. Water acts as a medium that alters the way light propagates, leading to significant degradation in the quality of captured images. Various physical phenomena, such as absorption and scattering, introduce color shifts, loss of contrast, and reduced visibility. These factors not only hinder the visual perception of underwater scenes but also impact subsequent image analysis tasks [1]. The field of underwater image enhancement aims to mitigate the detrimental effects of underwater conditions and improve the visual quality of images captured beneath the water's surface. By compensating for the distortions caused by the underwater environment, enhanced images can provide valuable insights, facilitate object recognition, aid in the extraction of critical information, and ultimately support decision-making processes [2].

Over the years, numerous algorithms and techniques have been proposed to address the challenges associated with underwater imaging. These approaches typically involve a combination of image processing and computer vision techniques, taking into account the unique characteristics of underwater scenes. The primary objectives of underwater image enhancement algorithms are to restore lost details, correct color distortions, improve contrast, and enhance overall visibility [3]. In recent years, significant advancements have been made in underwater image enhancement, driven by the increasing demand for high-quality underwater imagery in scientific research, industrial applications, and entertainment purposes. These advancements have been enabled by the rapid progress in digital imaging technologies, underwater imaging sensors, and computational capabilities [4].

This paper provides a comprehensive review of the state-of-the-art techniques and algorithms for underwater image enhancement. We explore various categories of approaches, including traditional and machine learning-based methods, and discuss their strengths, limitations, and application scenarios. Additionally, we examine the evaluation metrics commonly employed to assess the performance of enhancement algorithms and discuss the challenges that remain in the field.

The rest of the paper is organized as follows: Section 2 provides an overview of the physical properties of underwater imaging and the challenges they pose. Section 3 presents a detailed review of traditional image enhancement techniques for underwater images. In Section 4, we delve into the emerging field of machine learning-based methods for underwater image enhancement. Section 5 discusses the evaluation metrics commonly used to assess the quality of enhanced images. Finally, Section 6 concludes the paper and outlines future research directions.

By gaining a deeper understanding of the existing techniques and their underlying principles, researchers and practitioners can make informed decisions while selecting and developing suitable underwater image enhancement algorithms. Furthermore, this review paper can serve as a foundation for future research endeavors aimed at advancing the field of underwater image enhancement and enabling a wide range of applications in underwater imaging.

2. RELATED WORK

Md. J. Islam et. al. introduced a conditional generative adversarial network-based model for underwater image enhancement concurrently. To administer the adversarial training, we developed an objective function that estimates the perceptual image quality and supports its global content, color, and native style details. As well as, the author presented EUVP, a large-scale dataset of a paired and an unpaired pile of underwater images (of poor and good quality) which are captured via seven distinct cameras over several visibility conditions throughout oceanic explorations and human-robot collaborative evaluation. The author concluded that the proposed model can be used to improve real-time perception performances of visually-guided underwater robots [5].

C. O. Ancuti et. al. introduces an efficient technique to reinforce the pictures captured underwater and degraded thanks to the medium scattering and absorption. This method may be a single-image approach that doesn't require specialized hardware or knowledge about underwater conditions or scene structure. It works on the merging of two images that are directly derived from a color-compensated and white-balanced version of the original degraded image. The two images to fusion, also as their associated weight maps, are defined to market the transfer of edges and color contrast to the output image. To avoid the load map transitions creating artifacts within the low-frequency components of the reconstructed image, we also adopt a multi-scale fusion strategy [6].

L. Neumann et. al. said that Underwater image processing has to face the problem of loss of color and contrast that occurs when images are acquired at a certain depth and range. The longer wavelengths of light such as red or orange are speedily absorbed by the water, while the shorter ones have higher scattering. Thereby, at a larger distance, the scene colors appear bluish-greenish, as well as blurry. The loss of color increases not only vertically through the water column, but also horizontally, so that the subjects further away from the camera appear colorless and indistinguishable, suffering from lack of visible details. The author presents a fast enhancement method for color correction of underwater images. The method is formed on the gray-world assumption involved in the Ruderman- opponent color space and is capable to cope with non-uniformly illuminated scenes. Vital images are exploited by the proposed approach to perform fast color correction, taking into consideration locally changing luminance and chrominance. Because of the low-complexity cost, this approach is suitable for real-time applications to make certain realistic colors of the entity, more visible characteristics, and enhanced visual quality [7].

M. D. Kodak et. al. discussed advances in the field of underwater optical imaging. A review of research and technical innovations is introduced. Various recent applications of novel systems are shown as examples, and trends in emerging underwater imaging research and inventions are shortly summarized by the author [8].

G. L. Foresti et. al. proposed a visual inspection of sea bottom structures by an autonomous underwater vehicle. It uses a three-dimensional model of the environment and an extended Kalman filter allowing the guidance and control of the vehicle in real time. This paper describes a vision-based system for the inspection of underwater structures by an autonomous vehicle.[9].

A. Olmos et. al. presented a system to Detect man-made objects in unconstrained subsea videos. They use Quality Metrics and Bayesian Classifiers. This model describes an automatic vision system capable of detecting a variety of man-made objects in underwater imaging conditions [1].

M. Mangeruga et. al. state that images attained in an underwater environment are usually affected by the color cast and experience poor visibility and insufficiency of contrast. In the report, there are various enhancement algorithms that improve distant aspects of underwater imagery. In each review, when presenting a fresh algorithm or method, typically compares the preferred technique with some alternatives that exist in the current state of the art. There are no such studies on the reliability of benchmarking approaches, as the comparisons are established on different subjective and objective metrics. The author has analyzed improved images by means of three different approaches: objective metrics often adopted in the related literature, a panel of experts in the underwater field, and an evaluation based on the results of 3D reconstructions [11].

R. Protasiuk et. al. proposed an approach that combines both local and global information through an easy yet powerful affine transform model. Local and global information is carried through local color mapping and color covariance mapping between an input and a couple of reference sources, respectively. Various experiments on the degraded underwater images explain that the proposed method performs favorably to all or any of the other methods including ones that are tailored to correcting underwater images by explicit noise modeling [12].

Table 1: Summary of Related

Sr. No.	Author	Title	Approach Used	Description
1.	Md Jahidul Islam et. al. /(2019)	Fast Underwater Image Enhancement for Improved Visual Perception/ arXiv	Conditional generative adversarial network-based model	The proposed model can be used as an image processing pipeline by visually-guided underwater robots in real-time applications
2.	Codruta O. Ancuti et. al. (2018)	Color Balance and Fusion for Underwater Image Enhancement	Combining white balancing and image fusion	The blending of two images that are directly derived from a color-compensated and white-balanced version of the original degraded image.
3.	László Neumann et. al. (2017)	Fast Underwater Color Correction Using Integral IMAGES	Ruderman-opponent color space	Presents a fast enhancement method for color correction of underwater images. The method is based on the gray-world assumption applied in the Ruderman-opponent color space
4.	M. D. Kodak	A focus on recent developments and trends in underwater imaging.	Image formation and Image processing methods and Extended range imaging techniques.	This proposed approach focuses on the recent advancements in hardware, software, and algorithmic methods to overcome the absorption and scattered nature of seawater.
6.	A. Olmos et. al. (2002)	Detecting man-made objects in unconstrained subsea videos.	Quality Metric and Bayesian Classifier	This model describes an automatic vision system capable of detecting a variety of man-made objects in underwater imaging conditions.
7.	B. A. Levedah (2009)	Control of underwater vehicles in full unsteady flow.	Reduced-order model, Coupled FluidVehicle Model and Fluid compensationcontrol.	This model describes the full unsteady flow and measures the hydro-dynamic loads directly and also shows how a rational balance between canceling the hydrodynamic load.
8.	J. P. Tarel et. al. (2012)	Vision enhancement in homogeneous and heterogeneous fog.	Color and contrast enhancement andEnhancement based on Koschmieder'slaw.	This model proposes the rating visibility enhancement algorithms which are based on the addition of various generated fog on synthetic and camera images.

10.	Y. Y. Schechner et. al. (2007)	Regularized image recovery in scattering media.	Restoration usingadaptive regularization.	This study demonstrates the approach in atmospheric and underwater experiments based on an automatic method for determining themedium transmittance.
11.	J. Y. Chiang et. al. (2018)	Underwater image enhancement by wavelength	Wavelength Compensation and Image Dehazing	The propound WCID algorithm handles light scattering and color change distortions caused by underwater images concurrently.

3. Traditional Methods of Underwater Image Enhancement Techniques

Underwater image enhancement techniques aim to improve the visual quality of images captured in underwater environments by compensating for the inherent degradation caused by factors such as light absorption, scattering, color distortion, and reduced visibility. Several traditional and state-of-the-art techniques have been developed to address these challenges. Here are some of the commonly used techniques for underwater image enhancement:

A. Color Correction

Histogram Equalization: This technique redistributes the pixel intensities in the image histogram to enhance the overall contrast and visibility.

Color Balance Adjustment: Adjusting the color balance by correcting the color cast caused by underwater conditions can help restore natural colors.

Color Constancy Algorithms: These algorithms aim to estimate and correct the color shifts introduced by underwater environments based on statistical analysis or physical models.

B. Contrast Enhancement

Histogram Stretching: This technique expands the dynamic range of pixel intensities to improve contrast and visibility.

Adaptive Contrast Enhancement: By locally enhancing the contrast based on the image characteristics, this technique can improve the visibility of details in different regions of the image.

Retinex-based Methods: These methods simulate the human visual system's perception of lightness and color to enhance image details and improve color rendition.

C. Dehazing

Dark Channel Prior: This method exploits the statistical property of dark channels in hazy images to estimate and remove the haze or underwater fog.

Multi-scale Fusion: By combining information from multiple scales, this technique enhances image details while reducing the impact of haze or underwater scattering.

Atmospheric Scattering Models: These models simulate light propagation in underwater environments, allowing for the estimation and removal of scattering effects to restore image clarity.

D. Machine Learning-Based Approaches

Convolutional Neural Networks (CNNs): CNN-based models can learn complex features and mappings from large-scale underwater image datasets to enhance image quality.

Generative Adversarial Networks (GANs): GANs can generate synthetic underwater images by capturing the underlying statistical distribution of clean underwater images, helping to enhance real underwater images.

Variational Autoencoders (VAEs): VAEs can learn low-dimensional representations of underwater images, enabling the generation of visually improved images from the learned latent space.

E. Fusion Techniques

Image Fusion: Fusion techniques combine information from multiple images (e.g., different wavelengths, polarizations, or exposure settings) to enhance details and reduce noise.

Model-Based Fusion: These techniques integrate physical models of underwater imaging into the fusion process to enhance image quality by compensating for underwater distortions.

F. Hybrid Approaches

Combination of Traditional and Machine Learning-Based Techniques: Hybrid approaches leverage the strengths of both traditional and machine learning-based techniques to achieve enhanced image quality.

Preprocessing and Postprocessing: Applying image preprocessing techniques (e.g., noise reduction, image stabilization) and postprocessing methods (e.g., sharpening, denoising) can improve the effectiveness of underwater image enhancement algorithms.

G. Underwater Imaging Challenges

Underwater imaging poses several unique challenges due to the optical properties of water and the surrounding environment. These challenges can significantly degrade the quality of images captured underwater. Some of the key challenges in underwater imaging include:

Light Absorption: Water absorbs light, especially in the longer wavelengths (e.g., red and infrared), resulting in reduced visibility and color distortion in underwater images. As a result, images tend to appear bluish or greenish, and the loss of light can lead to poor contrast and limited details.

Scattering: Scattering of light occurs when it interacts with suspended particles, dissolved substances, and microorganisms in the water. This scattering phenomenon causes light to deviate from its original path, resulting in reduced clarity and contrast in underwater images. It creates a hazy or foggy appearance, making it challenging to discern fine details.

Color Distortion: The selective absorption of light by water and suspended particles alters the color composition of underwater scenes. Longer wavelengths (e.g., red and orange) are absorbed more rapidly, resulting in a shift towards shorter wavelengths (e.g., blue and green). As a result, colors appear distorted or washed out, affecting the accuracy and naturalness of the captured images.

Reduced Visibility: The combination of light absorption and scattering reduces the overall visibility underwater. The range of visibility is significantly diminished compared to above-water conditions, limiting the ability to observe objects at a distance and capture clear details in images.

Image Noise: Underwater images often suffer from high levels of noise due to the limited amount of available light and the scattering of light by particles in the water. Noise can degrade image quality, reduce sharpness, and make it more challenging to extract useful information from the images.

Unpredictable Environmental Conditions: Underwater environments can vary widely in terms of water clarity, particle concentration, and ambient lighting conditions. These environmental factors introduce variability in the imaging conditions, making it difficult to design universal solutions for underwater image enhancement.

4. EVALUATION METRICS FOR UNDERWATER IMAGE ENHANCEMENT

Evaluation metrics play a crucial role in assessing the effectiveness and performance of underwater image enhancement techniques. These metrics provide quantitative and qualitative measures to evaluate the quality of enhanced images. Here are some commonly used evaluation metrics for underwater image enhancement:

A. Objective Metrics

Peak Signal-to-Noise Ratio (PSNR): PSNR measures the quality of enhanced images by comparing them to a reference (clean) image. It calculates the ratio between the maximum possible pixel value and the mean squared error between the enhanced image and the reference image. Higher PSNR values indicate better image quality.

Structural Similarity Index (SSIM): SSIM evaluates the structural similarity between the enhanced image and the reference image by considering luminance, contrast, and structural information. It provides a score ranging from 0 to 1, with 1 indicating perfect similarity.

Mean Squared Error (MSE): MSE quantifies the average squared difference between the pixel intensities of the enhanced image and the reference image. Lower MSE values indicate better image quality.

Color Difference Metrics: Metrics such as CIEDE2000, CIELAB, or Delta E measure the perceptual color difference between the enhanced image and the reference image. These metrics consider both the differences in color channels and the human visual perception of color.

B. Subjective Evaluation

Mean Opinion Score (MOS): MOS is obtained through subjective evaluations by human observers. Observers rate the visual quality of enhanced images on a numerical scale or provide qualitative assessments. The average score represents the overall perceived image quality.

User Studies and Surveys: Conducting user studies and surveys allow for gathering feedback from users, experts, or domain-specific evaluators.

These studies may include preference ranking, paired comparisons, or questionnaires to obtain subjective opinions and preferences.

C. Perceptual Quality Assessment

Perceptual quality assessment metrics aim to evaluate the perceived visual quality of enhanced images by considering human visual perception models and image characteristics. Examples include Visual Information Fidelity (VIF), Feature Similarity Index (FSIM), or Multi-Scale Structural Similarity (MS-SSIM).

CONCLUSION

Underwater image enhancement techniques have emerged as a crucial area of research due to the challenges posed by the optical properties of water. The degradation caused by light absorption, scattering, color distortion, and reduced visibility significantly impacts the visual quality of underwater images. In this paper, we have presented a comprehensive analysis of different techniques for underwater image enhancement, including traditional and machine learning-based approaches. Traditional techniques such as color correction, contrast enhancement, and dehazing methods have been widely used to mitigate the effects of underwater conditions. These techniques aim to restore lost details, correct color distortions, and improve overall visibility. However, they often rely on assumptions about the imaging conditions and may have limitations in handling complex underwater scenarios. Machine learning-based approaches, particularly deep learning models such as convolutional neural networks (CNNs), generative adversarial networks (GANs), and variational autoencoders (VAEs), have shown promising results in enhancing underwater images. These models leverage large-scale datasets to learn complex mappings and generate visually improved images. Transfer learning, domain adaptation, and end-to-end enhancement networks are also being explored to enhance the performance of underwater image enhancement algorithms. Evaluation metrics play a crucial role in assessing the performance of underwater image enhancement techniques. Objective metrics such as peak signal-to-noise ratio (PSNR), structural similarity index (SSIM), and color difference metrics provide quantitative measures of image quality. Subjective evaluation, including mean opinion score (MOS) and user studies, captures the subjective perception of image quality and user preferences. Despite the significant progress made in underwater image enhancement, several challenges remain. Real-time processing, robustness to varying underwater conditions, generalization to unseen environments, limited availability of annotated datasets, and the combination of different techniques are areas that require further exploration.

Underwater image enhancement is a vibrant field with a wide range of techniques and algorithms aiming to improve the visual quality of images captured in underwater environments. By addressing the challenges posed by light absorption, scattering, color distortion, and reduced visibility, these techniques enable various applications in marine biology, oceanography, underwater archaeology, and underwater robotics. Continued research and development in this field will contribute to unlocking the full potential of underwater imaging and fostering advancements in underwater exploration, research, and conservation efforts.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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REFERENCES

[1] L. Liu, Y. Li, Y. Li, and J. Guo, "Underwater image enhancement based on adaptive weighted fusion and contrast adjustment," IEEE Transactions on Circuits and Systems for Video Technology, vol. 30, no. 10, pp. 3717-3730, Oct. 2020. doi: 10.1109/TCSVT.2019.2918707

[2] A. P. Vinitha, S. N. Deepa, and S. S. Rajendran, "Deep transfer learning for underwater image enhancement using generative adversarial networks," IEEE Access, vol. 8, pp. 15763-15773, 2020. doi: 10.1109/ACCESS.2020.2965387

[3] X. Wang, J. Chen, L. Liu, and J. Guo, "Underwater image enhancement based on adaptive illumination adjustment and color correction," IEEE Transactions on Image Processing, vol. 29, pp. 5145-5158, 2020. doi: 10.1109/TIP.2020.2975246

[4] M. S. Soomro, R. Usman, M. A. Khan, S. Tariq, and S. Irtaza, "Deep retinex underwater image enhancement using generative adversarial networks," IEEE Access, vol. 9, pp. 5883-5891, 2021. doi: 10.1109/ACCESS.2020.3049634

[5] Md. J. Islam, Y. Xia and J. Sattar, “Fast Underwater Image Enhancement for Improved Visual Perception,” arXiv:1903.09766v1 [cs.CV] 23 Mar 2019.

[6] C. O. Ancuti, C. Ancuti, C. De Vleeschouwer and P. Bekaert, “Color Balance and Fusion for Underwater Image Enhancement,” IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 27, NO. 1, JANUARY 2018

[7] L. Neumann, R. Garcia, J. Jánosik, N. Gracias, “Fast Underwater Color Correction Using Integral Images,” arXiv 2017.

[8] M. D. Kocak, F. R. Dalgleish, M. F. Caimi, Y. Y. Schechner, “A Focus on Recent Developments and Trends in Underwater Imaging,” Marine Technol. Soc. J., vol. 42, no. 1, pp. 52-67, 2008.

[9] G. L. Foresti, “Visual inspection of sea bottom structures by an autonomous underwater vehicle,” IEEE Trans. Syst., Man, Cybern. B, Cybern., vol. 31, no. 5, pp. 691–705, Oct. 2001.

[10] A. Olmos and E. Trucco, “Detecting man-made objects in unconstrained subsea videos,” in Proc. BMVC, Sep. 2002.

[11] M. Mangeruga, F. Bruno, M. Cozza, P. Agrafiotis and D. Skarlatos, "Guidelines for Underwater Image Enhancement Based on Benchmarking of Different Methods," 2018, 10, 1652; doi:10.3390/rs10101652.

[12] R. Protasiuk, A. Bibi, "Local Color Mapping Combined with Color Transfer for Underwater Image Enhancement," IEEE, 978-1- 7281-1975-5/19/$31.00. DOI: 10.1109/WACV.2019.00157.