Underwater Image Enhancement Using Digital Image Processing Techniques

NIRUDEESWAR
21BCE5484
Department of Computer Engineering and Engineering
Email:nirudeeswar.r2021@vitstudent.ac.in

PALANIAPPA K
21BCE1712
Department of Computer Engineering and Engineering
Email:palaniappa.k2021@vitstudent.ac.in

MADHUKIRAN REDDY
21BCE1723
Department of Computer Engineering and Engineering
Email:madhukiranreddy2021@vitstudent.ac.in

***Abstract*—Underwater imaging is critical for applications such as marine research, underwater robotics, and oceanography. However, underwater images suffer from severe quality degradation caused by physical properties of water, such as light absorption, scattering, and noise. These factors result in color distortion, loss of sharpness, and low contrast, limiting the usability of such images in practical applications. This paper presents an effective image enhancement pipeline that integrates digital image processing techniques, including white balance correction, Contrast Limited Adaptive Histogram Equalization (CLAHE), and fast non-local means denoising. By addressing key challenges in underwater imaging, the proposed method restores natural colors, improves contrast, and reduces noise. Experimental results demonstrate substantial improvements in image quality, making this approach suitable for real-time applications and future integration with advanced machine learning techniques.**

***Index Terms*—Underwater imaging, image enhancement, white balance, CLAHE, noise reduction, marine robotics.**

I. Introduction

Underwater images provide valuable insights into marine ecosystems, seabed mapping, and archaeological sites. They are also essential for underwater navigation systems in robotics, enabling precise operation in unstructured aquatic environments. Despite their importance, capturing high-quality underwater images remains a significant challenge due to several environmental factors:

- **Color Distortion:** The absorption of light in water is wavelength-dependent. Longer wavelengths (e.g., red) are absorbed more rapidly than shorter wavelengths (e.g., blue and green), resulting in unnatural color tones.
- **Light Scattering:** Suspended particles scatter light, causing blurriness and reducing the visibility of objects in the image.
- **Low Contrast:** Reduced light penetration, especially in deep waters, results in images with poor contrast and lack of detail.

To overcome these challenges, researchers have developed various enhancement techniques, ranging from traditional image processing methods to deep learning approaches. This paper focuses on a computationally efficient, straightforward methodology using Python and OpenCV for enhancing underwater images.

II. Related Work

Several studies have explored methods for enhancing underwater images. Traditional techniques include histogram equalization, which globally enhances contrast but often overamplifies noise. Advanced methods, such as dark channel prior (DCP) and red channel restoration (RCR), target specific underwater imaging artifacts but require high computational resources. Deep learning-based methods, such as convolutional neural networks (CNNs) and generative adversarial networks (GANs), have shown promising results; however, they require extensive training data and computational power. This paper adopts a hybrid approach, combining effective preprocessing, enhancement, and denoising techniques suitable for real-time applications without deep learning dependencies.

III. Image Acquisition

The images used for this study were collected from publicly available underwater datasets and custom images captured using consumer-grade cameras. The dataset represents various underwater conditions, including:

- Shallow waters with natural lighting.
- Deep waters with artificial lighting.
- Environments with varying turbidity levels.

These diverse conditions ensure the robustness of the proposed method across different underwater scenarios.

IV. Methodology

The proposed method consists of three main stages: preprocessing, enhancement, and postprocessing.

A. Preprocessing

- **White Balance Adjustment:** To counteract the loss of red wavelengths and correct the overall color balance, white balance adjustment was applied. This involved estimating the dominant color cast and scaling the RGB channels to restore natural colors.
- **Color Space Conversion:** The images were converted from RGB to alternative color spaces (e.g., LAB or HSV) to perform specific operations like contrast enhancement and noise reduction more effectively.

B. Enhancement Techniques

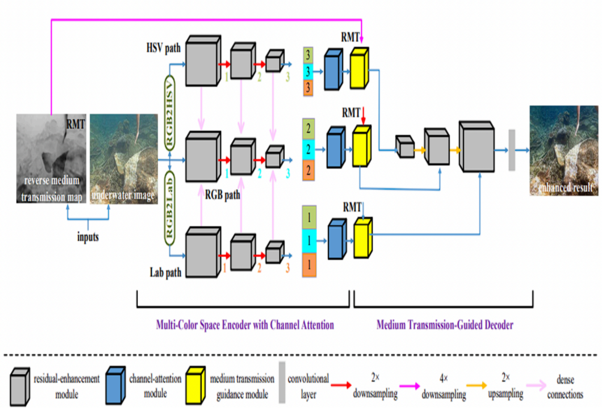
- **Contrast Enhancement with CLAHE:** CLAHE improves local contrast by adaptively equalizing the histogram in small, non-overlapping regions of the image. This prevents the over-amplification of noise in homogeneous areas and ensures better detail preservation.
- **Edge Preservation:** To maintain the sharpness of edges while enhancing contrast, edge-preserving filters were applied in conjunction with CLAHE.

C. Noise Reduction

- **Fast Non-Local Means (NLM) Denoising:** Fast NLM calculates weighted averages of similar patches across the image to suppress noise while preserving textures and edges. This technique effectively reduces noise introduced during the capture process or enhancement stages.

D. Postprocessing

- **Output Storage and Analysis:** The enhanced images were saved in high-resolution formats for further analysis and visualization. Qualitative analysis involved visual inspection, while quantitative metrics such as Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index (SSIM) were used for evaluation.



V. Results and Discussion

The proposed method was applied to various underwater images to assess its effectiveness.

A. Visual Results

- **Color Restoration:** White balance adjustment successfully restored the natural colors of underwater scenes, particularly in red-deficient areas.
- **Contrast Improvement:** CLAHE significantly improved visibility in low-light regions without introducing artifacts.
- **Noise Reduction:** Non-local means denoising removed noise effectively, maintaining the integrity of edge details.

B. Quantitative Analysis

- **PSNR:** An increase in PSNR values across all images indicated reduced noise levels.
- **SSIM:** Higher SSIM scores reflected enhanced structural similarity with reference high-quality images.

C. Comparison with Existing Methods

The proposed method was compared with conventional histogram equalization and advanced methods like RCR. The results demonstrated that the proposed approach outperformed traditional methods in color restoration and noise suppression while being computationally lighter than advanced techniques.

VI. Applications

The enhanced images find applications in:

- **Marine Research:** Improved visibility aids in identifying and monitoring marine life and ecosystems.
- **Underwater Robotics:** Enhanced visuals facilitate navigation, mapping, and object detection in autonomous underwater vehicles (AUVs).
- **Oceanography and Environmental Monitoring:** Enhanced images support data collection for climate studies and pollution assessment.
- **Photography and Videography:** Restored colors and clarity provide aesthetic and professional-quality images for underwater photographers.

VII. Future Work

The proposed method can be extended to include:

- **Integration with Deep Learning:** Using CNNs or GANs for adaptive and context-aware enhancement.
- **Real-Time Implementation:** Optimizing the method for deployment on embedded systems or GPUs for real-time processing.
- **Multispectral Data Integration:** Combining data from visible and non-visible spectra (e.g., infrared) for enhanced detail recovery.
- **Dynamic Environments:** Adapting the technique to handle varying conditions such as water currents, changing lighting, and high turbidity.

VIII. Conclusion

This paper presents a computationally efficient approach for enhancing underwater images using white balance correction, CLAHE, and fast non-local means denoising. The proposed method effectively addresses key challenges such as color distortion, low contrast, and noise, significantly improving the quality of underwater images. By ensuring simplicity and adaptability, the method is suitable for real-time applications. Future advancements will explore the integration of deep learning models and real-time processing to further enhance performance and usability.

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