A Comparative Analysis of Underwater Image Enhancement Techniques

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Abstract

Underwater imaging is critical for various applications, including marine biology and underwater exploration. However, underwater images often suffer from color distortion, contrast reduction, and detail loss due to the scattering and absorption of light by water. To address these challenges, various image enhancement techniques have been proposed, such as deep learning-based methods, physical models, and specific enhancement techniques. In this paper, we will perform a comparative analysis of these techniques using the widely used UIEB benchmark dataset. We evaluate their effectiveness in improving the visual quality of underwater images and provide insights into their limitations. We expect that deep learning-based methods generally outperform other techniques in terms of objective and subjective quality measures. However, physical models and specific enhancement techniques can still provide valuable improvements for certain types of images. This research can help researchers and practitioners choose appropriate methods for underwater image enhancement and inspire further developments in this field.

1 Introduction

Researchers are interested in exploring the underwater environment and analyzing its imaging for various applications such as ocean exploration, marine research, and military operations. The utilization of underwater resources is of significant importance to humans. That is the reason why remotely operated and autonomous vehicles with high-quality imaging systems are used to investigate the underwater environment. Developing effective enhancement techniques is crucial for sophisticated imaging tasks.

The underwater environment refers to the area surrounded by water in natural or artificial bodies of water such as oceans, seas, rivers, and aquifers. This environment is vital for sustaining life and serves as a natural habitat for a majority of living organisms. Humans frequently carry out various activities in accessible underwater areas. As a result, it is crucial to comprehend the traits of underwater imaging models for conducting research across various fields.

When dust particles are present in an underwater medium, they cause scattering. This occurs when light reflects from the outside of an object and interacts with the floating particles in the imaging medium. Two types of scattering affect underwater images: forward scattering and backward scattering[1]. Forward scattering leads to a blurry image as light deviates from the object to the camera. Backward scattering results from light reflecting from water or floating particles before reaching the object, leading to a low contrast and hazy effect on the image [1; 2; 3].

As per the Lambert-Beer empirical law, the reduction in light intensity relies on the characteristics of the medium it travels through [4]. In water, the intensity follows an exponential decay pattern, which is known as attenuation. Attenuation occurs due to the effects of absorption and scattering, which lead to a loss of energy and a change in the direction of electromagnetic energy. The combination of absorption and scattering in water causes a decrease in image quality, resulting in blurriness and reduced contrast. This problem is more pronounced in underwater conditions with high turbidity or when using strong artificial lighting. Artificial lighting can create non-uniform lighting in the scene, which leads to reflections that obscure image details and create bright spots. Furthermore, the presence of biological fluorescence and macroscopic particles in water can contribute to the degradation of underwater images. [5]

The extent of light absorption in water depends on the wavelength, with red light being absorbed first due to its longer wavelength. As a result, the colors of light vanish with increasing water depth, and underwater images tend to have a bluish tint, as blue light penetrates the furthest distance in the water medium owing to its short wavelength. [4; 5]

To address these issues, it is crucial to conduct research to create effective and high-performance enhancement techniques. Image enhancement refers to the process of improving the visual quality of an image by increasing its sharpness, contrast, or brightness, and reducing noise or distortion. The purpose of image enhancement is to make it easier to observe and analyze the features present in the image.

Several methods have been proposed for underwater image enhancement, including contrast stretching, histogram equalization, dehazing, and color correction. Other methods of image enhancement include deep learning-based methods. These methods utilizes a convolutional neural network (CNN) or reinforcement learning.

This study involves an analysis of various techniques for enhancing underwater images, which are evaluated for their ability to enhance visual quality using the UIEB benchmark dataset[6]. The study aims to provide insights into the limitations of these techniques.

2 Related Work

Underwater image enhancement is significant for obtaining clear images which are vital for understanding the real-life underwater scenario. Zhang [8] found that degraded images are often dominated by green color, resulting in poor visual clarity. Enhanced images provide more information and superior visual quality with a balanced distribution of red, blue, and green colors. Therefore, there is a necessity for enhancement and restoration methods to acquire high-quality images in both research and practical applications.

Haze Removal Techniques: Dehazing has become popular in various application domains that use digital imaging and computer vision. Underwater images are hazy due to floating particles which cause absorption and scattering of light rays as they pass from air to water. Dehazing plays an crucial role in enhancing images that are degraded by environmental factors such as fog or haze, making them suitable for further processing.

Cui [10] developed an underwater light field image restoration and enhancement technique by converting input images into four-dimensional data. They used dark channel prior and pyramid image fusion for haze removal.

Barros [12] developed a single-shot image restoration technique that combines a physics-based model for light propagation and quality metrics to reduce degradation and artifacts caused by attenuation and scattering effects. Zhang [13] explored a multi-scale fusion strategy for underwater image restoration, using the optical underwater model to obtain a restored image, followed by white balance and contrast enhancement and fusion for improved color correction and contrast.

Li and Li[14] proposed an underwater image restoration approach that uses a deep-sea optical imaging model to determine seawater properties, and a dual dark channel model to remove haze. They also utilize a Laplacian pyramid-based image fusion method to improve visibility in turbid scenes under artificial illumination, preserving shadow contrast and reducing backscatter in each frame.

Khan [15] presented a pipeline corrosion estimation using an enhancement and restoration algorithm that reduces blurring effects and improves image contrast, aiding the estimation process.

Lu [11] introduced a light field imaging method for spectral color correction of low-intensity underwater images, along with an underwater image depth estimation method based on a light field camera and deep convolutional neural network. Lu then [9] proposed an adaptive underwater image restoration technique that uses multi-scale cycle generative adversarial networks (MCycleGAN) and dark channel prior (DCP). Their deep learning approach employs a multi-scale structural similarity index measure (SSIM) loss to enhance contrast and correct color in the restored images.

Contrast enhancement techniques: Contrast is crucial for image quality, created by different luminance levels between adjacent planes, allowing objects to stand out from their background. Our vision is sensitive to contrast rather than absolute luminance, allowing us to perceive the world despite illumination variations. However, if contrast is too concentrated in one range, important information can be lost. To represent all image details, contrast must be optimized. Many algorithms have been developed to address these issues in underwater image processing.

Güraksin [22] use a differential evolution (DE) algorithm to enhance contrast in underwater images. The algorithm stretches the R, G, and B channels using parameters obtained from the DE. On the other hand Zhang [19] developed the LAB-MSR method for enhancing underwater images. They used bilateral and trilateral filters on the CIELAB color channels, resulting in reduced halo artifacts and improved performance. The method is based on the retinex algorithm, which mimics the human visual system. Later Sankpal and Deshpande [18] proposed a contrast enhancement algorithm for degraded underwater images based on Rayleigh stretching of an individual color channel using maximum-likelihood estimation of the scale parameter, energy correction, and stretching algorithms applied on RGB and HSI colour models.

Priyadharsini [16] proposed a contrast enhancement method for acoustic images using Stationary wavelet transform (SWT). Low-frequency sub-band is modifed using a Laplacian flter and the masking technique, resulting in higher peak signal to noise ratio. Güraksin[17] developed an underwater image enhancement technique using discrete wavelet transform (DWT) and differential evolution algorithm to optimize contrast and brightness.

Sun [20] have developed a deep CNN network that employs convolution layers for encoding and deconvolution layers for decoding, which has been widely applied to different types of images including colored photographs in recent works. Although there are still some issues about deep networks, this model can enhance images in an adaptive way without considering the physical environment and handle images with varying levels of noise. On the other hand, Bindhu and Maheswari [21] have used linear image interpolation and limited image enhancer to remove distortion, improve contrast, and increase resolution. Their approach has shown good performance compared to other state-of-art methods, as indicated by mean squared error (MSE), PSNR, and entropy values.

Color correction techniques: Underwater images appear greenish due to the dominance of blue and green colors with shorter wavelengths. Zhang [23] observed that the mean of the red channel is insignificant and the RGB histogram does not cover the range [0,255]. A color correction technique is needed to improve visual information.

Sankpal[24]proposed a method for correcting non-uniform illumination in underwater images using maximum-likelihood estimation. The image is separated into color channels, and histogram stretching is done to obtain a corrected image. The method performs better than other methods according to image quality metrics.

Zhang [25] developed a retinex model for illumination adjustment in underwater images. The method extracts an illumination map and applies gamma correction while preserving edge structures and smoothing textures. It corrects colour cast and outperforms other methods in terms of appearance and processing time, according to experiments. It also yields the best underwater image quality measurement (UIQM) values.

Liu [26] proposed a deep residual framework for enhancing underwater images using CycleGAN and a reconstruction model very-deep super-resolution reconstruction model (VDSR). They used an underwater Resnet model and batch normalization layers to accelerate convergence and improve visual effects. The method achieved significant improvement, as evidenced by the highest score of UIQM.

3 The Approach

Based on the literature review we conducted, it was observed that the majority of studies extends three primary methods for performing image enhancement which are haze removal, color correction and contrast enhancement. We have decided to make comparative analysis of one of the dehazing methods, also color correction and contrast enhancement methods which can also be achieved using deep learning based approaches. We will implement and test these methods using UIEB dataset.

For the case of dehazing, we have decided to implement single image haze removal using dark channel prior. [27] The dark channel prior is based on the observation that most outdoor haze-free images have at least one color channel with pixels of very low intensity close to zero, which is equivalent to the minimum intensity being close to zero. The dark channel is defined as the minimum value of each color channel of an image within a local patch. The observation is that for an outdoor haze-free image, except for the sky region, the intensity of its dark channel is low and tends to be zero, which is called the dark channel prior. Steps of the algorithm has been shown below:

1. Compute the dark channel prior of the input hazy image.
2. Estimate the global atmospheric light in the input image.
3. Compute the transmission map of the input image using the dark channel prior and atmospheric light.
4. Remove the haze from the input image using the estimated transmission map and atmospheric light.
5. Clip the pixel values of the output image to the range of [0, 255].

As a deep learning based method, we have decided to implement a CNN model for underwater image enhancement, called Water-Net[7]. This model is specifically designed to address the challenges posed by underwater image degradation. To generate the inputs for Water-Net, we applied three algorithms, White Balance (WB), Histogram Equalization (HE), and Gamma Correction (GC), to the original underwater image. Water-Net employs a gated fusion network architecture that learns three confidence maps to combine the three input images and produce an enhanced result.

Another method we will implement and test is based on traditional image processing techniques. The approach used to enhance underwater images includes color correction, white balancing, contrast enhancement, unsharp masking, and fusion. First, the images are color corrected by compensating for the degradation of the red and blue channels, followed by white balancing using the Gray World algorithm. Then, the contrast of the color-corrected image is enhanced using global histogram equalization, and the image is sharpened using unsharp masking. Finally, two techniques are used for image fusion: averaging-based fusion and PCA-based fusion. The PCA-based fusion involves flattening the components of both images into a column vector, finding the mean, covariance matrix, and eigenvectors of the concatenated matrix, and obtaining the coefficients for each channel for both images to obtain the fused image. [28; 29]

4 Experimental Results

At this stage, we have not obtained any experimental results as our focus has been on implementing the various techniques we have discussed in the approach section.

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