An effective underwater image enhancement method based on CLAHE-HF

Mingshi Luo, Yang Fang, Yimeng Ge
School of Computer Science, Xi’an Shiyou University, Xi’an 710065, China
mingshixsyu@126.com

Abstract. In order to solve the problem that the unbalanced illumination and noise induce poor contrast, uneven brightness and poor clarity to underwater image, an effective underwater image enhancement method based on spatial and frequency domain is proposed in this paper. Firstly, Contrast Limited Adaptive Histogram Equalization technology is used in spatial domain to enhance the local contrast of different regions of the image according to the distribution of pixel values of each region, which can not only ensure the image texture clarity and detail characteristics, but also suppress the noise. Secondly, Homomorphic Filtering technology is used to enhance the image details and reduce the noise in the image in frequency domain. Two sets of image data that verify the effectiveness of the proposed method were provided. The experimental results show that, compared with the traditional underwater image enhancement methods, the peak signal-to-noise ratio (PSNR), mean square error (MSE) and information entropy of the proposed method are combined optimal.

1. Introduction
At present, many countries bring underwater ecological protection, rational exploitation and efficient utilization of underwater resources into the core of scientific and technological development. In recent years, underwater image processing technology has been widely concerned and highly valued by researchers, and achieved remarkable results. But low resolution, low contrast, poor clarity, uneven illumination and low signal-to-noise ratio are the common problems in the underwater images. Light attenuation and backscattering noise seriously deteriorate the image in the imaging process. In the process of underwater image feature extraction and matching, the accuracy will be greatly affected. Therefore, it is necessary to enhance the underwater imaging quality, especially the image taken in unclear water, by adopting the optimal image enhancement algorithm before image subsequent processing (such as target recognition, image registration, image mosaic, etc.).

The imaging process of underwater image is quite different from that of terrestrial image: (i) the light intensity exponentially decay as light travels in the water[1], which causes low contrast and unclear contour texture for the image captured by the sensor. As the water depth increases, light intensity will decay even more quickly in the water, especially in deep water. The imaging objects often have low resolution and poor brightness due to insufficient illumination, which are difficult to be recognized; (ii) for underwater images, the effect of forward scatter as light propagating underwater causes its point spread phenomenon[2]. The existence of this phenomenon makes most of the object information in the image obscured by these ‘magnified’ point sources, and the underwater image with lower resolution becomes more blurred; and (iii) a large number of theories show that the light intensity with different wavelengths propagating in water have different decay speeds, which is one of the important reasons for the color distortion of underwater images. If in the pure water, at about 5m deep, the red light
disappears first; at 10m water depth, the orange light disappears; at 20m water depth, the yellow light disappears; at 30m water depth, the green light disappears; the blue light has the shortest wavelength, so it can spread far and wide underwater.

The underwater image sharpening methods can be divided into image restoration method and image enhancement method[3]. The underwater image enhancement method does not consider the imaging mechanism of the image, but only focuses on how to achieve the image enhancement effect by adjusting the pixel value of the image. Image enhancement methods mainly include: underwater image enhancement algorithm based on histogram, underwater image enhancement algorithm based on Retinex, underwater image enhancement algorithm based on filtering and signal processing, underwater image enhancement algorithm based on fusion. Singh proposed a recursive histogram equalization image enhancement method based on exposure[4]. This method can obtain lower mean square error and higher peak signal-to-noise ratio, but it cannot effectively solve the problem of color distortion. Zhang proposed the extended multi-scale Retinex underwater image enhancement algorithm[5], which extended the multi-scale retinal enhancement algorithm with color restoration (MSRCR) to CIELAB color space, and successfully suppressed the halo phenomenon in the process of image enhancement. However, this method has too many parameters to achieve underwater image with real-time processing. Shen Yu combined Bilateral filter and Tetrolet transform, proposed an underwater image sharpening algorithm in Lalpha beta color space[6]. This algorithm realizes underwater image sharpening processing, but did not fully consider the selective absorption attenuation of water to light, making the color of processed image still biased.

At present, the existing underwater image enhancement methods have insufficient robustness and adaptive ability, and cannot make adaptive adjustment when enhancing different types of degraded images. To solve the above problems, this paper proposes an effective underwater image enhancement method in spatial and frequency domains, which is suitable for different scenarios, tones and types of underwater image.

2. Underwater image enhancement method based on CLAHE-HF

In order to make the image edge details clear, this paper proposes a combination of frequency domain and spatial domain enhancement algorithm. The improved algorithm, which uses a homomorphic filtering combined with the CLAHE[7], processes descending images in underwater. Firstly, the CLAHE method is used to enhance the local contrast of the image according to the pixel value distribution of each region. Then the homomorphic filtering algorithm is used to enhance the image detail and reduce the noise in the image. And the image texture clarity and the details of the feature are obtained, while suppressing the enhancement of noise.

2.1. Algorithm Flow

The flow chart of the algorithm presented in this paper is shown in Fig.1. The specific image enhancement process algorithm is as follows:

1. Divide the image into 32x32 sub-regions;
2. Find the gray histogram of each partial sub-area, and let the gray level on each partial area have the same number of pixels, that is, obtain the average number of pixels:

$$N = \frac{N_x N_y}{N_{\text{gray}}}$$  \( (1) \)

In the formula (1), \( N_{\text{gray}} \) is the number of gray levels in the sub-region; \( N_x \) is the number of pixels in the x -axis direction of the sub-region; and \( N_y \) is the number of pixels in the y -axis direction of the sub-region. Limiting the number of pixels contained in each gray level is not allowed to exceed \( K \) times the average value \( \bar{N} \) ( \( K \) is the intercept limit coefficient), then the actual shear limit value \( N_{CL} \) can be:

$$N_{CL} = K\bar{N}$$  \( (2) \)
(3) The number of pixels larger than $N_{CL}$ in the histogram is cropped, and the total number of pixels

\[ N_{ap} = \sum_{i=0}^{N_{gray}} N_i \]

in the cropped portion is calculated. And the number of pixels $N_{ap}$ in which the total number of pixels intercepted is dispersed to each gray level is obtained.

\[ N_{ap} = \sum_{i=0}^{N_{gray}} N_i \]

(3)

The process of reallocation can be expressed as follows:

\[
\text{if } H(i) > H_{CL}, \quad H(i) = N_{CL} \\
\text{else if } H(i) + H_{ap} \geq N_{CL}, \quad H(i) = N_{CL} \\
\text{else } \quad H(i) = H(i) + N_{ap}
\]

(4)

where $H(i)$ is the number of pixels in the $ith$ gray level in the original region. After the above allocation, the number of remaining pixels is $N_{lp}$, and the step value of the assigned pixel is given by the following formula:

\[ S = \frac{N_{gray}}{N_{lp}} \]

(5)

For the remaining pixel values, the values calculated by the above formula are sequentially assigned from the minimum gray level until the number of pixels is 0, that is, a new histogram is obtained.

(4) The new histogram equalization process after the interception is obtained for each partial region.

(5) Taking the center point of each sub-block as a reference point, obtaining its gray value, performing gray-scale linear interpolation on each pixel in the image, using bilinear interpolation method, and mapping each pixel point by its phase. The mapping of the corresponding regions of the four reference points is determined. The gray values corresponding to the four reference points $(x_-,y_-), (x_-,y_+), (x_+,y_-)$ and $(x_+,y_+)$ in the image are $G_-(i), G_+(i), G_-(i)$ and $G_+(i)$ respectively. The interpolation formula of the calculated points is as follows:

\[
G(i) = a[bG_-(i) + (1-b)G_+(i)] + (1-a)[bG_-(i) + (1-b)G_+(i)]
\]

(6)

Among them $a = \frac{y-y_-}{y_+-y_-}, b = \frac{x-x_-}{x_+-x_-}, G(i)$ represents the gray value at point $(x,y)$.

(6) Logarithmic transformation of the enhanced image:

\[
\ln f(x,y) = f_0(x,y) + \ln f_0(x,y)
\]

(7)

(7) Fourier transform:

\[
F(u,v) = F_0(u,v) + F_0(u,v)
\]

(8)

(8) Multiply $F(u,v)$ by the homomorphic filter function $H(u,v)$:

\[
G_{in}(u,v) = H(u,v)F(u,v) = H(u,v)F_0(u,v) + H(u,v)F_0(u,v)
\]

(9)

(9) Inverting the Fourier transform:

\[
g_{in}(x,y) = g_{in}(x,y) + g_{in}(x,y)
\]

(10)

(10) Find the homomorphic filtered image by exponential transformation:

\[
g(x,y) = \exp(g_0(x,y)g_0(x,y))
\]

(11)
The image is divided into $32 \times 32$ non-overlapping sub-regions. The number of pixels larger than $N_{v_{	ext{max}}}$ in the histogram is calculated. The number of pixels in each gray level is $N_{w_{p}} = \sum \frac{N_{v}}{N_{v_{	ext{max}}}^p}$. Gray linear interpolation is used. Logarithmic transformation is applied: $\ln f(x, y) = \ln f_s(x, y) + \ln f_r(x, y)$. Fourier transform $F(u, v) = F_f(u, v) + F_r(u, v)$. Multiplied by homomorphic filtering function: $G_{f}(u, v) = H(u, v)F(u, v)$. Fourier inverse transformation is used. The final enhanced image is obtained by exponential transform.

Fig. 1 Procedure of underwater image enhancement based on CLAHE-HF

2.2. Principle of CLAHE for underwater image enhancement
An image histogram is an algorithm used to characterize the statistical relationship between each gray level of a digital image and its frequency of occurrence, and is an important statistical property of the
image. Its mathematical formula is as follows:

\[ P(r_k) = \frac{n_k}{N} \quad (k = 0, 1, 2, \ldots, L - 1) \]  

(12)

where \( P(r_k) \) is the probability of the occurrence of the \( k \)th gray level of the image \( f(x, y) \), \( r_k \) is the gray level of the \( k \)th gray level, \( n_k \) is the number of pixels whose gray value is \( k \) in the image, and \( N \) is the total pixel of the image Number; \( L \) is the total number of gray levels.

CLAHE extends the gray level of the original image from a relatively concentrated gray interval to an average distribution within the entire gray interval. Underwater images are usually affected by uneven illumination. And in complex and harsh underwater environments, the overall brightness of the image is dark and the background brightness is uneven. For these weak points of underwater images, the histogram equalization has an enlarged image gray value. The distribution range enhances the contrast of the image, which can stretch the dynamic range of the image grayscale, highlight some details, and achieve relatively good results. However, this algorithm also has its drawbacks. It is attributed to the global processing method. When dealing with images with different original illumination, the dark areas are darker, the bright areas are brighter, and the texture information is seriously lost. Therefore, the underwater image processing is not satisfactory. The adaptive histogram equalization algorithm differs from the commonly used histogram equalization algorithm in that it adjusts the image brightness by finding the local histogram of the image, thereby effectively improving the image contrast. Adaptive Histogram Equalization (AHE) distributes the brightness by calculating the local histogram of the image, which can enhance the local contrast of the image and obtain richer image texture information. However, the algorithm also has defects in the image enhancement. The enhancement of image noise cannot be effectively avoided in the process.

CLAHE is an improvement to the adaptive histogram equalization algorithm[7,8]. The algorithm first intercepts the histogram according to the method shown in Fig. 2, and then calculates the value of the conversion function to avoid image noise enhancement, and also preserves the advantages of the contrast adaptive histogram equalization algorithm[9]. Thus, both image internal texture and external contour information could be effectively obtained. The specific implementation steps are as follows:

1. Dividing the image into non-overlapping sub-regions.
2. Find the gray histogram of each partial sub-area, and let the gray level on each partial area have the same number of pixels, that is, obtain the average number of pixels (as shown in Formula (1)).
3. In the histogram, cut the number of pixels larger than \( KN \) ( \( K \) is the interception coefficient), and then find the total number of pixels \( \sum N_i \) in the intercepted area, as shown in Fig.2, and then obtain the cropped by \( \frac{\sum N_i}{N_{gray}} \) calculation. The total number of pixels is divided into the number of pixels in each gray level.
4. The intercepted histogram obtained by each region is subjected to equalization processing, and a new gray value is obtained by the transform function.

![Fig. 2 Schematic diagram of histogram interception](image)

2.3. Principle of underwater image enhancement based on homomorphic filtering
The homomorphic filtering algorithm is a very important frequency domain processing method in digital image enhancement, which can not only improve the image contrast, but also compress the dynamic range of the image[10]. The idea of the algorithm is to first convert the image to the logarithmic domain, then re-adjust the grayscale range of the image to solve the problem of uneven image brightness, and
improve the texture details of the dark region without changing the texture information of the bright region. It is suitable for images with low local gray value and uneven brightness[11]. According to the illumination reflection model, an image is represented by multiplying the illumination component and the reflection component. And the value of the product is a positive scalar, which is proportional to the radiant energy of the target object. That is, the product of the illumination function $f_i(x, y)$ and the reflection function $f_r(x, y)$ can constitute an image function $f(x, y)$, which can be expressed as:

$$f(x, y) = f_i(x, y)f_r(x, y), \quad 0 < f_i(x, y) < \infty , \quad 0 < f_r(x, y) < 1$$

(13)

In the formula (13), $f_i(x, y)$ is the original image, $f_r(x, y)$ is the illumination component, that is, the low-frequency information in the image, which is independent of the scene; $f_r(x, y)$ represents the reflection component, that is, the high-frequency information in the image, that is, the details of the scene, and illumination has nothing to do. Typically, the illumination component and the reflection component of the image contain distinct frequency domain features. The portion of the spectrum presented in the form of illumination component changes gently, and the variation range is relatively obvious, resulting in a large dynamic range of the gray value of the image. When the image is stored in bits, the occupied space is large, and the amount of important information contained is small. In contrast, the part expressed by the reflection component, especially the shadow part, has a blurred texture and unclear details, thus expanding the dynamic range of this part.

The homomorphic filtering is based on the equation (13) to separately filter the two parts of the multiplication. The core idea is to make the original image the two-component product as a logarithm operation, then turn it into a simple addition operation. Finally, it is converted to frequency domain by Fourier transform. According to the previously selected filter function, the effect of reducing the low frequency component and increasing the high frequency component is achieved, and the final enhanced image is obtained by exponential operation using the inverse Fourier transform. After this process, the image contrast can be effectively increased, and the dynamic range of the image is compressed. The whole process of homomorphic filtering is shown in Fig.3.

The specific process steps are as follows:

1. Logarithmic transformation:

$$\ln f(x, y) = \ln f_i(x, y) + \ln f_r(x, y)$$

(14)

2. Fourier transform:

$$F(u, v) = F_i(u, v) + F_r(u, v)$$

(15)

3. Multiply $F(u, v)$ by the homomorphic filter function $H(u, v)$:

$$G_{\text{in}}(u, v) = H(u, v)F(u, v) = H(u, v)F_i(u, v) + H(u, v)F_r(u, v)$$

(16)

4. Inverting the Fourier transform:

$$g_{\text{in}}(x, y) = g_{\text{in}}(x, y) + g_{\text{in}}(x, y)$$

(17)

5. Find the homomorphic filtered image by exponential transformation:
Underwater images often suffer from uneven illumination due to the influence of natural light, and the average gray level of each part would be significantly different. Whether the average gray level is low or high, it may cause the image texture to be blurred and is difficult to recognize. After the underwater image is processed by the homomorphic filter, the low frequency component is reduced while raising the high frequency component, the texture definition of the underwater image is enhanced, and the contrast of the underwater image is improved. In addition, the dynamic range of gray scale is compressed, so the algorithm can obtain a more significant enhancement effect when dealing with underwater images with uneven illumination and unclear texture.

3. Experimental result evaluation and performance analysis

Different from the general image quality evaluation method, the underwater image cannot obtain the true achromatic image of the target scene as a reference standard. Therefore, most of the subjective evaluation methods and objective evaluation methods without reference standards are used to evaluate and analyze underwater images.

As shown in Fig.4, (a) is the original underwater image to be processed, (b) is the result of the CLAHE algorithm enhancement processing, (c) is the result of the homomorphic filtering algorithm, and (d) is the algorithm of this paper. The sizes of all images are 450*338. As shown in Fig.4(b), the CLAHE algorithm can stretch the dynamic range of the image gray scale, highlight some details, and limit the noise amplification to avoid introducing more noise, but it cannot solve the uneven illumination in the image. Underwater image color cast problem; as shown in Fig.(c) after the homomorphic filtering process, it can be seen that the processed image details are more abundant, the image brightness is improved, and the image details are not damaged and the image is smoother. But the contrast is not significantly enhanced. The experimental results (d) show that the method can effectively enhance the image quality in turbid water, not only improve the edge details of the underwater image, but also eliminate the original noise points in the image, which can clearly show the distant reef, water grass and water body in the original image. The original light and shadow in the natural state, the texture details of objects such as tropical fish and reefs are also more clear.
Table 1 corresponds to the peak signal-to-noise ratio (PSNR), mean squared error (MSE), and information entropy of the image in Fig. 4 after CLAHE enhancement, homomorphic filtering enhancement, and the method described in this paper. The smaller the MSE after image processing means the better the processing effect; the higher the PSNR means the better the image processing effect; the larger the information entropy means the higher the disorder of information and the larger the amount of information contained. The results show that from the perspective of objective evaluation, the CLAHE algorithm has the largest PSNR value and the smallest MSE value, and the effect is better. But subjectively, it cannot deal with the problem of color cast and uneven illumination of underwater images. For the homomorphic filter enhancement algorithm, the PSNR value is the smallest, the MSE value is the largest, and the effect is the worst, but it can better deal with the problem of underwater image color cast and illuminance unevenness. The objective evaluation indexes of the algorithm are higher than the homomorphic filtering algorithm, and the information entropy is higher than the CLAHE method and the homomorphic filtering method, which indicates that the external contour and internal texture details of the image are clearer, the color is more distinct, and the recognition is stronger. In addition, subjectively, the method proposed in this paper is obviously better than the results obtained by the former two alone.

|           | PSNR | MSE     | Entropy of information |
|-----------|------|---------|------------------------|
| CLAHE     | 29.8641 | 67.0913 | 6.9940                 |
| HF        | 25.8268 | 169.9826| 7.2778                 |
| Improved method | 28.3657 | 70.1440 | 7.6706                 |

Another set of experimental data is shown in Fig. 5, (a) is the original underwater image to be processed, (b) is the result of the CLAHE algorithm enhancement processing, (c) is the result of the homomorphic filtering algorithm alone, and (d) For the processing results of the algorithm in this paper, the size is 367*305. The original turbid water body is blue in color, and it is impossible to see the details of the texture of the fish. After processing, it can clearly see the details, shape and contours of the fish in the vicinity, and the subjective visual appearance is more natural. The light changes in the water can be clearly observed, the contrast of the objects in the water is significantly improved, and the texture details of the fish in the dimly lit area can be restored well.
Fig. 5 Comparisons between the enhancement methods proposed in this paper and the traditional enhancement methods (II)

Table 2 corresponds to the peak PSNR, MSE, and information entropy of the original underwater image in Fig.5 after CLAHE enhancement, homomorphic filtering enhancement, and enhancement of the method described in this paper. The results also show that the method proposed in this paper is significantly better than the results obtained by the previous two treatments.

|                | PSNR  | MSE   | Entropy of information |
|----------------|-------|-------|------------------------|
| CLAHE          | 30.5419 | 57.3974 | 7.3208             |
| HF             | 26.2235 | 155.1435 | 6.8741              |
| Improved method| 29.3435 | 69.8760 | 7.4826               |

4. Conclusion
An underwater image enhancement method based on spatial and frequency domain is proposed in this paper. Firstly, in the spatial domain, the CLAHE method is used to enhance the local information of the image, and the color image after noise suppression is obtained. Secondly, homomorphic filtering is used to improve the contrast of the whole image in frequency domain. Using these two steps, the optimal enhancement of underwater image can be achieved. The experimental results show that the proposed method solves the problem of underwater image color cast, uneven illumination, and weak contrast on the basis of better retaining the details of the image, and optimizes the enhancement effect. Compared with the single CLAHE or HF enhancement methods, the comprehensive performance of the proposed method is the best. But the independent index of PSNR and MSE is not optimal, so we will further improve the PSNR and MSE performance of the proposed method in the next work.

Acknowledgments
This work was financially supported by the Key R&D Program Projects in Shaanxi Province (2018SF-409).

References
[1] Hou W, Woods S, Jarosz E, et al. Optical turbulence on underwater image degradation in natural environments[J]. Applied Optics, 2012, 51(14):2678.
[2] ZHEN Yi, Cheng Shuwei, et al. The caculation of shear slippage of light-weight aggregate concrete composite floor slabs[J].Industrial Construction, 2007,37(s1):579-591.
[3] Li Li, Wang Huigang, Liu Xing. Underwater image enhancement based on improved dark priori
and color correction[J]. Journal of Optics, 2017, 37(12): 1211003 (in Chinese).

[4] Singh K, Kapoor R, Sinha S K. Enhancement of low exposure images via recursive histogram equalization algorithms[J]. OPTIK-International Journal for Light and Electron Optics, 2015, 126: 2619-2625.

[5] Zhang S, Wang T, Dong J Y, et al. Underwater image enhancement via extended multi-scale Retinex[J]. Neurocomputing, 2017, 245: 1-9.

[6] Shen Yu, Party Jianwu, Wang Yangping, etc. Colour underwater image sharpening algorithm based on Tetrolet transform[J]. Journal of Optics, 2017, 37(9): 0910002 (in Chinese).

[7] Zuiderveld K. Contrast Limited Adaptive Histogram Equalization[J]. Graphics Gems, 1994:474-485.

[8] Reza A M. Realization of the Contrast Limited Adaptive Histogram Equalization for Real-Time Image Enhancement[J]. Journal of Vlsi Signal Processing Systems for Signal Image & Video Technology, 2004, 38(1):35-44.

[9] Pizer S M, Johnston R E, Ericksen J P, et al. Contrast-limited adaptive histogram equalization: speed and effectiveness[C]. Visualization in Biomedical Computing, 1990. Proceedings of the First Conference on. IEEE, 1990:337-345.

[10] Adelmann H G. Butterworth equations for homomorphic filtering of images[J]. Computers in Biology & Medicine, 1998, 28(2):169.

[11] Agarwal T K, Tiwari M, Lamba S S. Modified Histogram based contrast enhancement using Homomorphic Filtering for medical images[C]. Advance Computing Conference. IEEE, 2014:964-968.