Study on Underwater Image Denoising Algorithm Based on Wavelet Transform

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Abstract. This paper analyzes the application of MATLAB in underwater image processing, the transmission characteristics of the underwater laser light signal and the kinds of underwater noise has been described, the common noise suppression algorithm: Wiener filter, median filter, average filter algorithm is brought out. Then the advantages and disadvantages of each algorithm in image sharpness and edge protection areas have been compared. A hybrid filter algorithm based on wavelet transform has been proposed which can be used for Color Image Denoising. At last the PSNR and NMSE of each algorithm has been given out, which compares the ability to de-noising

1. Introduction

Underwater laser imaging technology plays an important part in the exploration of underwater information such as detecting underwater information. However, due to the special water medium, the image will be subject to noise pollution so that the resolution will be decreased. A great deal of manpower and material have been invested in researches of underwater laser ranging, imaging and other fields by many countries such as The United States, the former Soviet Union , and breakthrough has been made in some key directions [1].

There's difference between the characteristics of water and air that laser transports in, which brings great difficulties in underwater target detection using laser. Mainly in the following two points [2]:

1. The effect of laser ranging accuracy and imaging results due to the backscattering of beam by sea water.

2. The limition of the target detection distance due to the strong attenuation of light waves by sea water.

In recent years, a lot of researches on the backscattering and attenuation of laser in seawater have been done at home and abroad, which bring great breakthroughs in underwater laser detection imaging technology, detection distance and image quality[2]. Among them the scattering model of underwater laser has been described in reference [1] which improves the median filter, but the improvement of image processing effect is not obvious. The Wavelet Threshold Denoising has been introduced in reference [2], but the advantages of the algorithm have not been reflected.A variety of commonly used image processing algorithms have been described in reference [3] which simulate them also, but the relevant evaluation parameters of noise canceling have not been given.

In this paper, the transmission characteristics of laser underwater are discussed first, the attenuation of the laser under water is analyzed and the scattering model is calculated. Furthermore, the noise of underwater laser imaging is analyzed, the common noise suppression algorithm and their advantages and disadvantages are given. At last, a filtering algorithm based on wavelet transform is proposed and

simulated, and the Peak Signal to Noise Ratio, Normalized Mean Square Error and operation hours of each algorithm are calculated, which show the advantage of wavelet threshold denoising.

2. Analysis of Underwater Laser Propagation
The attenuation and scattering characteristics of laser signal in water have been analyzed in his chapter.

2.1 The attenuation of laser signal in water
The attenuation coefficient of laser is relatively large in the short wavelength and long wavelength region, but small in the blue-green region. That's what we called Seawater Optical Window as usual, which played an important role in the development of ocean optics. So far, most of the lasers used in ocean lasers are blue-green lasers, so that the laser attenuation in the water is the smallest, which can reach the deeper Detection distance [3].
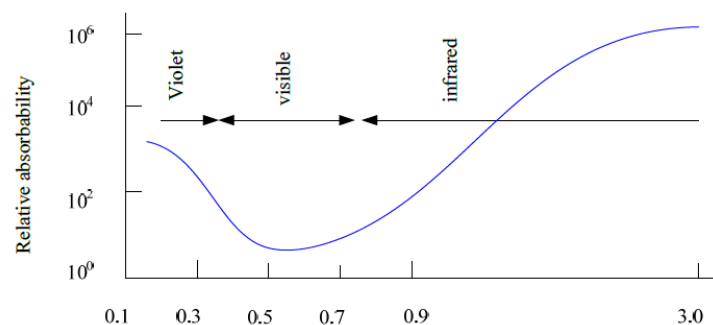

Figure 1 relative absorption coefficients of light waves at different wavelength

It can be seen from the trend diagram of the relative absorption coefficient of wavelength in Figure1 that the attenuation of ultraviolet and infrared light band in water is great large so that they can't be used in water. However, the attenuation of blue-green light in the visible light band is minim, for example, the attenuation lengths of the light waves in 0.4900μm and 0.6943μm are 11m and 2m. It shows that the transmission performance of blue light in water is better than red light.

2.2 The scattering of aqueous media
The reduction of signal to noise ratio of underwater laser imaging receiving system is the major effect of the scattered light which will bring a strong background noise. As the imaging distance increases, the screen contrast reduced and the image contrast decreases so that underwater optical imaging becomes more difficult[4]. What's more, because of the particles, plankton in seawater and the flow of water, the noise will be generated inevitably for the underwater images which causes the decrease of imaging quality further[5].
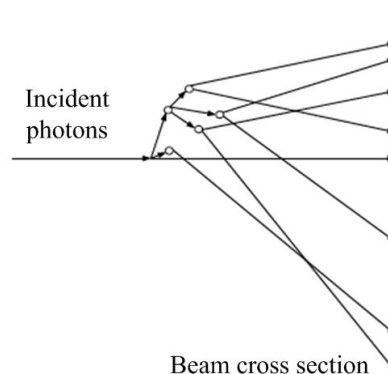

Figure 2 forward scattergram of water molecules to light

2.2.1 The forward scattering. As we can be seen from Figure 2, the forward scattering increases the laser transmission distance significantly, and the farther the transmission distance, the greater the role of forward scattered light, which is advantageous to underwater illumination, but disadvantageous to underwater beam scanning and imaging because it will degrades resolution and target background contrast.

2.2.2 Backscattering. The scattering of light in the direction opposite to the propagation direction is called backscattering. Strong backscattered light will saturate the receiver without receiving any useful information, that's why the main research tries to overcome the impact of backscatter in underwater ranging, imaging and other applications. There are the following methods of overcoming the effects of backscattering: Using a suitable filter and analyzer; Separating emission sources and receivers as far as possible. Using the distance gating technology is the most effective method still now [6].

3. Underwater Image Denoising Algorithm

Digital image processing is generally from the beginning of image filtering so it's necessary to understand the type and nature of the noise.

3.1 Classification of image noise

One of the important factors that cause the image resolution to decrease is the noise which from the image acquisition and transmission process. It is necessary to know the type and nature of noise because the processing of the image is generally started with image filtering. From the category point of view, the main noise has the following:

(1) Gaussian noise: It is the most common kind of noise which the various unstable factors of imaging system are often expressed through.

(2) Salt and pepper noise: The noise that shows larger and smaller gray scale values in a certain pixel or a region is what we called salt and pepper noise.

(3) Fixed mode noise: It is due to imperfections in the system devices. Because it does not have randomness, we also call it "The clutter".

The actual image signal is often affected by correlated noise, signal-related noise, and various other distributed noises. Therefore, it is impossible to strictly determine and calculate noise.

3.2 Common denoising methods

Here are some common denoising algorithms: Wiener filter, median filter, average filter algorithm

3.2.1 The Adaptive Wiener Filter. The Adaptive Filter can adjust the current filter parameters by the filter parameters that can be obtained empirically which make it adapt to the statistical properties of unknown or time-varying of signals and noise [7]. The smoothing effect of the filter is small when the local variance is large and stronger when the local variance is small. The ultimate goal of the Adaptive Wiener Filter is to minimize Mean Square Error $\sigma^2 = E[(f(x,y)-F(x,y))^2]$ of the restoring image $f(x,y)$ and the original image $F(x,y)$. This method is useful for preserving edges and other high-frequency parts of an image but its calculation is large.

3.2.2 The Median Filtering. The Median Filtering is a nonlinear signal processing method which can overcome the image detail blur caused by linear filtering under certain conditions and effective for filtering pulse noise and image scanning noise. The median filter not only removes noise but also protects the edges of the image which can obtain a more satisfactory recovery effect. It's convenient that the Statistical Properties of Images is not necessary. However, the Median Filtering is not suitable for processing the image with a lot of points, lines, spire details. The Median Filtering can be represented by the following formula:

$$\hat{f}(x,y) = \underset{(s,t)\in S_{xy}}{Med} \left\{ g(s,t) \right\} \tag{1}$$

3.2.3 The Average Filter. Here are two average denoising filtering algorithms：The Arithmetic Average Filter；The Geometric Average Filter.

(1) The Arithmetic Average Filter

Arithmetic Average Filter is a simple average filter. Sxy represents a coordinate group of the rectangular image window that the center is at (x,y) and the dimension is m×n. The arithmetic mean process is to calculate the average of the interfered images $g(x,y)$ in the defined area Sxy. The value of the restored image $\hat{f}(x, y)$ at any point (x,y) is the arithmetic average calculated by the pixels of the area defined by S_{xy}:

$$\hat{f}(x, y) = \frac{1}{mn} \sum_{(s,t)\in S_{xy}} g(s,t) \tag{2}$$

This can be achieved by a convolutional template whose coefficient is 1/mn.

(2) The Geometric Average Filter
The image restored with the geometric average filter is given by the following expression:

$$\hat{f}(x, y) = \frac{mn}{\displaystyle\sum_{(s,t)\in S_{xy}} \frac{1}{g(s,t)}} \tag{3}$$

The harmonic averaging filter is more effective for salt noise and gaussian noise, but not suitable for pepper noise.

3.2.4 The wavelet denoising. The basic methods of wavelet denoising are: The wavelet transform modulus maxima denoising; The wavelet transform inter-scale correlation denoising; The nonlinear wavelet threshold denoising.

(1) The wavelet transform modulus maxima denoising

The wavelet transform modulus maxima denoising method is based on the different propagation characteristics of signal and noise at each scale of wavelet transform, removing the modulus maxima point generated by noise, preserving the modulus of the signal corresponding to the maximum point, and then reconstructing the wavelet coefficients by the residual modulus maxima points, restoring the signal at last.

(2) The wavelet transform inter-scale correlation denoising

There is a correlation between the wavelet coefficients corresponding to the image features in different scale space (resolution)，which we called the correlation between the scales. This correlation is fixed in the wavelet transform decomposition process which reflects the multi-scale nature of space. In the same scale space, the important wavelet coefficients are concentrated in some areas, and this correlation is called intra-scale correlation. According to the above characteristics of wavelet transform between signal and noise at different scales, it is possible to enhance the signal and suppress the noise by multiplying the wavelet coefficients of adjacent scales directly.

(3) The nonlinear wavelet threshold denoising

The wavelet transform has strong data decorrelation, which can make the energy of the signal concentrate in a small number of wavelet coefficients in the wavelet domain, while the noise is distributed in the entire wavelet domain, corresponding to a large number of small wavelet coefficients. The amplitude of the wavelet coefficient of the signal is larger than the amplitude of the wavelet coefficients of the noise after wavelet decomposition so that we can keep the wavelet coefficients of the signal, leaving most of the noise wavelet coefficients reduced to zero by the threshold method.

The qualitative comparison of the three denoising methods is shown in Table 1.

Table 1 The qualitative comparison of the three denoising methods

denoising methods	modulus maxima	inter-scale correlation	threshold denoising
Calculation	Large	Relatively large	Small
Stability	Stable	Relatively stable	Depend on SNR
Effection	Relativel Good	Good	Good
Range	Low SNR	High SNR	High SNR

*3.3 Color Image Denoising Algorithm Based on Wavelet Threshold*

There is different denoising ability for different noise, and their respective advantages and disadvantages for the common denoising methods. For example, The Median Filter has better denoising ability to impulse noise, but less effect on Gaussian noise. The Average Filter has better denoising ability to Gaussian noise, but not conducive to protect the edge of image so that the image becomes indistinct. The Wiener filter is useful for preserving edges and other high-frequency parts of the image, but computationally expensive

The following proposes a filtering algorithm based on the wavelet threshold filter, which can not only remove the image of Gaussian noise and salt and pepper noise better, but also preserve the image clarity better. The algorithm is based on the wavelet threshold filtering algorithm and use the median filter combined with mean filter combination, which makes the threshold selection of the algorithm easy. After wavelet threshold denoising, the Fourier transform and Butterworth high-pass filter are used to preserve the edges of the image.

The threshold functions which is divided into hard threshold function and soft threshold function in the threshold denoising algorithm, represent different processing strategies and estimation methods for the wavelet coefficients that exceed and fall below the threshold.

The most important thing in the threshold denoising algorithm is how to choose threshold and threshold function because the noise still exists in the denoised image if the threshold is large, and important image features will be filtered out if the threshold is small. Intuitively speaking, for a given wavelet coefficient, the greater the noise, the large the threshold. So most of the threshold selection process is calculating a threshold according to the statistical characteristics of the wavelet coefficients. Therefore most of the threshold selection process is for a set of wavelet coefficients, which means a threshold is calculated according to the statistical characteristics of the group of wavelet coefficients.

The flow chart of the hybrid noise filtering algorithm is shown in Figure 3.
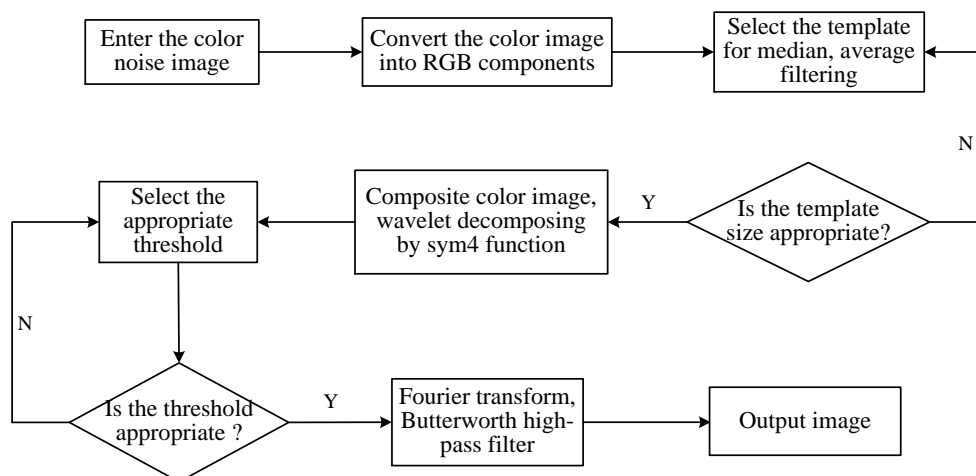
Figure 3 The flow chart of the hybrid noise filtering algorithm

4. Simulation Experiment and Result Analysis

In this chapter, the related algorithms introduced in the previous chapter are simulated and the PSNR and NMSE of each algorithm has been given out, which compares the ability to de-noising.

4.1 Quality Evaluation of Noise Canceling

Some common image fidelity measurement parameters are given: Mean Absolute Error (MAE), Mean Square Error(MSE), Normalized Mean Square Error(NMSE), Signal to Noise Ratio(SNR), Peak Signal to Noise Ratio(PSNR) [8].

The SNR above 40dB shows excellent image quality close to the original image, 30~40dB usually indicates that the image quality is good that distortion can be perceived but acceptable, 20~30dB shows poor image quality; the SNR below 20dB means the image is unacceptable [9].

The PSNR and NMSE are used as the objective evaluation index in this paper. The following describes its calculation method.

$$PSNR = 10 \cdot \log \frac{255^2}{\frac{1}{MN} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left(f(i,j) - p(i,j) \right)^2} \tag{4}$$

$$NMSE = \frac{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \left(f(i,j) - p(i,j) \right)^2}{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} f(i,j)^2} \tag{5}$$

In the formula, M and N mean the height and width of the image respectively; $f(i,j)$ mean the pixel value of the original image; $p(i,j)$ means the pixel value of the filtered image. The larger the SNR, the better the noise smoothing effect, while the smaller the MSE, the less the edge of image loss [10].

4.2 Experimental simulation and result analysis

In this paper, the MATLAB is used to analyze the image processing. The filtering effects of some commonly used filtering functions are compared, Figure 4 shows the original noise image, Figure 5 to Figure 9 show the images processed by the usual filtering algorithm, and Figure 10 to Figure 12 show the images processed by the three wavelet algorithms.
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Figure 4 original noise image   **Figure 5** 3×3 median filtering
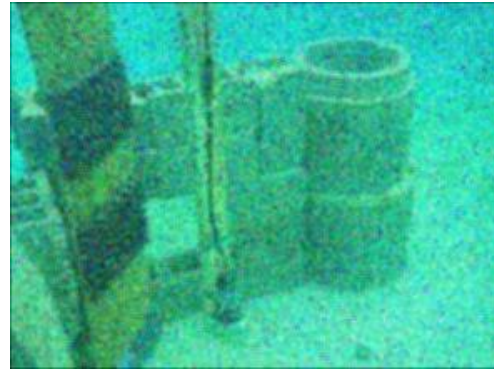
Figure 6 5×5 median filtering

Figure 7 3×3 average filtering

Figure 8 5×5 average filtering

Figure 9 Wiener filtering

Figure 10 wavelet threshold filtering

Figure 11 modulus maxima filtering

Figure 12 scale correlation filtering

By contrast, the image can reflect the smaller median filter and the mean filtered image, but the noise removal is less, and the larger template can remove the noise better, but it will make the image edge blurred. In addition, compared to other commonly used algorithm, the Wiener filter's image clarity is better, but the pepper noise removal capacity is weak. Compared with the three wavelet denoising algorithms, the image filtered by the modulus maxima is blurred and the image information is distorted. However, the image processed by wavelet threshold filtering and scale correlation filtering is clearer, and the edge of image can be well protected.

Table 2 Comparison of PSNR and NMSE in Common Algorithm

Evaluation	PSNR	NMSE
3×3 median	33.0417	0.0308
5×5 median	33.8768	0.0333
3×3 average	32.0843	0.0302
5×5 average	31.7273	0.0356
Wiener	34.8971	0.0209

Table 3 Comparison of PSNR and NMSE in Wavelet filtering

Evaluation	PSNR	NMSE
wavelet threshold	37.7064	0.0160
modulus maxima	36.0106	0.0199
scale correlation	37.3846	0.0152

Table 2 shows that the Wiener filter has the highest PSNR value, the best noise removal effect, and the lowest value of NMSE, and the better protection of the image edge in the commonly used image processing algorithms. Table 3 shows that PSNR is slightly lower than the other two algorithms and NMSE is slightly higher for the three wavelet denoising algorithms; the PSNR and NMSE of the wavelet threshold filter and the scale correlation filter are close.

Table 4 algorithm program running time

Algorithm	wavelet threshold	modulus maxima	scale correlation
Running time	2.15s	4.82s	2.53s

Table 4 shows that the time spent of filtering the modulus maxima is close to that of threshold filtering, but the scale-dependent filtering is computationally intensive and takes a long time to run. Comparing the PSNR value, RMS value and running time of the three algorithms, when the threshold is more appropriate, the wavelet threshold filter algorithm has a higher SNR and a shorter running time, which is superior to the other two algorithms.

5. Conclusions

The paper introduces the transmission characteristics of underwater laser signals and summarized the types of underwater imaging noise. In this paper, commonly used noise suppression algorithms were elaborated, including wiener filtering, median filtering, mean filtering. Furthermore the advantages and disadvantages of each algorithm are analyzed. Then based on the proposed three wavelet denoising algorithms, the peak signal SNR and normalized mean square error of each algorithm are calculated, and the running time of each algorithm are also compared. Finally, it is found that the wavelet threshold filtering algorithm not only removes noise effectively, increases the SNR of the image and protects the edge of the image better, but also has shorter running time than the other two algorithms.

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