A Survey on Image Enhancement and Restoration Techniques

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Abstract—Image Enhancement is one of the most essential and important techniques used in image processing. Image enhancement can help improve the visibility and eligible of different kinds of images. It is important to develop this advanced technology since it could be used in the broad fields of information technology, digital application and so on. This paper presents a review of image enhancement processing techniques which includes the histogram-based image technologies, frequency domain technologies which is achieved through image-based and physics-based. The last part included in our paper is image restoration technologies, which is a processing technique to improve the quality of image by recovering degraded images to the original one. These are three of the most significant fields in the development of image enhancement. Our paper mainly focuses on these three aspects. At the same time, these three aspects will be explained in detail. This technology has already been used skillfully in some practical fields.

Keywords: Histogram equalization; frequency filter; Blind deconvolution; Regularization; Richardson-Lucy algorithm

1. INTRODUCTION

Digital signal processing technology, which is an application of digital technology, refers to continuous signal digitization after processing technology. The development of computer and digital signal processing technology and the rapid development of digital electronic technology are closely related. In preprocessing, digital signal processing technology can handle systematic noise and improve the signal-to-noise ratio. It can perform algorithmic calculations in the processing stage to improve data reliability and processing speed. Digital signal processing technology is widely used, including communication, automatic control, image processing, radar signal transmission, sound processing and many other advanced technologies. At the same time, digital signal processing technology also occupies a very important position in academic and research fields. Digital signal processing technology has more mature applications in three fields: communication field, image processing field, and sound processing field.

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In the field of communication, digital signal processing technology can help technicians improve channel capacity, improve communication quality, and reduce communication costs. This technology can also preprocess the signal, suppress the interference signal, and improve the signal-to-noise ratio; The bit error rate is controlled to improve data reliability.

In image processing, digital signal processing technology can compress data and reduce storage space while processing digital images. At the same time, the image can be enhanced, the image quality can be improved and the information in the image can be processed intelligently. This field has a broad application prospect.

In sound processing, digital signal processing technology is mainly used for low-pass, high-pass and other filter processing of sound, and other technologies are mostly used for secondary processing of input sound in the later period so that the output audio and music become more perfect. The development of digital signal processing technology has many mature applications today, and the development trend of signal nursing technology in the future has not stopped.

In terms of hardware, SCM is more and more powerful, processor chip is being updated, and the capability and precision of DSP will be enhanced. The background of this paper is focused on the image enhancement and recovery. Most commonly used approaches to enhance the image are the histogram equalizing, the smoothing of the image, the sharpening and the false colour. Histogram is a graph that shows the brightness and darkness distribution of an image. Equalizers are used to equalise a highly unevenly distributed image in order to enhance image quality. Smoothing and sharpening are used to improve the texture and texture of the picture, and to enhance the clarity of the picture. Fake colour is to transform the original black-and-white picture into a coloured picture, and to express the difference between the intensity and the intensity of the image. The method of image recovery is achieved through image filtering.

In practical applications, because the original image cannot meet the ideal requirements, for example, the illumination is very uneven, some parts of the image are too bright, some parts are too dark; The average brightness difference of camera images obtained at different time is too large. Moving objects in the shooting some movement, and the image itself mixed with disturbed stripes and noise bright spots. Image enhancement and restoration is an important part of image preprocessing. The study of image enhancement and restoration is a long-term task. So far, there are still many theoretical and technical difficulties. This is mainly because several quality indicators are difficult to account at the same time. For example, the noise in the image is eliminated, while the clarity of the image is reduced. Therefore, people are committed to studying the optimal method which can consider many quality indicators.

2. HISTOGRAM-BASED IMAGE ENHANCEMENT TECHNIQUES

2.1. Histogram equalization

The histogram equalization method is one of the most commonly used and effective methods in airspace enhancement. It changes the gray histogram in the original image from a concentrated gray interval to evenly distributed throughout the whole gray area. As shown in Figure 1, the image's contrast is significantly improved after the histogram equalization method, thus making the image clearer and achieving the purpose of image enhancement.

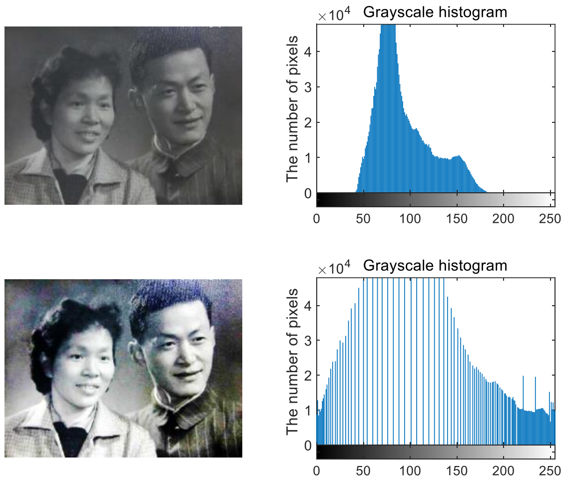

Figure 1 The changes caused by histogram equalization on image and its histogram (original)

Histogram equalization is one of the most popular and efficient ways to enhance the image. But it is possible that the mean luminance will be altered by this approach, which will cause the picture to deteriorate, make the picture appear unnatural, and lose the characteristic of the picture. In order to solve this problem, Kim et al introduced Luminance Preservation Bi-Histogram Equalization (BBHE) in 1997 [1]. In this approach, the image is split into 2 sub-images to be balanced according to the mean luminance.

In 1999, Wang and his colleagues presented Dual Sub Image Histogram Equalization (DSIHE) [2], in which the mean luminance is replaced by mean luminance. The results show that the minimal mean luminance of the raw picture and the output image are more precise and precise when the mean is taken as the separating point.

A novel Quadrant Dynamic Histogram Equalization (QDHE) algorithm was presented by Ooi and Isa in 2010 [3]. Firstly, the histogram is split into 4 subhistograms according to the middle luminance of the input picture, and then the enhancement ratio is calculated according to the average of the appearance of the picture. Then, a new dynamic range is allocated for every sub-histogram, and the final result is even. A major merit of QDHE lies in its lack of strength saturation, noise-amplifying and over-enhancing effect. Therefore, the proposed approach can be used to improve the quality of the picture taken under low-light conditions.

Furthermore, in 2015, Lin et al utilized Average Histogram Equalization (AVHEQ) to improve the contrast and keep the luminance of the image [4]. This approach includes the following steps: Color Channel Extension, Histogram Averaging, and Image Reconstruction. This method doesn't need to split the picture into several sub-images, and it doesn't need to modify the histogram to avoid artifacts. At the same time, it is better than other conventional approaches (figure 2).

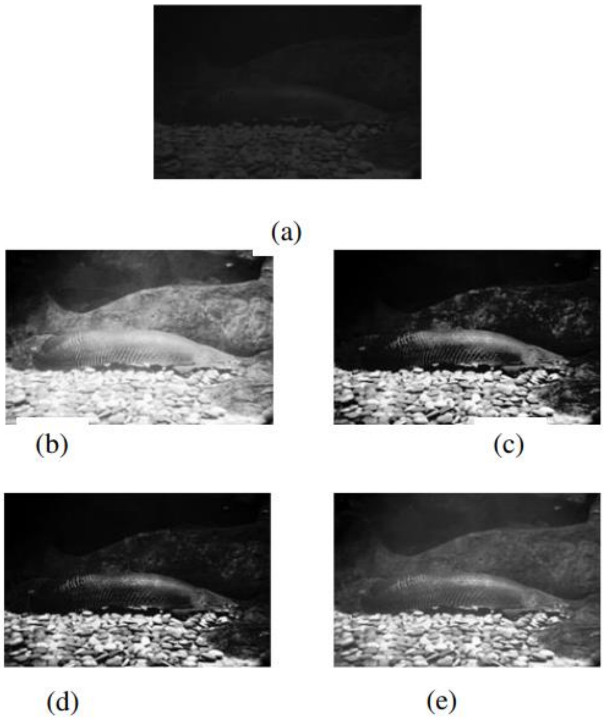

Figure 2 The comparison of enhancement result based on histogram modification: (a) Original image, (b) HE, (c) BBHE[1],(d) BHEPL[5], and (e) QDHE[3].

Generally speaking, the Histogram Equalization (HE) technique has gained wide popularity because of its easy realization and rapid processing. But there are a lot of shortcomings in this technique, for example, there are more noise, lower contrast of useful signals, and more likely to result in over-enhancing and artefacts. Though there has been a certain improvement in this problem due to the appearance of new algorithms, their efficiency remains unsatisfactory in the case of non-uniform illumination, because most of them rely on global histogram equalization.

2.2. The classifications of Histogram-Based image equalization

Histogram-Based image equalization methods are classified as global histogram equalization[6], local histogram equalization[7] and histogram matching.

Based on the classification of image equalization, we can divide it into three categories: Global Histogram Equalization [6], Partial Histogram Equalization[7] and Histogram Matching.

1) Global histogram equalization: The global histogram equalization method directly processes the histogram of the whole image.

The steps of global histogram enhancement are given below:(1) Calculate the grayscale histogram of the images. (2) Calculate the cumulative histogram of the image (To ensure that the size relationship of the processed pixels remains unchanged, only the contrast of the image increases). (3) Perform grayscale value transformation. (4) Obtain the processed images.

The advantages of this method are its simple calculation and fast speed. But it is sensitive to noise, prone to lose image details, and causes over-enhancement in some areas. So this method is suitable for processing some images with low contrast

2) Local histogram equalization: Unlike the global histogram equalization method, the local histogram equalization method processes a small area to enhance more detail.

The steps of local histogram enhancement are given below: (1) Select a neighborhood and calculate its histogram. (2) Perform histogram equalization on the selected neighborhood. (3) Transfer the center pixel of the neighborhood to the next pixel and perform histogram equalization on the moved neighborhood. (4) Repeat step three until all pixels have been modified.

The main advantage of local histogram equalization is local adaptation, which can maximize the enhancement of image details. This method has better accuracy than global histogram equalization in improving image contrast. But it involves in more computations and it is difficult to manipulate the enhancing image quality

3) Histogram matching: In some cases, images with uniformly distributed histograms are unnecessary, and sometimes images with specific distribution histograms are needed to enhance certain grayscale levels in the image. In this case, we can process images through histogram matching.

Histogram matching is a conversion of an image, which transforms the original image's histogram into the desired histogram shape through point operations.

The steps of histogram matching are given below: (1) Equalize the histogram of the original image. (2) Specify the expected histogram and find the equalization transformation function for the specified histogram. (3) Map the original histogram to the specified histogram accordingly. (4) Determine the number of pixels at each grayscale level in the new image and calculate their probability distribution density to obtain the final histogram.

The shape of the histogram of the original image after histogram matching is similar to that of the expected image, and the features of the entire image after histogram matching are also similar to the expected image.

Histogram-Based image equalization methods can be applied to Computer Vision, such as defogging collected images.

3. FREQUENCY DOMAIN TECHNIQUES

Image recovery and enhancement can be realized by using image based and physics based techniques. Conventional approaches to enhance the resolution of the picture have been proposed, for example, the white balance, the histogram equalization, the contrast limitation of the histogram. However, this approach is not effective on the complicated physics features (figure 3).

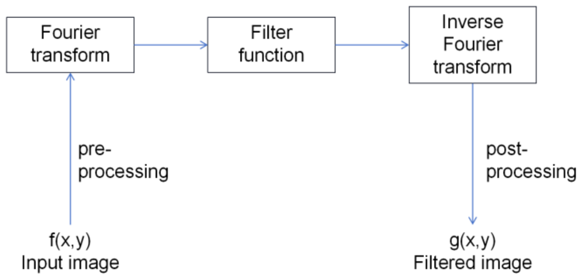

Figure 3 Basic steps of frequency domain image enhancement.

It is well known that the high frequency image components generally correspond to the edge areas with large variation of the pixel values. The low frequency component, however, indicates a smooth background area in an image. Typically, a Fourier Transform (FFT) is employed to convert a spatial domain image to a frequency domain in a transform-domain image [8]. Then, the high frequency component is enhanced, and the low frequency is restrained, so that the image quality is enhanced.

There are a lot of problems in some pictures, such as hazed ones, that the high frequency and low frequency components of the edge area are different from those of the background area. Thus, it is possible to enhance the image quality by employing the transform-domain approach [9], for example, the homomorphic filter, the high boost filter, the wave - transformation and so on.

In 2010, Prabhakar and Kumar [10] proposed a new method for the correction of uneven lighting and smoothness of the image. A review of the literature shows that image based pre-processing methods employ a variety of different combinations of standard filters. In this paper, we present a new approach based on image pre-processing to improve the performance of underwater images. The technology is composed of 4 kinds of filters, which are the same kind of filter, wavelet denoising, bipartite filter, and contrast equalizing. The filters are applied in sequence on degraded underwater images. The image-based pre-processing algorithms employ an isotropic filter to smooth the image. Finally, we used an improved Bayesshrink function to remove noise.

Nowadays, Wavelet transform is widely used to enhance the image. In 2016, Amjad [11] proposed a wavelet-based fusion approach to improve the performance of blurred underwater images. First of all, we extend the value of the original image to the full extent of HSV Color Model, and then CLAHE is used to create two fused images. Next, the wave - based fusion is composed of a lowpass and highpass filter which removes undesirable low-and high-band signals from the picture, and obtains the exact approximate coefficients individually so as to facilitate the fusion.

In 2017, Vasamsetti[12] proposed a new approach to enhance the performance of underwater images. Because altering the sign of a wavelet factor may lead to unwanted changes in the image, they use Discrete Wavelet Transformation (DWT) to produce two degradation grades and gather approximate and detailed reactions for those portions to construct gray scale images for R-G-B channels. At the same time, it can be applied to pre-process the technology of detecting and tracing under water in order to improve the precision of high level VRS.

But there are still a few problems. Though the transformation field has been used to enhance the visual quality and contrast, it is prone to overmagnify the noise and cause the color distortion. So there's a lot of work to do. Scientists continue to make great efforts to do so.

4. IMAGE RESTORATION TECHNIQUES

4.1. Blind deconvolution

Image restoration is a processing technique to improve image quality by recovering degraded images to their original state. Currently, there are various methods for image restoration.

However, a challenge in image restoration is obtaining an accurate estimate of the Point Spread Function (PSF) for the restoration algorithm. Image restoration methods that do not rely on PSF knowledge are called blind deconvolution algorithms. Blind deconvolution methods have garnered significant attention, involving degrading a given original image to produce a degraded image and then utilizing blind deconvolution techniques to restore it, resulting in visually improved quality.

Commonly, image restoration methods assume knowledge of the Imaging System's PSF, even though it's often unknown. In cases where the PSF is unknown, blind deconvolution becomes an effective means of image restoration, using the `deconvblind` function for recovery.

Subsequently, the 'edge' function is called to identify regions with significant grayscale variations in the image. Based on prior knowledge, a grayscale variation threshold is chosen. The image is then subjected to dilation to expand the processing region. The next step involves using a defined WEIGHT array for image reconstruction, yielding the restoration results.

The algorithm's advantage lies in restoring the image and the Point Spread Function. It achieves image restoration for blurry images even without prior knowledge of distortion. The image restoration is implemented using MATLAB, and improvements have been made to address the distortion in the restored image. During the image restoration process, the PSF is reconstructed, and the image is reconstructed, resulting in the restored image [13].

When restoring degraded images, the lack of prior information about the image poses a challenge. The original information of the degraded image is either unknown or partially known. In such cases, the result of image restoration is not unique. In practical engineering applications, obtaining prior knowledge of the degraded image and the degradation function is difficult. In this context, blind image deconvolution methods become more practical. The main challenge when using this approach in image restoration is how to obtain the degradation function used in the restoration algorithm and make an appropriate estimation of it.

4.2. Regularization

In addition, another commonly used image restoration technique is regularization. Regularization is an important image restoration technique that addresses ill-posed inverse problems by utilizing the smoothness of images as a constraint. However, this regularization approach often leads to blurred edges in the recovered images. To tackle edge sharpening issues, numerous researchers both domestically and internationally have explored regularization methods that preserve edges. They have proposed techniques that effectively reduce edge degradation. During the solving process, it's generally necessary to address the problem on the basis of introducing non-quadratic regularization functionals, which turns the process into a nonlinear problem. Some scholars have tackled this nonlinear problem by utilizing the concept of 'semi-quadratic regularization.' Moreover, some researchers have derived optimal solutions using deterministic methods based on this foundation. Subsequently, a renowned ROF model was introduced by scientists [14]. This model builds upon total variation methods, which to some extent, enhance the quality of image restoration. The total variation regularization term within this model helps retain details and edge features of the image. This approach yields excellent results and significantly advances the progress and development of image restoration techniques [15].

4.3. The Richardson-Lucy algorithm

For starters, X-Ray Microscopy can be improved by using digital signal imagery[17]. X-Ray Microscopy is one of the features of a biological specimen. Sometimes people need to use short exposure because X radiation would cause structure changes in the objects under room temperature. Consequently, the image quality will be reduced because of the low signal to noise ratio. Digital image processing can decrease the fuzzy degree. The improvement of the contrast at the microscopic level is an additional method of application of X-Ray Microscopy. In the raw image, it is hard to identify the 20-nm-thick structure due to its low contrast ratio. Nevertheless, it is possible to see the object after it has been fixed. The Richardson-Lucy algorithm is an efficient way to remove the noise. The Richardson-Lucy algorithm would combine with a reject-band filter to fix the image and reduce some shadows in the fixation. Experimental evidence shows that when SNR is low (SNR)[17] is higher, there is a significant reduction in noise, an improvement in image quality, and an improvement in the result quality for photos with a long exposure period. The other advantage of this approach is that it makes it possible to distinguish small structures which are not visible in the original image. The Richardson-Lucy algorithm, for instance, is a kind of iteration image deconvolution technique that can be applied to enhance the image quality due to blur or noise.

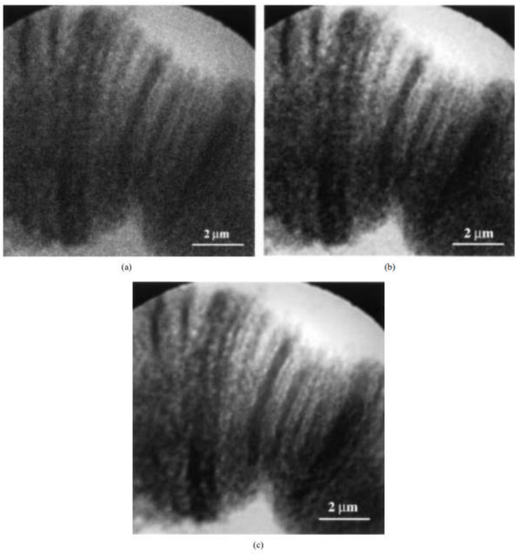

Figure 4 Results of the noise reduction applied on images of giant chromosomes from Chironomus Thummi larvae. (a) Original image acquired after 0.1 s of exposure time. The corresponding estimated radiation dose is of the order of 10^5 Gy. (b) Result of the noise suppression after three iterations of the modified Richardson–Lucy algorithm applied on the original image obtained after 0.1 s of exposure time. (c) Original image acquired with 5 s of exposure time. The total exposure time was about 10 s, and the corresponding estimated radiation dose is 10^7 Gy[17].

Based on W.H. Richardson and L.B. Lucy's independent development in 1972, it has been applied to many areas including astronomy, microscope and medicine. It is one of the most widely used techniques in astronomy due to the fact that it keeps the number of counts and the nonnegativity of the source object[16].

This method is based on the inverse of image de-focusing. The algorithm uses an iterative refinement of the estimation of the raw image, which is based on a mathematic model of the degradation. The method is based on the principle of comparison of observation and estimation, and then iterative adjustment is made in order to reduce the variance (figure 4).

The Richardson-Lucy algorithm procedure consists of several important steps. First, an estimate is produced from the original image. The algorithm calculates the difference between the observed and the estimated image at each iteration. This difference is divided by the convolution of the estimate and the imprecision kernel to obtain the error image. The estimate is updated by convolution with this error image. This cycle of comparing, calculating the error, and updating the estimate is repeated for several iterations or until convergence is reached.

However, it is important to note that the algorithm may amplify noise in the observed image during this process, as is often the case with iterative decomposition methods. The strength of the Richardson-Lucy algorithm is its ability to reverse the decomposition process and recover image details. Still, its effectiveness depends on the accuracy of the decomposition model and the specific characteristics of the image distortion. Over the years, variations and improvements have been introduced to mitigate noise amplification and improve overall performance. During the experiment of X-Ray Microscopy, the edge spread function (ESF) can be estimated by recording the profile of an edge. The edge spread function can know the approximate line spread function (LSF)[16]. This method requires a perfect edge below the microscope's depth of field and a high signal-to-noise ratio. In X-Ray Microscopy, the final resolution is directly related to the smallest size of the micro-manufacturable structure. Because the micro-structuring method is used in manufacturing zone plates, it is difficult to build the edge that is used in ESF. In some experiments, the source of the edge can be some other objects, for instance, a gold edge obtained by cutting gold-coated polyimide film can be used.

5. Image Enhancement And Restoration Based On Deep Learning

Deep learning is a branch of machine learning. It is a learning method based on artificial neural networks, which can automatically learn features and representations from data. The deep learning model consists of multi-layer neural networks, each layer gradually extracting more abstract and advanced features through learning. This gives deep learning advantages in dealing with complex data patterns and large-scale data. In recent years, deep learning has been widely applied in image processing, including image enhancement and image restoration.

In 2017, Ignatov et al. constructed a large dataset (DPED) [18]containing over 6K photos, which were simultaneously captured using three mobile phones and one DSLR under various outdoor conditions. Then the author proposes a new image enhancement algorithm for these three paired datasets. By learning the mapping relationship between mobile phone photos and DSLR photos, they can elevate mobile phone photos to the level of DSLR.

Huang et al. proposed the RSGUNet in 2018[19], a novel CNN-based approach for perceptual image enhancement. RSGUNet has excellent target and subjective enhancement performance, as well as low computational complexity, making it very suitable for perceptual image enhancement on mobile devices.

In 2019, Tatsugami et al. developed a CT image restoration technique, a deep learning-based image restoration (DLR) method, which incorporates a noise and artifact reduction filter by the deep convolutional neural network (DCNN)[20]. On DLR images, the image noise was lower and the coronary artery margins were sharper than those on hybrid IR images.

The problem with deep learning is weak generalization, and training models typically perform poorly on unfamiliar data. And many deep learning models cannot explain why they can achieve good results or why they perform poorly. This is also a problem that needs to be solved.

6. Evaluation And Assessment Metrics

6.1. MSE (Mean Squared Error)

In statistics, MSE is used to measure the average of the squares of the errors—that is, the average squared difference between the estimated values and the actual value. The smaller the value of MSE, the better the quality of the image to be evaluated. The formula for MSE is as follows:

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \quad (1)$$

6.2. PNSR (Peak Signal-to-Noise Ratio)

Peak signal-to-noise ratio calculates the difference between two images in decibels. The higher the PSNR value, the better the quality of the output image. Its calculation is based on mean square deviation, and the calculation formula is(MAX_I is the peak signal energy):

$$\mathrm{PNSR} = 10 \cdot \log_{10}\left(\frac{{MAX_I}^2}{\mathrm{MSE}}\right) \quad (2)$$

6.3. SSIM (Structural Similarity)

Structural Similarity is used to measure the similarity between two images. It can be used to evaluate three aspects of an image, luminance, contrast, and structure. The formula for SSIM is as follows:

$$\mathrm{SSIM} = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)} \quad (3)$$

with:

μ_x: the pixel sample mean of x;

μ_y: the pixel sample mean of y;

σ_x^2: the variance of x;

σ_y^2: the variance of y;

σ_{xy}: the convariance of x and y;

$c_1 = (k_1L)^2$, $c_2 = (k_2L)^2$: two variables to stabilize the division with weak denominator;

L: the dynamic range of the pixel-values;

k_1=0.01 and k_2=0.03 by default.

7. CONCLUSION

In conclusion, it is important to note that histogram-based image enhancement methods significantly improve the quality, visibility, and contrast of images. Analyzing the distribution of grayscale values of pixels using histograms provides valuable tools for image enhancement in various applications. The histogram alignment method, one of the fundamental techniques, is widely employed to enhance contrast by reallocating pixel intensity levels. This leads to sharper images, making it an effective tool in different contexts. The restoration and improvement of images are achieved primarily through image-based and physics-based techniques. Traditional methods like white balance and histogram equalization enhance image clarity and color saturation but are ineffective for complex images. Transform-domain techniques shift images to the frequency domain through Fourier Transform, enhancing high-frequency details and suppressing low-frequency backgrounds. Hazed underwater images, where high-frequency and low-frequency components are too similar, benefit from methods like homomorphic and high-boost filters, wavelet-transform, etc. A study in 2010 by Prabhakar and Kumar proposed a technique combining homomorphic filtering, wavelet de-noising, bilateral filtering, and contrast equalization to enhance underwater image quality. Wavelet-based approaches gained traction, with Amjad (2016) using wavelet fusion for enhancing hazy underwater images and Vasamsetti (2017) presenting a wavelet-based perspective enhancement technique. Challenges persist, as these methods can amplify noise and distort colors, necessitating further research to refine them.

Image restoration improves images that have been degraded using techniques such as blind deconvolution that do not rely on knowledge of the Point Spread Function (PSF). Improves picture quality even if PSF is unknown. In X-ray microscopy, digital signal processing holds significant potential for improving image quality. Methods like the Richardson-Lucy algorithm can address issues related to low signal-to-noise ratios, enhance contrast, and improve resolution without losing image quality. These advancements enable better visualization of structures that were previously hard to distinguish. Despite substantial improvements in histogram methods, challenges such as noise amplification and color distortion persist. Transformation-based methods, like wavelet techniques, solve these problems somewhat. Researchers continue to refine these methods to strike a balance between noise reduction and image enhancement. In a broader spectrum of image processing, these methods coexist with physical techniques, each finding application based on the complexity of the considered images. Despite all challenges, ongoing research and innovations in image enhancement underscore the importance of developing methods that cater to a wide range of image processing scenarios. With the evolution of technology and increasing computational power, further progress can be expected in addressing the limitations of existing methods and obtaining more accurate, detailed, and visually appealing images.

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