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Underwater Image Processing: Technical Study and Experiments

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Abstract: *Our ultimate objective is to develop an underwater embedded system implementing image processing capabilities, that can be integrated to Autonomous Underwater Vehicles and diving Sonars. In this scope, this paper aims at presenting a technical study of a set of image processing techniques and their applications in underwater environment. It gives a description of the major issues that are specifics to underwater image processing field, and lists some of the known references that worked on the subject. Hence, the theoretical aspect of Image Restoration, Color Correction and Image Enhancement is described. The efficiency of the selected algorithm were evaluated through simulations and showed its ability to restore and process underwater image with good performances.*

Keyword: *Underwater Image Processing; Image Enhancement; Restoration; Color Correction; Embedded System.*

1. INTRODUCTION

Underwater image processing constitutes an important tool in observing the sea floor. Hence, it is usually present in many applications such as Autonomous Underwater Vehicles (AUVs), inspection of underwater structures, biological researches and fish localization in submarine environment. Waterproof cameras are commonly used for underwater image sensing, however, they can suffer from many issues such as light attenuation, low contrast, non uniform lighting, blurring, bright artifacts, color diminished and noise.

In recent years, with the development of underwater vehicles [1,2,3], the need to be able to record and process a huge amount of images has become increasingly important. In addition, the moment the camera goes into the water, a whole new set of challenges appear.

Indeed, marine corrosion deteriorates materials quickly and the access and modifications of sensors are costly, both in time and resources. In addition, the physical properties of the water affect the behavior of light. Thus, the appearance of a same object may change with variations of depth, organic material, currents, temperature and more.

In one of our previous works, the paper titled "IoT Embedded System Communications for Wireless Underwater Depth and Temperature Monitoring"[4], presented a real time embedded system, that implements a set of sensors, and could be integrated to any further architecture such as Autonomous Underwater Vehicles and Diving Sonars, for water depth and temperature monitoring. In this paper, we follow up by studying the fundamentals required for the integration of a camera sensor to our system. In this paper we present methods that can be used for the underwater image processing such as Image Restoration, Image Enhancement and Color Correction. The reminder of this paper is organized as follows. Section 2 describes the problematic of underwater image and the related works. Section 3 gives a brief review of

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Image Restoration basics, Section 4 presents the Image Enhancement and Color Correction techniques in underwater environment based on Bazeille algorithms. Finally, Conclusions are given in Section 5.

2. LITERATURE REVIEW

2.1 Problematic of underwater image

In underwater environment, light interacts with water medium through two processes: absorption, which is the loss of power as light travels in the medium depending on the index of refraction of the medium and the scattering which refers to any deflection from a straight-line propagation path. Deflection can be due to particles of size comparable to the wavelengths of travelling light (diffraction) or when particulate matter with refraction index different from that of the water (refraction) [5]. There are many difficulties in underwater image processing [6]:

Light attenuation: This attenuation limits the visibility about 20 meters in clear water and less than two meters in turbid water. The attenuation of light is caused by two phenomena: absorption and diffusion due to pure water itself and other components such as dissolved organic matter and suspended particles.

Artificial light source: The rapid attenuation of light requires the addition of an artificial light source to provide sufficient light. Unfortunately this type of artificial lighting has a tendency in the water to illuminate the stage of non-uniform manner producing a large spot effect, ie a very bright area in the center of the image and dark areas on the edges.

Distance between the camera and the scene: the very variable distance between the camera and the scene modifies the attenuation of the colors and generally causes an important blue or green dominant.

The non-stability of the vehicle in the current still affects the contrasts in the image.

2.2 Related works

Intelligent use of image pre-processing can provide benefits and solve problems that ultimately lead to better local and global feature detection [7, 8]. As an example of image pre-processing, image enhancement doesn't require a priori knowledge of the environment. Image enhancement has been employed by many researchers in different domains as [9,10]. They are usually simpler and faster than the image restoration techniques.

Stéphane Bazeille, Isabelle Quidu, Luc Jaulin, Jean-Phillipe Malkasse proposed a set of algorithms to pre-process underwater images [6,11]. The algorithms have the advantage that are automatic and don't require parameter adjustment. Moreover, they were used as a preliminary step of edge detection which is used in many researches [12]. Figure 1 shows an example of image before and after image enhancement using Stéphane Bazeille et al. technique [6]. Bazeille algorithm was applied in underwater image preprocessing for Automated Photogrammetry in High Turbidity Water [13] to increase the SIFT and SURF descriptors extraction quality in order to solve the problem of surveying an underwater archaeological wreck in a very high condition of turbidity.

Kashif Iqbal, Rosalina Abdul Salam, Azam Osman and Abdullah Zawawi Talib [14] presented a method using slide stretching algorithm both on RGB and HIS color models to enhance underwater images. First of all, their method performs contrast stretching on RGB and secondly, it performs saturation and intensity stretching on HIS color model. The advantage of applying two stretching models is that it helps to equalize the color contrast in the image and also addresses the problem of lighting. In Figure 2 an example image before and after Kashif Iqbal et al. technique are shown.

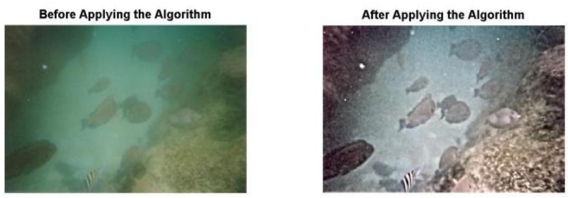

Figure 1 Image before and after image enhancement using Stéphane Bazeille et al. technique [5]

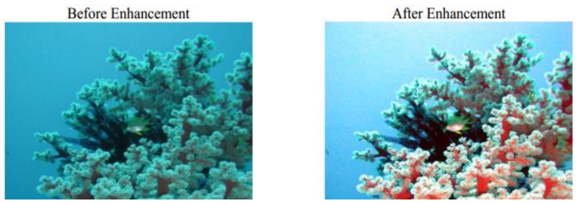

Figure 2 Image before and after image enhancement using Kashif Iqbal et al. technique[5]

Majed Chambah, Dahbia Semani, Arnaud. Renouf, Pierre Courtellemont, and Alessandro Rizzi [15], proposed a method of color correction based on the ACE model. ACE "Automatic Color Equalization" is based on a new calculation approach, which combines the Gray World algorithm with the Patch White algorithm, taking into account the spatial distribution of information color. The ACE is inspired by human visual system, where is able to adapt to highly variable lighting conditions, and extract visual information from the environment.

Figure 3 shows an example of images processing results, presented by [15].

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Figure 3 Example of Image enhancement (a) before, (b) after using Majed Chambah et al. technique [5]

3. IMAGE RESTORATION

Image restoration aims to model the degradation process and then invert it, obtaining the new image after solving. It is generally a complex approach that requires plenty of parameters that vary a lot between different water conditions. The original image " f " is recovered from the observed image " g " using (if available) explicit knowledge about the degradation function " h " (also called point spread function PSF) and the noise characteristics " b " as shown in Figure 4:

$$g(x, y) = f(x, y) * h(x, y) + b(x, y) \quad (3.1)$$

Where * denotes convolution. The better the knowledge we have about the degradation function, the better are the results of the restoration. However, in practical cases, there is insufficient knowledge about the degradation and it must be estimated and modeled [5].

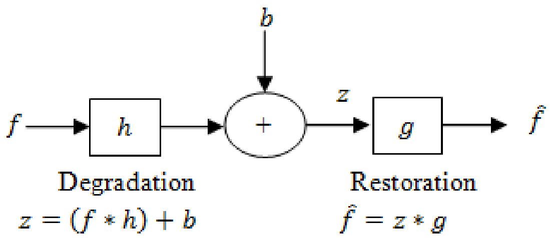

Figure 4 The process of the image restoration

3.1 Underwater Image Color Restoration

Jaffe-Mcglamery image model is based on:
Linear superposition: $\boldsymbol{E_t = E_d + E_f + E_b}$ **(3.2)**
Where "E_t" the total irradiance, "E_d" direct component is the light reflected by the object surface and entered the camera without scattering, "E_f" forward-scattered component is the amount of light that is reflected by the object and entered the camera after scattered at a small angle, "E_b" back scatter is the light reflected not by the object but still entered the camera due to scattering in the medium.
Further, the attenuation modeling for medium-light interaction, where the intensity of the light traveling in a liquid decreases exponentially:

$$I_{\lambda,d} = I_{\lambda,0} e^{-c_\lambda . d} \quad (3.3)$$

The focus has been given to the direct component only, due to back scatter component which doesn't carry information about the scene (verified by Zhang and Negahdaripour (2002) [16]), and forward scattered component which can be treated as blurring. The main objective of the proposed color restoration method is to recover the degraded underwater color information, so that the recovered images are similar to those in taken in the air. It is necessary to define the relationship between the two intensity values in two different mediums air "$I_\lambda(l', z', c_\lambda')$" and water "$I_\lambda(l, z, c_\lambda)$".

$$I_\lambda(l', z', c_\lambda') = I_\lambda(l, z, c_\lambda)\left(\frac{z}{z'}\right)^2 . \frac{(\cos \alpha')^3}{(\cos \alpha)^3} e^{-c_\lambda'\left(\frac{z'}{\cos \alpha'}+\frac{l'}{\cos \theta'}\right)+c_\lambda\left(\frac{z}{\cos \alpha}+\frac{l}{\cos \theta}\right)} \quad (3.4)$$

Where the primes (') represent the values in air, the color information can be recovered using a number of geometric parameters and the attenuation coefficients for the two mediums. Therefore, the color restoration becomes the problem of estimating these values [17].

3.2 Experimental results [17]

The unknown geometric parameters that are dependent on the environments are the distances between the light sources and the objects (z and z'), distances between the object surfaces and the cameras (l and l'), the approaching angles of the ray vectors (α and α'), and the departing angles (θ and θ') for the two different mediums. Refer to Figure 5 for the notations.

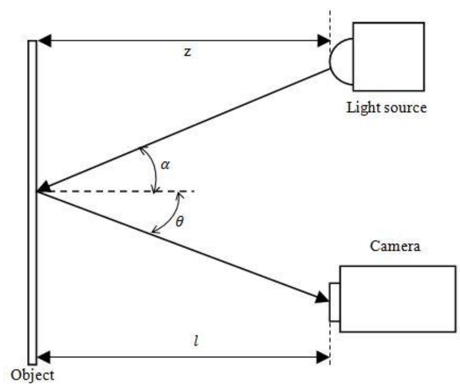

Figure 5 Light refraction in liquid [17]

For the experiments carried out in this study [17], the following values have been used for the geometric parameters:

$$z = z', l = l', z \approx l, \theta = \theta'=0 \text{ and } \alpha = \alpha'=0.$$

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Other unknowns remaining in (3.4) are the attenuation coefficients (c_λ and c_λ') of the traveling mediums. Attenuation coefficients are functions of the wavelengths of light. For the three color channels, red, green, and blue, the attenuation coefficients have been set as in Table1 [17]. In quantitative point of view, the changes in the pixel intensities after the restoration process are summarized in Table 2 [17].

4. IMAGE ENHANCEMENT AND COLOR CORRECTION USING BAZEILLE ALGORITHM

4.1 Bazeille algorithm

Bazeille et al. [6,11] presents a new automatic method of pre-processing images underwater. The proposed algorithm, which does not require manual parameterization or a priori information, makes it possible to attenuate the aforementioned defects and to improve significantly the quality of the images. The lighting, the noise, the contrasts and the colors are corrected sequentially. The existing preprocessing steps are:

- Removing potential Moirés effect.
- Resizing and extending symmetrically the image.
- Converting color space from RGB to YCbCr.
- Filtering.
- Adjusting image intensity.
- Converting back to RGB and reverse symmetric extension.
- Equalizing color means.

4.1.1 Removing potential Moirés effect

A Moiré effect has the appearance of a wavy repetitive pattern on the image. It is not an underwater perturbation, and it is often considered as aliasing phenomena. Sampling Moiré mainly occurs in the analog to digital conversion process. Moiré pattern is removed via spectral analysis by detecting peaks in the Fourier transform and deleting them assuming that they represent the Moiré effect. Only few images suffer from Moiré degradation but removing it is important because the following processes enhance contrast so enhance the Moiré effect and consequently highly degrade results [6]. Removing the Moiré effect is not applied, because in our conditions this effect is not visible.

4.1.2 Resizing and extending symmetrically the image

Symmetric extension prevents from potential border effects and resizing to squared image, whose size is a power of two, speeds up the following process by enabling to use fast Fourier transform and fast wavelet transform algorithms [6]. In Figure 6 an example of extending symmetrically an image.

4.1.3 Converting color space from RGB to YCbCr

This color space conversion allows us to work only on one channel instead of processing the three RGB channels. In YCbCr color space we process only the luminance channel (Y) corresponding to intensity component (gray scale image). The two other components correspond to chroma color-difference. This step speeds up again all the following processings avoiding to process each time each RGB channels [6]. In Figure 7, an example of Converting color space from RGB to YCbCr.

4.1.4 Homomorphic filtering

The homomorphic filtering is used to correct non uniform illuminations and to enhance contrasts in the image. It's a frequency filtering, preferred to others techniques because it corrects non uniform lighting and sharpens the edges at the same time [6]. In the illumination-reflectance model, where image is defined as an intensity illumination and the reflectance function as follows:

$$f(x,y) = i(x,y).r(x,y) \quad (4.1)$$

Where F(x,y) is the image sensed by instrument, i(x,y) the illumination and r(x,y) the reflectance function. The illumination factor changes slowly through the view field, therefore it represents low frequencies in the Fourier transform of the image. On contrary, reflectance is associated with high frequency components. By multiplying these components a highpass filter can suppress the low frequencies. The algorithm is described as follows [6,18]:

- Separation of the illumination and reflectance components by taking the logarithm of the image give:

$$g(x,y) = ln(f(x,y)) = ln(i(x,y).r(x,y))$$
$$g(x,y) = ln(i(x,y)) + ln(r(x,y)) \quad (4.2)$$

- Computation of the Fourier transform of the log-image.

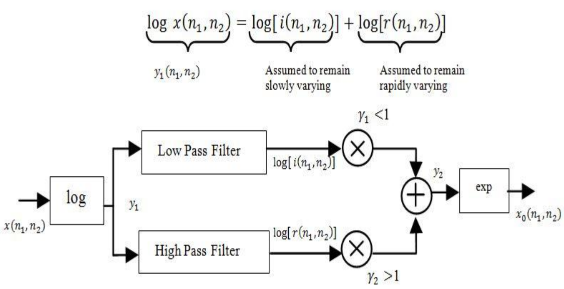

Figure 8 Homomorphic processing

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• High-pass filtering. There are different types of high-pass filters such as Gaussian, Butterworth, and Chebychev filters. Gaussian high-pass filter is used directly in the frequency domain. The filter applied to the Fourier transform decreases the contribution of low frequencies (illumination) and also amplifies the contribution of mid and high frequencies (reflectance), sharpening the edges of the objects in the image.

• Computation of the inverse Fourier transform to come back in the spatial domain and then taking the exponent to obtain the filtered image. Figure 8 shows a diagram summarizing the steps of homomorphic filtering. Based on Bazeille scripts, a simple implementation is summarized in Figure 9.

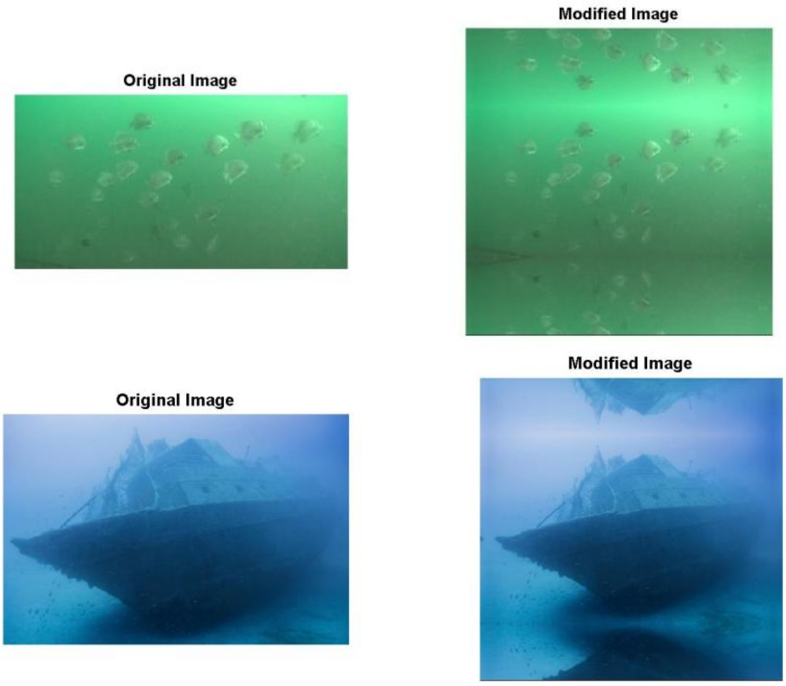

Figure 6 Resizing and extending symmetrically the image to get a squared image

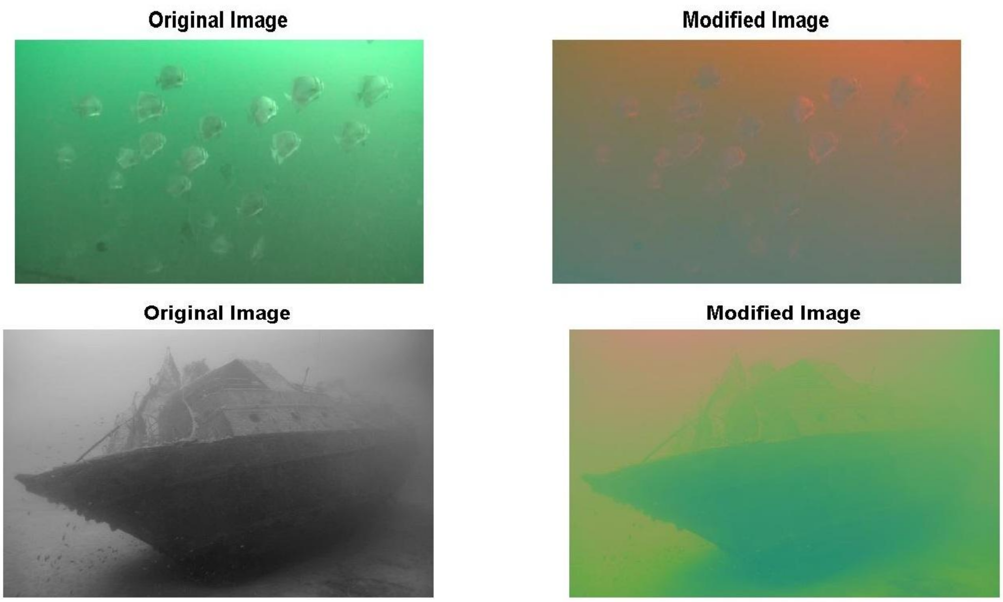

Figure 7 Converting color space from RGB to YCbCr (Luminance Chrominance)

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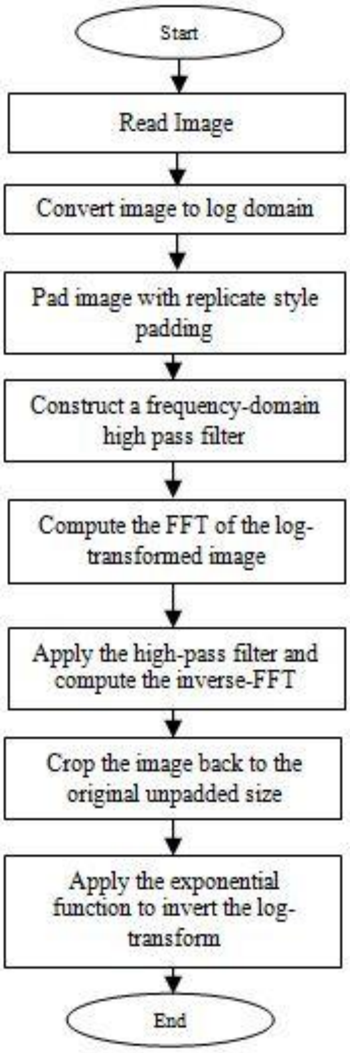

Figure 9 Homomorphic filtering flowchart

As an example of Homomorphic processing, Figure 10 shows the original (on the left) and the Homomorphic filtered (on the right) images together. If you compare the two images you can see that the gradual change in illumination in the left image has been corrected to a large extent in the image on the right.

4.1.5 Wavelet denoising

This noise currently important is further amplified by Homomorphic filtering. A step of denoising is so necessary to suppress it. A more precise explanation of the wavelet denoising procedure can be given as follows. Assume that the observed data is:

$$X(t) = S(t) + N(t) \tag{4.3}$$

Where S(t) is the uncorrupted signal with additive noise N(t). Let W(·) and W−1(·) denote the forward and inverse wavelet transform operators. Let D(·, λ) denote the denoising operator with threshold λ. We intend to denoise X(t) to recover Sˆ(t) as an estimate of S(t).

The procedure can be summarized in three steps [19]:

$$Y = W(X) \tag{4.4}$$

$$Z = D(Y, \lambda) \tag{4.5}$$

$$\hat{S} = W-1(Z) \tag{4.6}$$

D(·, λ) being the thresholding operator and λ being the threshold. In Figure 11 an example of Wavelet denoising is shown.

4.1.6 Anisotropic filtering

Anisotropic filtering allows us to simplify image features to improve image segmentation. This filter smooths the image in homogeneous area but preserves edges and enhance them. It is used to smooth textures and reduce artifacts by deleting small edges amplified by Homomorphic filtering [6]. The problem of isotropic filtering is the non-selective smoothing of the entire image. Although the location of the contours is preserved, it becomes blurred. In the case of anisotropic filtering, diffusion is limited or even prohibited in the areas of the image having contours. For this, a coefficient C controlling the diffusion varies as a function of the position in the image [20].

Anisotropic filtering is an iterative process. At each iteration, the contours are detected by computing the gradient of the image, and for each pixel a diffusion coefficient dependent on the value of the gradient is calculated. For low gradient values, we consider that we are in a homogeneous zone of the image, then diffusion is permitted with a high diffusion coefficient. On a contour characterized by a strong gradient, diffusion is limited by a small coefficient. A loop of the Anisotropic diffusion algorithm can be decomposed as follows [6]:

For each pixel: calculation of the differences with the nearest neighbors in the four North-South-East-West directions $\nabla_{N,S,E,W} I_{i,j}$ and calculation of the diffusion coefficient $CN_{i,j}, CS_{i,j}, CE_{i,j}, CW_{i,j}$ from the previous results. There are several possibilities for these calculations, the most used is the following:

$$\nabla_N I_{i,j} = I_{i-1,j} - I_{i,j} \qquad CN_{i,j} = g(|\nabla_N I_{i,j}|) \tag{4.7}$$

$$\nabla_S I_{i,j} = I_{i+1,j} - I_{i,j} \qquad CS_{i,j} = g(|\nabla_S I_{i,j}|) \tag{4.8}$$

$$\nabla_E I_{i,j} = I_{i,j+1} - I_{i,j} \qquad CE_{i,j} = g(|\nabla_E I_{i,j}|) \tag{4.9}$$

$$\nabla_W I_{i,j} = I_{i,j-1} - I_{i,j} \qquad CW_{i,j} = g(|\nabla_W I_{i,j}|) \tag{4.10}$$

$$g(\nabla I) = e^{\left(-\left(\left\|\frac{\nabla I}{K}\right\|^2\right)\right)} \quad (4.11) \quad \text{With } K=0.1\ [6]$$

- Changing the value of the pixel by:

$$I_{i,j} = I_{i,j} + \lambda.[C_N.\nabla_N I + C_S.\nabla_S I + C_E.\nabla_E I + C_W.\nabla_W I]_{i,j}$$

$$\text{with} \quad 0 \leq \lambda \leq 1/4 \tag{4.12}$$

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λ is set to 0.25 and the loop number of the algorithm set to 5 [6].

In Figure 12, an example of applying Anisotropic filtering is presented. where Figure 13 shows a simple implementation based on Bazeille.

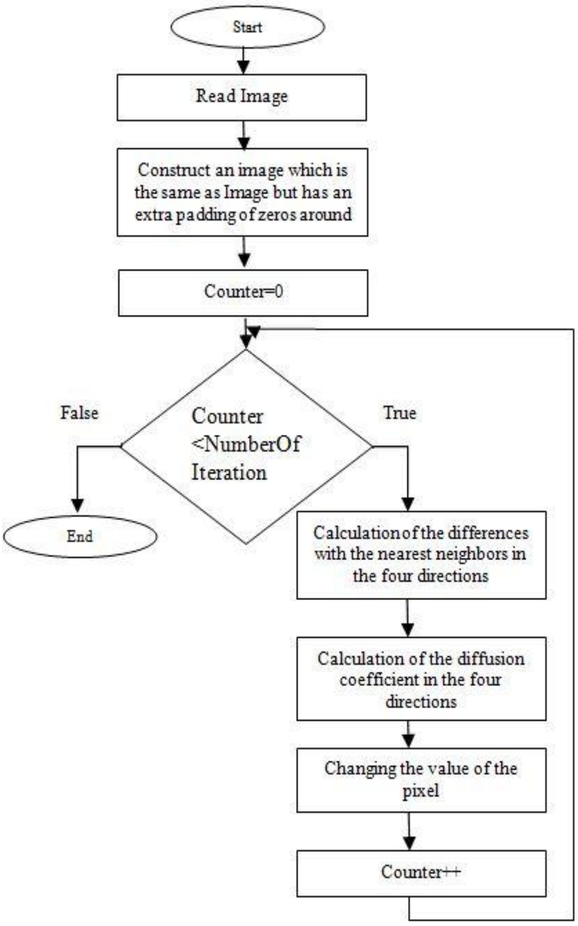

Figure 13 Anisotropic filtering flowchart

4.1.7 Adjusting image intensity

This step increases contrast by adjusting image intensity values. It suppresses eventually outliers pixels to improve contrast stretching. It then stretches contrast to use the whole range of intensity channel and if necessary it saturates some low or high values [6].

$$I_{i,j} = \begin{cases} \frac{I_{i,j} - min_I}{max_I - min_I} & if\ 0 < I_{i,j} < 1 \\ 0 & if\ 0 > I_{i,j} \\ 1 & if\ 1 < I_{i,j} \end{cases} \quad (4.13)$$

Dynamic expansion also called standardization is a very simple technique of enhancement. It consists of extending the intensity range of the pixels of the image so that it covers the full range of available values as [6]:

Figure 14 shows an example of Adjusting image intensity. Based on Bazeille scripts, a simple implementation is presented in Figure 15.

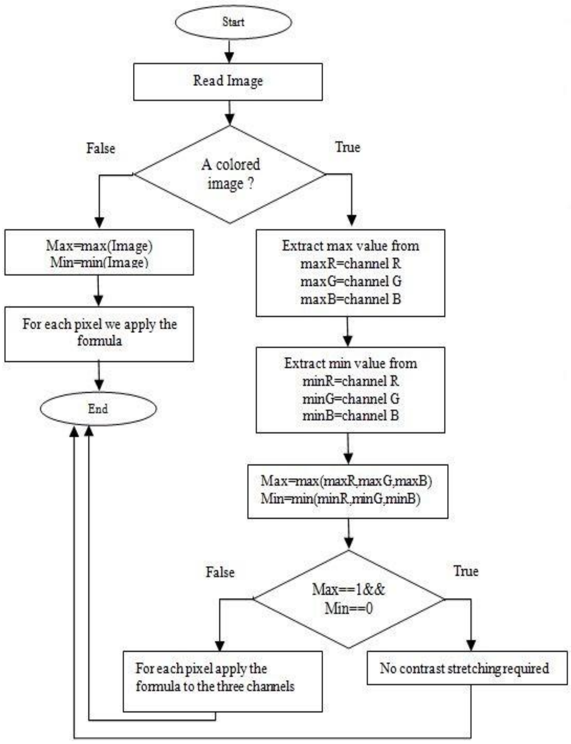

Figure 15 Adjusting image intensity flowchart

4.1.8 Equalizing color mean

In underwater imaging, color channels are rarely balanced correctly.

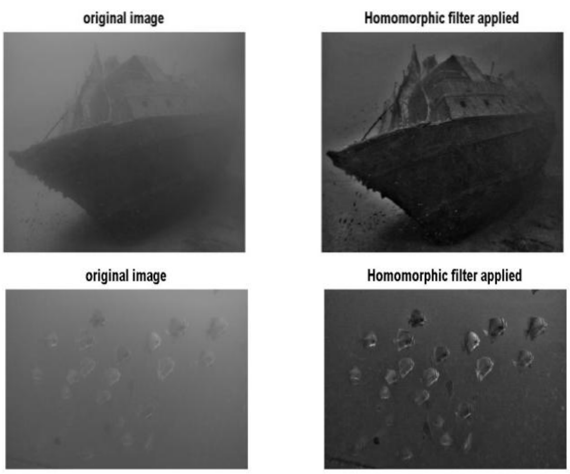

Figure 10 An example of applying Homomorphic processing

This step enables to suppress predominant color by equalizing RGB channels means. It is rather used

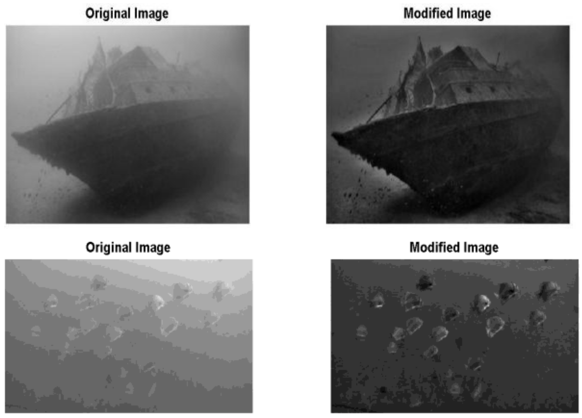

Figure 11 An example of applying Wavelet denoising

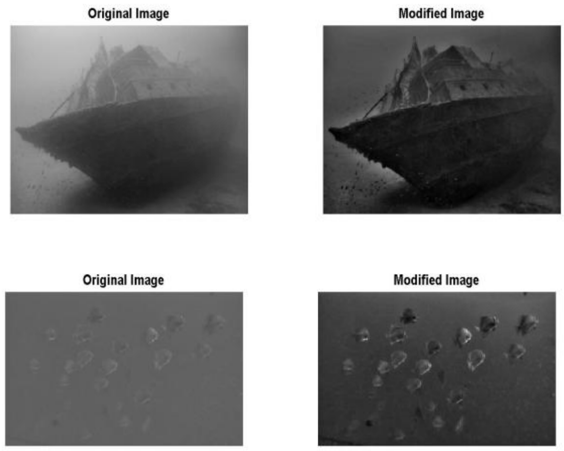

Figure 12 An example of applying anisotropic filtering

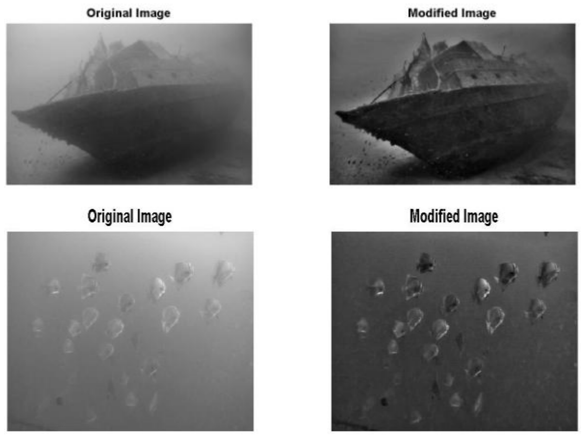

Figure 14 An example of Adjusting image intensity to produce a more pleasant image than to better segmentation, because segmentation is in general performed on gray image and color equalization does really not change the gray image [6].

The proposed algorithm is a linear translation of three RGB histograms, so as to equalize their averages. This simple method is a compromise to improve the visual quality of the image without a priori knowledge [6]. In Figure 16, an example of Equalizing color mean is given, while Figure 17 presents the result of a basic implementation using Bazeille scripts.

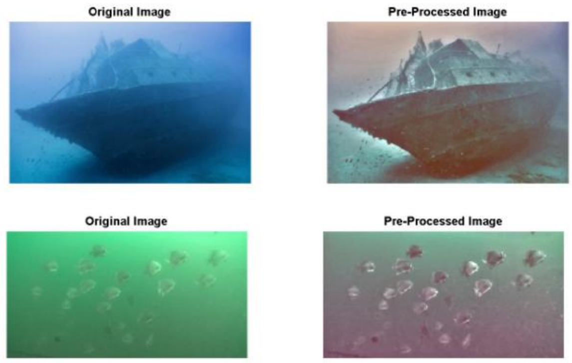

Figure 16 An example of Equalizing color mean

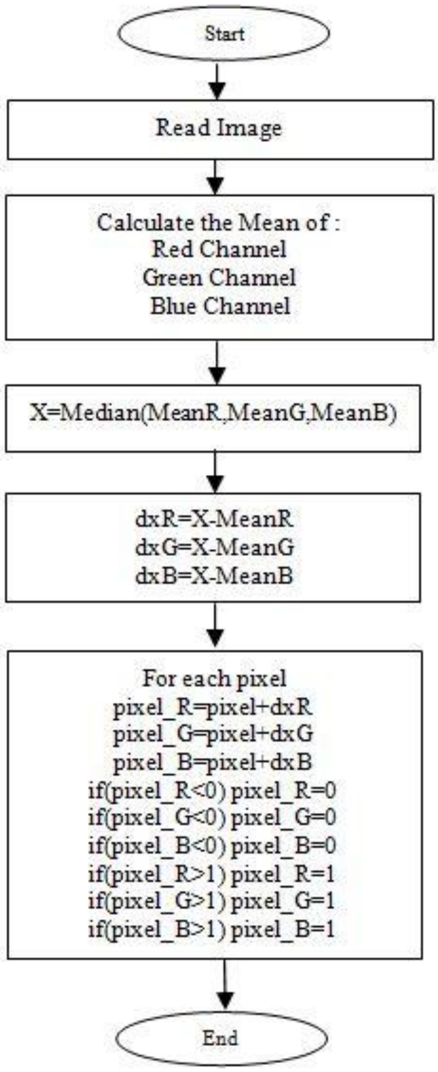

Figure 17 Equalizing color mean flowchart

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4.2 Experiments on Bazeille Algorithm

The experiments were conducted to evaluate the performance of Bazeille algorithms to process underwater images. Hence, the input images were chosen with non-uniform illuminations of light, low contrast, blurring and typical noise levels for underwater conditions. Using Matlab, the procedure involved in the preprocessing is as follows:

- Resizing and extending symmetrically the image with 5 pixels in border.
- Converting color space from RGB to YCbCr.
- Applying the homomorphic filter for correction of illumination and reflectance components, with alpha=0.5 and beta=2.5.
- Applying the Wavelet denoising using 6 stages and “Farras” as wavelet type.
- Applying the Anisotropic filtering, by setting number of iteration to 5, K=0.1 and λ=0.25 .
- Adjusting image intensity.
- Converting from YCbCr to RGB and reverse symmetric extension.
- Equalizing color mean.

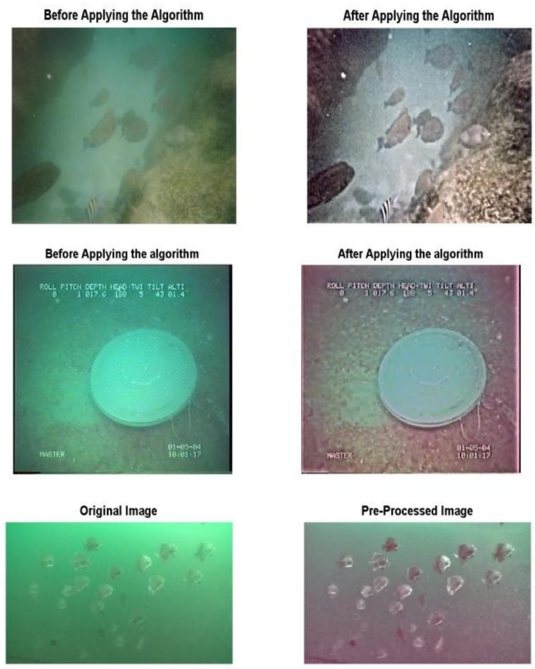

Figure 18 Bazeille Algorithm Experimental results

All the parameters are calculated or pre-adjusted empirically. The algorithm developed is fast and can be further optimized by a C-language translation.

The experiments show that this pre-processing significantly improves the visual quality and more particularly the contrasts and the contours of the objects in the image. Figure 18 shows the outcome of the experiment

5. CONCLUSION

This paper presented the result of our study on the integration of camera sensors and image processing capabilities to underwater embedded systems installed on Autonomous Underwater Vehicles. So far, we focused on the theoretical basics and simulations of some fundamental image processing techniques such as Image Restoration, Image Enhancement and Color Correction. We have seen that image restoration is more complex because, in practical cases, there is an insufficient knowledge about the degradation, and has to be estimated and modeled, compared to image enhancement which does not need a priori knowledge of the environment. Based on the state of art, we selected Bazeille algorithm and simulated its performance using empiric images, especially the removing of potential Moirés effect, Homomorphic filtering, Wavelet denoising, Anisotropic filtering, Adjusting image intensity and Equalizing color mean.

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