Image enhancement comparison to improve underwater cultural heritage survey

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Abstract. This work aims at presenting an underwater image application to obtain an improved 3D model of cultural assets. In 2016, more than 500 images were acquired by a GoPro Camera with a low resolution of 72 dpi and focal length of 3 mm, without flash and are now used to reconstruct the 3D model of some amphoras of a Roman shipwreck found in Albenga (Italy). We have applied state-of-art image enhancement techniques, such as ACE, CLAHE, LAB and SP algorithms, to improve the quality of underwater images affected by low contrast, poor visibility conditions, not uniform lighting, colour variations, noise and blur effect. The visual quality has been evaluated through quantitative metrics, like average luminance, information entropy, average gradient of image, UCIQE and UIQM. Then, our efforts have been devoted to the dense 3D point cloud generation using a SfM-MVS software. In particular, the 3D reconstruction results are in line with the metric evaluation: in fact, the more accurate 3D objects are obtained from that enhanced dataset with the highest measured image quality.

1. Introduction

The main research goal is the reproduction of a sufficiently accurate 3D model of underwater archaeological artefacts using digital photogrammetry. The examined archaeological site is located a few miles from Albenga, in Liguria (Italy) and preserves the wreck of a Roman cargo ship at a depth from the sea level ranging from 40 m to 50 m. The roman ship was carrying approximately 11.000/13.000 wine amphoras and various types of ceramics. In 1950 excavation campaign started and all the recovered amphoras are today visible at the Naval Museum of Albenga. In 2016, more than 500 photos were acquired by a GoPro Camera with a low resolution of 72 dpi and a focal length of 3 mm, without flash, during scuba diving. Due to the water depth, the images suffer from serious colour cast because of the red channel absorption; therefore, they appear bluish. The image enhancement becomes necessary to make them suitable for photogrammetric purposes.

22 most significative images are selected. First, they are pre-processed through state-of-the-art enhancement methods like ACE, CLAHE, LAB and SP algorithm and their combination. Then, their quality is assessed through objective metrics to carry out a comparison between the performances of the different algorithms. Therefore, the enhanced images are employed to perform a state-of-art digital photogrammetry pipeline, with the final purpose of creating the 3D reconstruction of the studied area.
2. Underwater image processing

Extracting valuable information for underwater scenes requires effective methods to correct colour, to improve clarity and to address blurring and background scattering, which is the ambition of image enhancement and restoration algorithms [1]. They are software-based approaches even defined in the latest review [1] as IFM-based image restoration methods and IFM-free image enhancement methods.

| Improvement Algorithms of Underwater Image [1]. |
|-----------------------------------------------|
| **Image Enhancement (IFM-free)** | **Image Restoration (IFM-based)** |
| CNN-based | Spatial-domain | Transform-domain | Prior-based | CNN-based |

The image restoration aims to recover a degraded image using a model of the degradation and the original image formation (IFM); it is essentially an inverse problem. It is strictly rigorous but requires many model parameters (like attenuation and diffusion coefficients that characterize the water turbidity) which are only scarcely known in tables and can be extremely variable. Another relevant parameter to estimate is the depth of a given object in the scene. IFM-based restoration methods need also to assess two key optical parameters: background light (BL) and transmission map (TM) [1]. Dark Channel Prior is one of the widely used as starting point for image dehazing development, both for outdoor and underwater images.

Image enhancement, instead, uses qualitative subjective criteria and its purpose is to provide a more suitable image for a specific application. It improves the contrast and colour of images mainly acting on pixel intensity re-distribution, without considering the specific principles of underwater image formation. IFM-free image enhancement methods change the pixels values in either the spatial domain or a transformed domain. This kind of approaches is usually simpler and faster than restoration process. In this research, we apply image enhancement techniques.

However, hybrid methods have been developed like in [2]: firstly, an efficient colour correction algorithm is applied to remove colour casts of underwater images and then, underwater image dehazing method is proposed to increase the visibility of underwater images. It includes a global background light estimation algorithm specialized for underwater images and a medium transmission estimation algorithm.

2.1. Implemented Procedure

In this research, state-of-the-art algorithms are applied for image pre-processing through a very useful and free tool developed by iMARECULTURE project [3]. It is possible to automatically process a dataset of underwater images without technical skills and any programming language is required to operate the software. Our dataset is enhanced through four of the implemented algorithms: Automatic Colour Enhancement [4], Contrast Limited Adaptive Histogram Equalization [5], Colour Correction Method on $l\alpha\beta$ [6] and Screened Poisson Equation for Image Contrast Enhancement [7].

After the first unsatisfactory results in the 3D model, a further image pre-processing method is elaborated. All the enhanced images were used as input for a second step of the enhancement process (Figure 1) obtaining 24 new double-enhanced dataset. Then, the image quality of each combination is evaluated by objective metrics. The images that have been firstly processed with the SP algorithm and then enhanced with CLAHE achieve the highest contrast and detail definition. So, even this new dataset is investigated and will be utilized for the 3D reconstruction. It will be termed SP-CLAHE method.
Figure 1. Schematic workflow of the enhancement procedure

In Figure 2, three representative images are visually compared with their enhanced versions. One is demonstrative of those images where diver presence is significant, the other two photos instead show mainly the amphorae potsherds.

Figure 2. The three representative images enhanced with the presented algorithms

3. Image quality assessment

These enhanced versions can be evaluated subjectively (by visual inspection) or objectively (by the implementation of an objective image quality measure). Objective metrics have been preferred even if subjective quality metrics are considered to give the most reliable results. On the other hand, they are expensive, time-consuming and impractical for real-time implementation and system integration [10]. Besides, no-reference metrics are necessary since there are not original undistorted images available to be compared. We choose multiple metrics that take into account the aspect of information richness and added noise, luminance, sharpness and the overall index of contrast, chroma and saturation like that proposed by Xie and Wang: average contrast AC, average information entropy AIE, and average luminance AL.

First, Average Luminance AL is investigated as done even in [8]. The luminance level of 127.5 is an optimal visible luminance since it is the value of an image with an ideally equalized histogram.

Entropy is, instead, interpreted as the average uncertainty of information; it is a statistical measure of randomness that can be used to characterize the texture of the input image. It can be determined from the histogram of an image of all grey levels. An image with the ideal equalization histogram
possesses the maximal information entropy of 8 bit. These metrics proposed by [9] is employed for underwater image evaluation in [8], [1], [10], [11], but it is even used in an outdoor environment such as to evaluate fog removal methods in [12].  

The average gradient ($G_c$) or Average contrast (AC) of the image represents the local variance among the pixels of the image. In fact [9] define the grey gradient of a point in a grey field as the contrast of this point, while the total contrast can be synthesized by means of three gradients of three colour components of RGB. Bigger is the $G_c$ value, better the resolution of the image. The AC or $G_c$ metric was previously used in [9], [11], [10], [8], and [13]. 

Even UCIQE and UIQM, properly created for the underwater field, are used to evaluate the image quality as already done in [1] and [2]. Underwater colour image quality evaluation (UCIQE) metric, which is a linear combination of chroma, saturation and contrast, is proposed by Yang [14] to quantify the non-uniform colour cast, blurring and low-contrast that characterize underwater engineering and monitoring images. The larger the UCIQE is, the better the underwater colour image quality will be.

The UIQM is instead proposed by [15] comprises three underwater image attribute measures: the underwater image colourfulness measure (UICM), the underwater image sharpness measure (UISM), and the underwater image contrast measure (UIConM). Each attribute is selected for evaluating one aspect of the underwater image degradation, and each presented attribute measure is inspired by the properties of human visual systems (HVS). Generally, a greater UIQM value corresponds to an image with better quality, and a 10% increase in terms of the UIQM measure value leads to a visually distinguishable improvement [15].

For practical reasons, we will report here only a sample of our results obtained through Matlab environment: the average values along all the 22 pre-processed images (Figure 3) and two representative images with its five enhanced versions (Table 2 and Table 3). The best performing algorithm, according to the metric definition, is marked in bold.

The SP-CLAHE method prevails on 4 of the 5 metrics analyzed and it is in line with literature findings. It is worth mentioning that these quantitative metrics implement only a blind evaluation of a specific intrinsic characteristic of the image and so are unable to identify problems in the enhanced images, as the ‘artefacts’ generated by SP correction [10]. The image enhancement can improve the information abundance contained in the image but even amplify the useless information, especially the noises. Even UCIQE and UIQM metrics, properly created for the underwater evaluation, focus on the intensities of low-level features such as contrast, chroma and saturation but ignore higher semantic or prior knowledge from human perception. To conclude, the used objective image quality methods favour the over-enhanced colourful images, which instead can be against the subjective preference to naturalness, as underline even in Wang’s review [1].

![Figure 3](image-url)
Table 2. Results of evaluation performed on G0030470 image.

|     | ACE       | CLAHE    | LAB       | SP        | SP-CLAHE  | ORIGINAL  |
|-----|-----------|----------|-----------|-----------|-----------|-----------|
| AL  | 47.5384   | 50.4712  | 47.3427   | 42.019    | 48.1797   | 49.3793   |
| E   | 6.3760    | 6.1565   | 5.8385    | 6.3022    | 7.4782    | 4.9258    |
| G   | 3.1650    | 2.9291   | 1.2266    | 4.9945    | 10.7105   | 1.0300    |
| UCIQE | 0.5307  | 0.4072   | 0.3656    | 0.5129    | 0.5644    | 0.3704    |
| UIQM | 0.5127   | 0.3793   | 0.3292    | 0.6304    | 0.5574    | 0.2443    |

Table 3. Results of evaluation performed on G0030474 image.

|     | ACE       | CLAHE    | LAB       | SP        | SP-CLAHE  | ORIGINAL  |
|-----|-----------|----------|-----------|-----------|-----------|-----------|
| AL  | 45.4278   | 48.1235  | 42.7784   | 49.2001   | 50.0913   | 47.0716   |
| E   | 6.0376    | 5.9212   | 5.3796    | 7.3178    | 7.7618    | 4.7010    |
| G   | 3.4542    | 3.2922   | 1.2777    | 16.8920   | 27.6607   | 1.1125    |
| UCIQE | 0.47495 | 0.39314  | 0.33632   | 0.58715   | 0.62946   | 0.35554   |
| UIQM | 0.39405   | 0.38336  | 0.33574   | 0.47627   | 0.35      | 0.24364   |

4. Underwater 3D model by photogrammetry

One of the most rapidly adopted and widely used techniques like photogrammetry, or Structure from Motion, is now often applied to record archaeological material underwater. Applying the principles of digital photogrammetry, many photos from a single camera can be used to automatically generate a detailed 3D model to map archaeological sites or compare sites before and after the removal of encrustations. But underwater photogrammetry has some key differences compared to conventional photogrammetry methods [16] such as limited access to the underwater object, no operational control on data acquisition when measurements are conducted by an unqualified scuba diver; poor illumination and colour absorption and significant light diffusion (the visibility in the water decreases with an increasing distance from the object). But also, the automatic photogrammetric process can fail due to occlusions and moving objects. A relevant drawback is even the impossibility to set up any ground control points with known coordinates in underwater environment. So other available methods that will provide us external data are strongly recommended [16]. To achieve good reliability of the 3D model, a scale bar and vertical buoys should be used on site to scale the object and determine the horizontal direction. Furthermore, the possibility of object deformation is highly decreased if the object is covered by images from all sides [16].

But in this research, the images were taken during a diving session without a planned image acquisition scheme. To scale the model, a frame is used. It has been set on the seabed by other scuba divers. On the same time, a local reference system is built. Between the points that result fixed in the scene like edges of amphora, three points are identified and marked in each image of a single dataset. Then, coordinates are assigned to those points in such a way to be coplanar. This procedure is followed for each dataset so that subsequent manipulations will be easier.

Even, the application of masks was necessary before the generation of the dense point cloud to remove the diver’s presence in some images. To prevent incorrect reconstruction results, the masked areas are then excluded during the processing of point cloud and texture.
After an automatic camera alignment step, the first outputs are six different 3D dense point clouds of high quality (Figure 4): one from the uncorrected dataset and five enhanced versions. Each dense cloud covers an area of around 35 m² (7 x 5 m).

As in [11], no filtering is performed to obtain the total number of points per dense point cloud, as well as to evaluate the resulting noise. Instead, the alignment parameters are not maintained fixed along the different datasets. Useful information such as camera positions and lens calibration are not available even for the original dataset and so, the enhancement process could also raise the camera alignment accuracy (Table 4). It will result in lower values of RMS reprojection error that is considered as the distance between the marked and the reprojected point on one image. It depends on the quality of the camera calibration (position and orientation) and the quality of the marked point on the images. So, it appears to be a good indicator of the enhancement performances.

**Table 4.** Comparison between image enhancement algorithms through 3D reconstruction indicators.

|                | Total points | Tie points | Reproj. error |
|----------------|--------------|------------|---------------|
|                | point        | point      | pix           |
| ORIGINAL       | 10329975     | 5065       | 4.25          |
| ACE            | +9%          | 5648       | +12%          | 3.18          |
| CLAHE          | +10%         | 4673       | -8%           | 5.39          |
| LAB            | +5%          | 5240       | +3%           | 4.91          |
| SP             | +4%          | 5769       | +14%          | 4.21          |
| SP-CLAHE       | -7%          | 5757       | +14%          | 2.83          |

*a Compared with the original dataset

From a visual inspection, it can be noticed how the highest number of points obtained with CLAHE enhancement actually corresponds to an amplified noise (Figure 4). It has also the highest RMS reprojection error (Table 4). On the other hand, the dense cloud elaborated from the SP-CLAHE
dataset has the lowest number of points and results to be also the more accurate with the lowest reprojection error and the easiest identification of the amphoras.

Second outputs of the photogrammetric procedure are the orthomosaics (Figure 5). In line with the retrieved GSD, they are generated with a resolution of 1.5 mm/pixel. Even in this case, the amphora potsherds are easy to identify only in the enhanced versions. On the other side, it is not always linked to the truthfulness of colour: the SP algorithm produces an “over-enhancement” while ACE gives the best lifelike colours. The orthomosaic is useful even to texturize the third output: the mesh defined as a collection of vertices, edges, and faces that defines the shape of a polyhedral object in 3D computer graphics. It is generated from the dense cloud and the best mesh comes out from the SP-CLAHE dataset. But again, it doesn’t appear so realistic in colour.

![Figure 5. Orthomosaics with a resolution of 1.5mm/pixel.](image)

To present a true picture of the site as far as possible, without any “artefacts”, a possible strategy could be to pre-process the images with the two-step method trying to produce a more accurate 3D model and, afterwards, to enhance the original images with another method such as ACE to achieve a textured model more faithful to the underwater reality (Figure 7).

![Figure 6. Mesh texturized with SP-CLAHE dataset.](image)  ![Figure 7. Mesh texturized with ACE dataset.](image)

5. CONCLUSION

In this research is shown how enough detailed 3D objects can be obtained even from low-quality images, strongly affected by low contrast, poor visibility conditions, not uniform lighting, colour variations, noise and blur effect. The photos were captured with an action camera with a low resolution of 72 dpi and 3 mm of focal length, without artificial light at 40 m depth and without a planned survey purpose. The image enhancement step result to be fundamental to reach that good results and the ease-of-use of the iMARECULTURE tool [3] allows to gain valuable time for the 3D reconstruction phase. On the other side, there is no control on the enhancement performance. In the future, the work will be focused on developing a proper CNN enhancement technique.

But anyway, the highest score in image quality assessment is obtained from those images before enhanced with the Screened Poisson algorithm and then subjected to a second step acting on the histogram equalization (CLAHE). Even if this enhanced version visually appears too much forced and artificial, it is fundamental to reach an accurate 3D object reconstruction. The improved contrast
stresses the amphorae shape and it ends in a more precise point matching process. In fact, the lowest RMS reprojection error (2.83 pixels) is achieved and a low noisy dense points cloud appears.

To face the unrealistic perception, it is recommended to use that dense cloud to produce an accurate mesh but then texturize it with orthophotos obtained by the ACE enhancement procedure. A more true-to-life 3D model will occur.

Finally, it is worth mentioning that in this publication, we deal with a single region of the roman shipwrecks where there are some well-preserved amphorae. In this way, especially in the 3D visualization, object identification is made easy. But similar results are achieved even in an area with high rates of amphorae potsherds. If for the objective quality metrics calculation, there is no difference in time computing, the same is not true for the 3D reconstruction. In fact, to set a common local reference system, markers must be manually placed on amphorae edges or shadows. They can be not easily recognizable.

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