Computer Image Recognition and Recovery Method for Distorted Underwater Images by Structural Light

Bijian Jian\textsuperscript{1,2,*}, Yongfa Ling\textsuperscript{2}, Xuebo Zhang\textsuperscript{2} and Jiawei Ou\textsuperscript{2}

\textsuperscript{1}School of Information and Communications, Guilin University of Electronic Science and Technology, Guanxi, China
\textsuperscript{2}Hezhou University, Guanxi, China

*Corresponding author: 201700119@hzxy.edu.cn

Abstract. When imaging through water surface, the random fluctuation of sea surface will cause the distortion of the target scene image, so the distorted image needs to be corrected and reconstructed. At present, distortion compensation mainly adopts iterative registration strategy based on image sequences which is difficult to satisfy the real-time observation. This paper presents a correction method based on active imaging of structured light for underwater image. Experimental results show that compared with the traditional iterative algorithm, the proposed algorithm cannot only improve the restoration accuracy, but also greatly shorten the processing time. Experimental test results demonstrate that the proposed algorithm has good recovery results.

Keywords: Image Restoration, Underwater Images, Image Registration, Structural Light.

1. Introduction
While imaging through water surface, the random fluctuation of sea surface will cause the distortion of the target scene image, so the distorted image needs to be corrected and reconstructed\cite{1-3}. The key problem of imaging through the gas-water interface lies in the addition of a stochastic fluctuating medium interface between the imaging system and the target, this fluctuating interface has far more impact on imaging than water absorption, scattering, turbulence, and the present relevant research is mainly conducted on how to compensate for the stochastic refraction problem.

At present, such research is mainly conducted from two aspects. One is the image recovery method based on image sequence \cite{4-6}. The scheme believes that distortion-free true images are hidden in the sequence of distorted scenes, assuming the scene and camera are stationary, using the same stationary scene image sequence to reconstruct the undistorted images. The registration technology based on image sequence requires obtaining a large number of image frames before starting processing, and ensuring that the scene between front and rear frames is absolutely stationary, so real-time becomes the biggest defect of such algorithms. The other is the recovery method based on real-time surface waveform estimation \cite{7}. Several estimation methods are harsh on the application conditions which require special lighting setting or special lighting conditions and the accuracy is difficult to meet the application requirements.
The 3D measurement of structural light has the advantages of high precision, fast speed and strong adaptability. In recent years, a lot of attention has been paid to the 3D measurement based on structural light [8-9]. Aiming at the long registration time of iterative registration algorithm and the impact of spatial environment on registration accuracy, this paper proposes an underwater image correction algorithm based on structured light. The performance of the proposed method is compared against a state-of-the-art method [6]. Experiments present that the proposed method has better performance.

2. Image Formation Through the Wave Surface

![Figure 1. The distortion process in underwater imaging](image)

In Fig. 1, $I_g(x)$ is the original image, $I(x,t)$ is the distorted image at the time $t$ and the relationship [6] between the two images can be describe by

$$I(x,t) = I_g(x + w(x,t))$$  \hspace{1cm} (1)

Where $w(x,t)$ is the unknown distortion over time, $x$ is coordinate vector $(x, y)$ representing pixel points on the image. According to Snell’s law [6], we can write the distortion to be

$$w(x,t) = \alpha \nabla h(x,t)$$  \hspace{1cm} (2)

Where $h(x,t)$ is the height of the water surface at time $t$, and $\alpha$ is a constant related to average water height and relative refraction index:

$$\alpha = h_0 \left(1 - \frac{n_1}{n_2}\right)$$  \hspace{1cm} (3)
Where \( h_0 \) indicates the average water depth, \( n_1, n_2 \) are the refractive index of two media respectively. When air-to-water imaging \( \alpha > 0 \), on the contrary, when underwater-to-air imaging \( \alpha < 0 \). Thus, Eq. 2 shows that the relationship between the deformation vector field and the water surface gradient field is linear.

As shown in Fig.1, according to Snell’s law, the camera will actually see scene point B instead of A, when through A dynamic water surface. \( d(x,t) \) is the displacement of a light ray experiences, the whole image distortion field at time t can be described by

\[
w(x,t) = Pd(x,t)
\]

(4)

Where \( P \) is the projection matrix of the camera. Eq.4 indicates that different pixels of the image captured by the camera can have different amount of warping due to the dynamic wave surface.

3. Methods

3.1. Overview

In order to effectively estimate warping field \( w(x,t) \) of the image \( I(x,t) \) captured from a camera at time t, we propose an image restoration approach for underwater distorted image based on structural light. The underwater image restoration model based on structured light as shown in Fig.2. We assume \( I_s(x) \) is the reference structural-light image, \( I_n(x,t) \) is the distorted of the reference structural-light image at time t. The relationship between the two images can be describe:

\[
I_n(x,t) = I_s(x + w(x,t))
\]

(5)

From Eq. 1 and Eq.5 we can conclude that if the warping field can be estimated at the same time, the distorted scene image also can be restored. Thus, the warping field \( w(x,t) \) can be obtained by registering the distorted structural-light image \( I_n(x,t) \) against the reference \( I_s(x) \). the distorted image can be recovery:

\[
I_g(x) = I(x + w'(x,t))
\]

(6)

Where \( w'(x,t) \) is the reverse warping field.
As Fig. 3 shown, the algorithm consists of three major parts:

a. Structural light extraction. Input the distorted image sequence $I(x,t)$, standard structured light image $I_s(x)$, and then distorted structured light images $I_n(x,t)$ are extracted based on three-channel separation;

b. Image registration. The spatial correction matrix $T$ of distorted structured light $I_n(x,t)$ and standard structured light images $I_s(x)$ is obtained based on non-rigid registration algorithm;

c. Stationary image reconstruction. Correction the geometric distortion of the distorted scene image $I(x,t)$ based on the correction matrix $T$.

**Figure 3.** Simple flow diagram of the proposed method.

### 3.2. Image registration

Similar to [6], a non-rigid registration of a free transform model based on the B spline is used to eliminate image distortion. On the basis of this algorithm, the sparse control point grid is transformed from the distorted image to the reference image. The image coordinate transformation function of each pixel point $(x,y)$ is
\begin{equation}
T(x, y) = \sum_{m=0}^{3} \sum_{l=0}^{3} B_m(v)B_l(u)\varphi_{l+i,j+m}
\end{equation}

\varphi_{ij} is the control vector, \(i = \left\lfloor \frac{x}{n_x}\right\rfloor - 1, j = \left\lfloor \frac{y}{n_y}\right\rfloor - 1\), \(u = x / n_x - \left\lfloor \frac{x}{n_x}\right\rfloor\), \(v = y / n_y - \left\lfloor \frac{y}{n_y}\right\rfloor\)

and B is the B-spline based functions are expressed as

\begin{align}
B_0(t) &= (1-t)^3 / 6 \\
B_1(t) &= (3t^3 - 6t^2 + 4) / 6 \\
B_2(t) &= (-3t^3 + 3t^2 + 3t + 1) / 6 \\
B_3(t) &= t^3 / 6
\end{align}

Where \(0 \leq t < 1\). Depending on the distance to the point \((x, y)\), each control point assigns a weight to coordinate transformation function by above functions. During B-spline registration, optimization algorithms are used to find control points until the best advantage is found.

4. Results and Discussion
To verify the performance of the proposed method implemented on MATLAB (MathWorks Co., USA), we made a comparison with the Oreifej method [6] using SSIM [10], PSNR [11], MSE and the running time.

4.1. Results of the same data set as the Oreifej method
The tested data sets are shown Fig.4 in which each data set was composed of 61 frames. The frame size of each sequence is 292 × 268 for “brick”, 293 × 253 for “Middle fonts”, and 284 × 255 for “tiny fonts” respectively. For the Oreifej method [6], the number of iterations was set to 5 times.

![Figure 4. Sample frame and original image of each data set.](image)
Quantitative comparisons between the proposed method and the Oreifej method [6] are made using intensity mean squared error (MSE), peak signal-to-noise ratio (PSNR), structural similarity (SSIM) calculations and processing time. For fair comparison, we employed the same data sets for both methods in the same operating environment. Fig. 5 shows the reconstruction results using different methods. It is worth noting that the Oreifej’s method took 5 iterations for its robust image registration to get the results showed in the third column, while our algorithm ran registration just once for arbitrary distorted frame. The comparison has been listed in Table 1, where the value of each performance indicator is the average of the processing results of the corresponding data set of the proposed method, because our method can process each image frame in real time.

Table 1 gives the PSNR, SSIM and MSE values for the outputs with different reconstruction algorithms after normalizing the images to [0-1]. It can be seen that the proposed algorithm outperforms in all data sets in terms of PSNR and MSE and SSIM. It can show that our method has a better recovery effect, in particular, the proposed restoration method takes shorter processing time than the Oreifej’s method.

Table 1. Performance comparison with the Oreifej’s method [7]

| Data sets   | Methods       | SSIM(High-Good) | PSNR(High-Good) | MSE(Low-Good) | Running time /s |
|-------------|---------------|-----------------|-----------------|---------------|-----------------|
| Bricks      | Oreifej[7]    | 0.6326          | 22.8288         | 0.0052        | 1470.846        |
|             | Proposed method | 0.8568          | 22.9180         | 0.0051        | 7.55            |
| Middle fonts| Oreifej[7]    | 0.7468          | 21.4650         | 0.0071        | 1417.152        |
|             | Proposed method | 0.7835          | 21.7417         | 0.0067        | 7.49            |
| Small fonts | Oreifej[7]    | 0.7082          | 24.1406         | 0.0039        | 1550.754        |
|             | Proposed method | 0.7517          | 24.5996         | 0.0037        | 7.69            |
4.2. **Results of the real through-water scene’s data**
While imaging through water surface, a camera was fixed above water tank in which the frame rate is 45 and each frame size is 500 × 500. Fig. 6 show that the algorithm can recover the distorted image well, which is consistent with the simulation results above.

![Figure 6. The restoration results in real scene by the proposed method](image)

5. **Conclusion**
In this paper, an underwater image restoration algorithm based on structured light is proposed. This method first estimates the deformation vector field of the wave surface, so as to realize real-time distorted image recovery. Experimental results show that compared with the traditional iterative algorithm, the proposed algorithm cannot only improve the registration accuracy, but also greatly shorten the processing time. Experiments with real through-water scenes have also proved the effectiveness of the method.

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