Underwater image conversion method based on multi-layer plane refraction model with light field processing method

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Abstract: In order to adopt the conventional visual measurement technology to underwater application, this paper proposes an underwater image conversion method based on a multi-layer plane refraction model, which converts the underwater image into an air image. First, under the multi-layer plane refraction model, the imaging process of the underwater camera is modelled in the form of a four-dimensional light field parameterization, and the direction vector of the air image is calculated using the light field direction information. Then, the perspective projection transformation is used to obtain the corresponding pixel coordinates of the direction vector and the image plane. Finally, the transformed air image is obtained by interpolation method, using the mapping relation of the corresponding image point coordinates before and after the transformation. Simulation and experimental results show that the average error of the corrected image is 0.56 pixel, and the high-precision air image provides strong support for subsequent underwater 3D reconstruction.

1. Introduction
Visual measurement technology is widely used in the field of exploration and development of the ocean [1][2], and the camera as its sensing unit plays a decisive role. However, the light will be refracted when it propagates underwater, which does not meet the perspective projection imaging model, and the image will have a large nonlinear distortion, which makes the accuracy of visual calculation based on the underwater image not guaranteed. If the underwater image can be converted into an air image, which conforms to the perspective projection principle, the conventional visual measurement technology can be quickly used to process the image.

In the early work, people often pre-processed the underwater image by restoration and enhancement [3]. Although it can improve the quality of the image, it cannot fundamentally eliminate the distortion of the image. Pizarro et al. [4] used uncertain measurement values to constrain possible matches, and proposed Zernike moments to describe the affine invariant characteristic, but it needs to meet the wide baseline condition. Xie et al. [5] compensated the nonlinear relationship of Snell's law through lens distortion, but when the incident angle becomes larger, the lens distortion cannot be fully compensated, and the restoration accuracy of the image cannot be guaranteed. Agrawal et al. [6] proposed a multi-layer plane refraction model, and used the direction vector to completely reproduce the transmission process of multi-layer refraction of light. Based on this, Jordt et al. [7] used a combination of
optimization algorithms and comprehensive analysis to reconstruct the light propagation model parameters of local water bodies, but the application was more limited.

This paper is based on a multi-layer plane refraction model, combined with a four-dimensional light field parameterized representation method. On the basis of preserving the ray information, the directional information and position information of the ray are used to obtain the mapping relationship between the image point coordinates. After linear interpolation and simulated optimization to determine the corresponding air image. Experimental results verify the reliability and accuracy of this method.

2. Theory

2.1. Underwater multiple interface refraction imaging model

Vision systems usually need to be encapsulated when working underwater, and the propagation of light in different media will cause refraction, which will cause the pinhole imaging model of traditional cameras (as shown in Figure 1) to fail. The actual underwater imaging process is shown in Figure 2. The object point passes through multiple layers of water, glass, and air to reach the image point. Where $P_c$ is the object point in the camera coordinate system, $P_w$ and $P_a$ are the image points in water and air respectively, $f$ is the focal length of the camera, $O$ is the optical center of the camera, $d$ is the distance from the optical center of the camera to the interface, $\theta_1$, $\theta_i$ and $\theta_2$, $\theta_i$ are the angles of refraction and incidence, respectively.

![Figure 1. Pinhole camera model](image1)

![Figure 2. Schematic diagram of underwater object point refraction imaging](image2)

2.2. Underwater multi-layer plane refraction model

As shown in Figure 3, combined with the four-dimensional parameterized representation of the light field [8], the multi-layer plane refraction model is defined after the camera distortion is corrected as follows: the camera coordinate system (the black coordinate system shown in the figure) is located at the optical center of the camera, and its Z-axis is parallel to the optical axis. With the multi-layer interface normal $n$ as the Z-axis (perpendicular to the imaging plane), the normal $n$ and the camera's Z-axis cross-multiply to the X-axis to build a multi-layer plane refraction coordinate system (the red coordinate system shown). The relationship between the two coordinate systems is as follows:

$$P_r = \bar{R} P_c + \bar{t}_c$$

$$\bar{R}_c = \begin{bmatrix} n \times z_c & n \times (n \times z_c) & n \end{bmatrix}$$

$$\bar{t}_c = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$$

$$z_c = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

(1)

The position plane $uv$ of the light field is defined in the x-plane of the multi-layer refraction coordinate system, and its coordinate origins coincide. The direction plane $st$ is a unit length from the position plane and is parallel to the position plane.
2.3. Image conversion method based on multi-layer plane refraction model

As shown in the figure above, the underwater object point \( P_c \) propagates back through the n-layer medium to the camera optical center, intersects the imaging plane at point \( P_w \), and the direct rays intersect with the imaging plane at point \( P_r \) (that is, the corresponding point of the air image obtained in this paper). In the underwater imaging system, only three mediums of water, glass and air are included (the thickness of the glass is small enough to be ignored), and the object point \( P'_c \) after refraction is located in the water medium layer. In the figure, \( n \) is the multi-layer interface normal, \( d_i \) is the distance between the interfaces, and \( \mu_i \) is the refractive index of each medium. The underwater image correction algorithm based on the multi-layer plane refraction model is as follows:

Step1: According to the pinhole imaging model, the relationship between the object point \( [x_c, y_c, z_c]^T \) and the imaging point \( [x_w, y_w]^T \) in the camera coordinate system can be established, and any image point \( P_w \) can determine a light passing through the optical center and pixels.

Iterate through all the image points \( P_w = [x_w, y_w]^T \) in the original image and calculate the corresponding light \( I_r \), and then convert it to the multi-layer refraction coordinate system \( I_r \) and express it in the four-dimensional parameterized form[9] of the light field \( L \) (where, \( K \) is the camera internal reference matrix):

\[
P_r = K P_c
\]

\[
I_r = K^{-1} P_r = \left[ \frac{1}{I_r(3)} \right]^{T} I_r(3)
\]

\[
L = \begin{bmatrix}
1 & 0 & 0 & I_r(3) \\
0 & 1 & 0 & I_r(3) \\
0 & 0 & 1 & I_r(3)
\end{bmatrix}
\]

(2)

Step2: Correct the refracted light.

Use the refraction expression \( R(s, t, n, a) \) [9] of the light field to correct the light back to the direct state \( L_r = R \times L \); and then convert \( L_r \) to a direction vector \( a_r = [s \ t \ 1] \) according to the light field conversion formula[8], the direction vector in the camera coordinate system is \( a_r = R \times a \).
\[ L_c = R(s, t, \mu, \mu) \odot L_c \]
\[ a_c = [s_c, 1] \]
\[ a_c = R_c \times a_c \]

Step 3: Calculate the corresponding image point \((P'_a = [x_a, y_a]^T)\) in the camera coordinate system.
At this time, the pixel coordinates of the camera have no lens distortion, and only the perspective projection of the light can be used to obtain the corrected pixel coordinates \(P'_a\) (the coordinates of the image points of the air image).

\[ P_a; Ka_c \]

Step 4: Interpolate to get the pixel value of the image point \(P'_a\).
Use the mapping relationship between image points \(P'_a\) and \(P'_w\) to obtain the pixel value of the corresponding image point of the corrected image, and the image point \(P'_w\) is mostly floating point coordinates. Therefore, this paper uses bilinear interpolation to obtain its corresponding pixel value, and finally obtains the corrected air image.

3. Simulation
The simulation process and results are shown in following figures. Considering the imaging characteristics of the lens, the edge distortion of the image is usually large, which is consistent with the simulation result in Figure 5 (c). The conversion algorithm is used to correct the distorted image Figure 5 (c) to the corresponding air image Figure 5 (d), and the correction result is smaller than the reference standard Figure 5 (b), which verifies the accuracy of the algorithm. However, as the underwater object distance decreases, as shown in Figure 6 (b) (c) (d), the nonlinear distortion of the underwater image increases significantly, but the correction algorithm can still correct the distorted image points.

![Simulation process](image4)

Figure 4. Simulation process

![Simulation results at 2 meters](image5)

Figure 5. Simulation results at 2 meters

![Simulation results at 1 meters](image6)

Figure 6. Simulation results at 1 meters
4. Simulation
As shown in Figure 7, an underwater binocular camera is used to shoot the calibration board, and the
depth of the calibration board from the camera is between 2 and 3 meter. The coordinates of 96 internal
corner points on the air image after conversion were extracted, and the actual coordinates of the internal
corner points were calculated by using underwater stereo vision matching. The results are shown in
Figure 8. The maximum error between the images is 0.4 pixel. Mean error of 15 experiments is 0.56
pixel. It can also be clearly seen from Figure 9 that the difference between the images before and after
the conversion, and the pincushion distortion at the edges of the image after the conversion obviously
disappear, further verifying the accuracy of the conversion method.

![Figure 7. Experimental environment](image1)

![Figure 8. Experimental results at 2 meters](image2)

![Figure 9. Images before and after conversion](image3)

5. Conclusion
This paper combines a light field processing method with a multi-layer plane refraction model, proposes
a new method for converting underwater image into an air image. The light is reconstructed in the form
of a four-dimensional parameterization of the light field, and the direction and position information of
the light is fully used based on the perspective projection transformation to obtain the image point
mapping relationship between the air image and the underwater image. Simulation and experimental
results verify the reliability and accuracy of the method.

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