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Underwater Camera Model and Its Use in Calibration*

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***Abstract*— The widespread use of the underwater camera provides an effective nondestructive means for underwater measurement in various scenarios. The underwater camera captures objects through at least one refraction by the interface between the water and the protecting house. It is a non-single viewpoint (non-SVP) imaging system and the assumption of single viewpoint (SVP) camera model is invalid. Always, we must calibrate the camera system to quantify the image deformation caused by refraction and to measure the object accuracy. However, it is sometimes difficult to be done. In this paper, we propose a novel flexible underwater camera model. Then, we present an underwater camera calibration method based on the proposed camera model to calibrate the underwater camera. Both synthetic and real experiments validate the proposed method.**

***Index Terms*— underwater camera model, underwater camera calibration**

I. Introduction

Underwater videogrammetry measurement systems employ stereo cameras or a single camera in a waterproof housing device, as shown in Fig. 1, which provides an effective nondestructive means for underwater measurement in various scenarios, including marine ecosystem studies [1], 3D kinematic analysis of swimming [2], estimation of biomass for aquaculture [3], seabed mapping [4] and underwater entertainment, as only a few examples.

Always, a camera, which placed in a waterproof housing device, looking through a flat interface between the waterproof housing device and the water yields a non-SVP system [5]. In underwater videogrammetry measurement, the most basic and most important technology is the underwater camera calibration, obtaining the parameters of the camera and the waterproof housing device. As we know, the refractive effects of water and the housing device make the calibration as a challenging work, which violates the assumption of the SVP camera model. As it is a non-SVP system, using the traditional camera calibration method introduces error in calibrating underwater camera intrinsic matrix and distortion parameters.

In recent decades, there are a few methods proposed attempting to solve the problem. Treibitz $et\ al.$ [5] and Telem $et\ al.$ [4] calibrated the imaging system parameters with known the camera parameters. Gourgoulis $et\ al.$ [2] and Li $et\ al.$ [6] used a large calibration frame to calibrate the camera, and Pessel $et\ al.$ [7] calibrates the camera without considering the water refraction effects. Ferreira $et\ al.$ [8] proposed an approximate method, Lavest $et\ al.$ [9] compared the parameters obtained in the water and in the air. Until now, there is no method to calibrate underwater camera intrinsic parameter with high accuracy. In this paper, we propose an underwater camera model and use this model to calibrate the camera intrinsic parameters underwater.

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Fig. 1. The example of the camera waterproof housing device

The remaining of this paper is structured as follows. In section II, we present the background theory. In section III, we proposed a new underwater camera model contains explicit terms for the water refractive effects. In section V, we present an underwater camera calibration method based on the proposed camera model. Finally, synthetic and real experiments validate our theory.

II. Background

A. Camera Model

The camera always satisfy the pinhole camera model [10]. The relationship between the image point $\tilde{\mathbf{x}} = [u, v, 1]^T$ and the corresponding world point $\tilde{\mathbf{X}} = [X, Y, Z, 1]^T$, both are in homogenous coordinate vector, can be given by

$$s\tilde{\mathbf{x}} = \mathbf{K}[\ \mathbf{R} \quad \mathbf{t}\ ]\tilde{\mathbf{X}} \tag{1}$$

where $(\mathbf{R}, \mathbf{t})$ are the camera extrinsic parameters. The camera intrinsic matrix $\mathbf{K}$ is given by

$$K = \begin{bmatrix} f & 0 & u_0 \\ 0 & f & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

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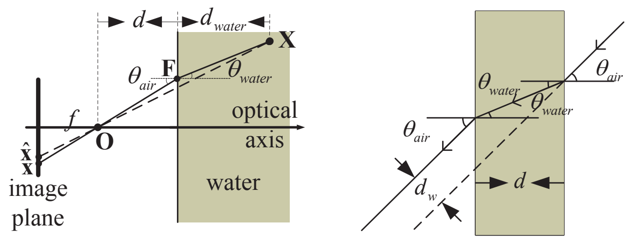
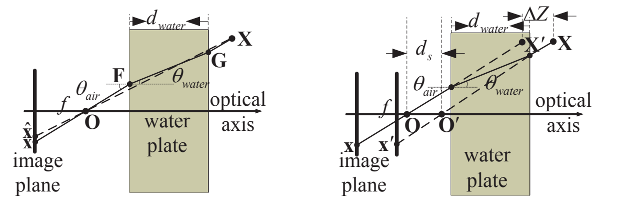


(a) (b)

Fig. 2. (a)The Schematic diagram of underwater camera imaging where the point $\mathbf{O}$ is the camera center; (b)A ray passing through a parallel plate.



(a) (b)

Fig. 3. Underwater camera imaging based on the plate refractive camera model

where f represents the focal length in the terms of pixel dimensions, (u_0, v_0) are the principal point.

In this paper, we consider the radial distortion with the first two terms only. Let (u, v) and $(\tilde{u}, \tilde{v})$ represent the ideal (distortion-free) pixel image coordinates and the real observed (distortion) pixel image coordinates. Similarly, (x, y) and$(\tilde{x}, \tilde{y})$ represent the ideal and real normalized image coordinates. According to [11], [12]

$$\begin{aligned} \tilde{u} &= u + (u - u_0)[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2] \\ \tilde{v} &= v + (v - v_0)[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2] \end{aligned} \tag{3}$$

where k_1 and k_2 are the coefficients of the radial distortion respectively.

B. Refraction

Consider a camera capturing an object in the water through a parallel glass, which is a window of the camera waterproof device. As the thickness of the glass is far less than the depth of the object in the water, the effects created by the glass are considered as part of the effects created by the water, as in [5]. Assuming that the optical axis is perpendicular to the interface between the water and the waterproof device. Hence, the setup has radial symmetry around the optical axis. In our study, we choose a plane that contains optical axis for formulating deviations, as shown in Fig.2(a). Assuming a ray emits from the object point $\mathbf{X}$ passing through the water and intersecting the interface at point $\mathbf{F}$, then refracting, and finally forming the image point $\mathbf{x}$ on the image plane. According to Snell's law [13], the refractive index of water is

$$n = \sin\theta_{air} / \sin\theta_{water} \tag{4}$$

where θ_{air} and θ_{water} are the angles of ray in the corresponding medium respectively. If there is no other medium between the object and the camera, the object point $\mathbf{X}$ will directly project on the image point $\hat{\mathbf{x}}$ on the image plane.

As illustrated in Fig. 2(b), the ray passing through a parallel plate causes a lateral displacement d_w with its direction unchanged,

$$d_w = d\sin\theta_{air}\left(1 - \frac{\sqrt{1 - \sin^2\theta_{air}}}{\sqrt{n^2 - \sin^2\theta_{air}}}\right). \tag{5}$$

III. Underwater Camera Model

Obviously, the heart of an underwater camera setup is a pinhole camera. Supposing that it is working in the camera coordinate frame and with the camera center at the origin. The camera imaging a space point $\mathbf{X} = [X, Y, Z]^T$ in the water is equivalent to the camera imaging the space point $\mathbf{X}$ with a parallel water plate, as illustrated in Fig. 3(a). Therefore, the underwater camera imaging problem is converted into a plate refractive imaging problem. We can solve the plate refractive imaging problem by the theory of the plate refractive imaging system [14]. Translating the space point $\mathbf{X}$ with displacement ΔZ along the optical axis to the new place $\mathbf{X}'$, as depicted in Fig. 3(b), which is converted into a perspective camera imaging problem at last. We obtain the new mapping

$$s\tilde{\mathbf{x}} = \mathbf{K}[\ \mathbf{I} \quad \mathbf{0}\ ]\tilde{\mathbf{X}}' \tag{6}$$

where $\tilde{\mathbf{X}}'$ is the homogenous coordinate vector of the space point $\mathbf{X}'$. As shown in Fig. 3(b), the space point $\mathbf{X}'$ can be written as

$$\mathbf{X}' = \mathbf{X} - \left[\begin{array}{ccc} 0 & 0 & \Delta Z \end{array}\right]^T. \tag{7}$$

According to the parallelogram principle, $d_s = \Delta Z$, and we can get the d_s from (5)

$$d_s = (Z - d)\, m \tag{8}$$

where d is the distance from the camera center to the water surface(or the parameter of waterproof device), Z is the depth of the space point, and

$$m = \left(1 - \frac{\sqrt{1 - \sin^2\theta_{air}}}{\sqrt{n^2 - \sin^2\theta_{air}}}\right). \tag{9}$$

For camera projection problem, from the plate refractive camera model [14], the underwater camera model is

$$s\tilde{\mathbf{x}} = \mathbf{K}[\ \mathbf{I} \quad -\mathbf{t}_d\ ]\tilde{\mathbf{X}} \tag{10}$$

where $\mathbf{t}_d = [0, 0, d_s]^T$ is the virtual camera center that can be computed [14]. For other problems, such as triangulation problem, as we don't know the depth of the object, so we can not obtain the virtual camera center directly.

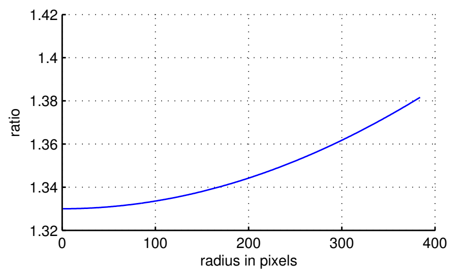


Fig. 4. The ratio (f'/f) between the focal length in water and air. Assuming $f = 900$, $n = 1.33$.

The (7) can be converted into the new form

$$\mathbf{X}' = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1-m & dm \end{bmatrix} \tilde{\mathbf{X}}. \tag{11}$$

Substitute (11) into (6), we can get the underwater camera model

$$s\tilde{\mathbf{x}} = \mathbf{K} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1-m & dm \end{bmatrix} \tilde{\mathbf{X}}. \tag{12}$$

which is related to d and m only. The d is a constant number, which is can be calibrated in the following.

Expand (12), the image point (u, v) can be obtained as

$$\begin{aligned} u &= \tfrac{fX}{(1-m)Z+dm} + u_0 \\ v &= \tfrac{fY}{(1-m)Z+dm} + v_0. \end{aligned} \tag{13}$$

When $d = 0$, the camera center is on the interface of water, the underwater camera setup can be considered as a SVP camera with the focal length varied according to m, as depicted in Fig. 5(a). The new focal length is

$$f' = f/(1-m). \tag{14}$$

In other words, the distortions can be modeled as a mere radial distortion. Fig .4 shows an example of the ratio between the real camera focal length and the virtual SVP camera focal length. At small angles, $\theta_{air} \ll 1$ and thus

$$1 - m \approx \frac{\sqrt{1-\theta_{air}^2}}{\sqrt{n^2-\theta_{air}^2}} \approx \frac{1}{n}. \tag{15}$$

Hence, the virtual SVP camera focal length is

$$f' \approx nf. \tag{16}$$

When $d \geq 0$, supposing the camera is designed for the water with the focal length f', we can consider the underwater camera setup as a SVP camera capturing the object passing through a parallel air plate, as illustrated in Fig. 5(b). Then we can use the theory of the plate refractive imaging system to deviation the new underwater camera model, which is similar to the plate refractive camera model in [14],

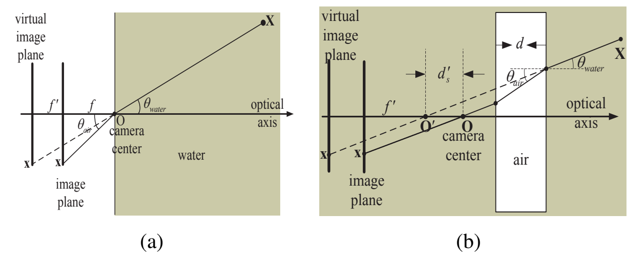


Fig. 5. (a) The camera center is on the surface of the water; (b) A SVP camera capturing the object passing through a parallel air plate

$$\mathbf{P}' = \begin{bmatrix} f' & 0 & u_0 \\ 0 & f' & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d'_s \end{bmatrix} \tag{17}$$

where d'_s is the camera center translation distance

$$d'_s = d\left(1 - \frac{\sqrt{1-\sin^2\theta_{water}}}{\sqrt{(1/n)^2 - \sin^2\theta_{water}}}\right). \tag{18}$$

IV. Underwater Camera Calibration

Camera calibration is the foundation of distortion rectification and 3D construction in computer vision. In actual applications, it is necessary to calibrate underwater camera in the water. Zhang's [12] method is a state-of-the-art camera calibration method to calibrate the camera in the air. But there is effective method to calibrate the camera intrinsic parameters in the water. In this section, we propose an underwater camera calibration method analogue to the plate camera calibration method in [14] to obtain the camera intrinsic parameters and the waterproof device parameter.

In order to distinguish the notations from the perspective camera model, we use $\mathbf{m} = [u, v]^T$ and $\mathbf{M} = [X, Y, Z]^T$ to present the corresponding coordinates of 2D image point and 3D space point in the water respectively. We also use a checkerboard pattern in the underwater camera calibration.

The process of underwater camera calibration is to minimize the algebra distance of $N \times M$ images points by Levenberg-Marquardt algorithm [15] with solving d in the curve fitting method

$$\sum_{i=1}^{N}\sum_{j=1}^{M} \left\| m_{ij} - \breve{m}(\mathbf{K}, k_1, k_2, \mathbf{R}_i, \mathbf{t}_i, n, d, \mathbf{M}_{ij}) \right\|^2 \tag{19}$$

where the second term is the projection of point $\mathbf{M}_{ij}$ in image j according to (17), followed by distortion according to (3). The recommended calibration procedure presented in $Algorithm$ 1.

V. Experiments

We designed a synthetic experiment and a real experiment to evaluate the underwater camera calibration method.

Algorithm 1 Underwater camera calibration

Input:

1: N images of checkerboard pattern captured in the water under different positions and orientations;

2: Refractive index of the water n;

Output:

Camera projection matrix $\mathbf{K}$, radial distortion parameters k_1,k_2 and the distance d.

Procedure:

3: Detect the corners m_{ij} of the checkerboard in the images;

4: Estimate the camera intrinsic parameters and extrinsic parameters using the method described in [12];

5: Initial the real camera focal length f by (16);

6: Initial different d based on the experience.

7: **while** $(changes > 1e-9)$ and $iteration < 60$ **do**

8:    Compute the parameters of (17).

9:    Refine all parameters except d by minimizing (19) using the method similar to [14];

10: **end while**

11: Calculate the smallest d according to (19) in curve fitting method. Then, repeat step 7-10.

A. Synthetic Experiment

The parameters of synthetic underwater camera are shown in Table I. The calibration checkerboard pattern contains $8 \times 10 = 80$ corner points with $3\mathrm{cm}$ square. Nine images are captured with different positions and orientations in the water. Table I shows the experiments results of our proposed method and Pessel's method [7], which without considering the water refractive effects.

TABLE I

SYNTHETIC EXPERIMENT CALIBRATION RESULTS

	f	u_0	v_0	k_1	k_2	d
truth	3715	2420	1630	0	0	50
our	3715.0	2420.0	1630.0	0.0	0.0	50
[7]	4945.3	2418.9	1629.2	0.3707	0.2606	NAN

B. Real Experiment

We experiment with a Nikon D7000 SLR camera with resolution of 4928×3264 pixels putting into a waterproof 1(b), captured 9 images of the checkerboard (Fig. 6), which contains $21 \times 29 = 609$ corner points with $14mm$ square, in the water. In the process of taking pictures, we locked the lens in order to ensure the same focal length. The first line in Table II is the experimental results of camera calibration in the air, which is considered as the true parameters. The second and the third line are the experimental results of underwater camera calibration in the water by different methods.

We can note that our proposed algorithm can successfully recover the camera intrinsic parameters, including focal lengths, principal points and distortion parameters. Meanwhile, we can get the distance from the camera center to the interface. Without considering the refractive effects is equivalent to considering the water refractive as extending the focal length and turning into radial distortion.

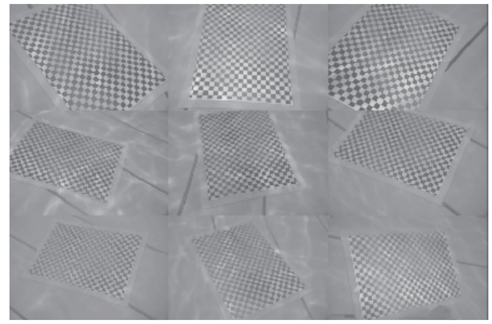


Fig. 6. The images captured underwater.

TABLE II

REAL EXPERIMENT CALIBRATION RESULTS

	f	u_0	v_0	k_1	k_2	d
[12]	4615.8	2448.6	1840	-0.0478	0.0120	NAN
our	4613.3	2450.4	1846.3	-0.0472	0.0108	98.7
[7]	6147	2450.7	1835.4	0.3573	-0.0803	NAN

VI. CONCLUSION AND PERSPECTIVE

This paper presents a novel underwater camera model, which converts the underwater camera into a special camera capturing images through an air plate. Then, we present an underwater camera calibration method to obtain the camera intrinsic parameters in the water. The proposed method can obtain robust results. We will research on underwater reconstruction and underwater image distortion rectification based on our proposed underwater camera model in the following research.

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