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Binocular Camera Calibration for Underwater Stereo Matching

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Abstract. This paper presents an efficient stereo matching method applied to underwater with a binocular camera. Since underwater calibration is an inconvenient task and the traditional imaging model in the air and the parameters of the camera are no longer applicable to the underwater because of the distortion caused by light refraction. To solve this problem, we proposed a way to calibrate the binocular camera in the air for underwater stereo matching. We studied the imaging principle of the camera, and derived the relationship of the camera between in the air and underwater. Then, we performed underwater stereo matching experiments using the parameters of the camera calibrated in the air and found it to be effective.

1. Introduction

Binocular stereo vision is an important branch of the research area in computer vision and it is mature. However, in order to adapt to the development and research of the underwater environment, our existing methods are not completely applicable. Because the same object is different in the air and underwater. The first step in stereo vision is calibration. Calibrating the camera in the air is easy, but underwater the camera calibration is no longer applicable, and underwater calibration is an inappropriate method because it is very inconvenient to calibrate underwater.

Besides, we found that the underwater image was distorted just like we changed a camera. So, this paper presents the imaging principle of the camera. For the camera, the classic model is mainly the projection transformation model of the pinhole camera. There are also many models for pinhole cameras, which are imaging models for cameras in the air. The ordinary camera placed underwater imaging model will change, resulting in very large distortion, which cannot play the role of the camera. And JR Martinez-de[1] proposed a low-cost automation system for fish farming and explained that underwater stereo vision is valuable.

Typically, the stereo calibration of the binocular camera requires a calculation of the internal and external parameters of the camera. In this paper, the stereo matching algorithm based on mutual information which has the accuracy of the global stereo matching algorithm[2]. It adopts the dynamic programming algorithm, so it has the speed of the local stereo matching algorithm. At present, the stereo matching algorithm is improved based on this matching algorithm. Kang Zhang[3] uses a cross-scale cost aggregation approach since the regularization term is independent of the similarity kernel, so various cost aggregation methods can be integrated into the proposed general framework.

2. Underwater Binocular Camera Calibration

The binocular vision system comes from the human visual structure. It can be understood that the camera replaces the human eyes. The binocular vision in this paper consists of two cameras mounted



on the same axis with the same performance. Two images of the same scene are collected at the same time from different angles, the parallax between them is calculated, and the 3D geometric information of the object is recovered based on the parallax principle. So, We need to first calculate the internal and external parameters of the camera under water. However, it is inconvenient to perform calibration underwater. To avoid direct underwater calibration, it can be considered that calibrating in the air and then use it under water.

2.1. Underwater Optical Model

For a camera. We know that the refractive indices of the medium in which the object and the image are n_o and n_i , respectively, and the refractive index of the lens glass is c . The focal length f has different values in different media, f_o represents the focal length of the medium in which the object is located, and f_i refers to the focal length in the medium in which the image is located[4]. See Figure 1 for details.

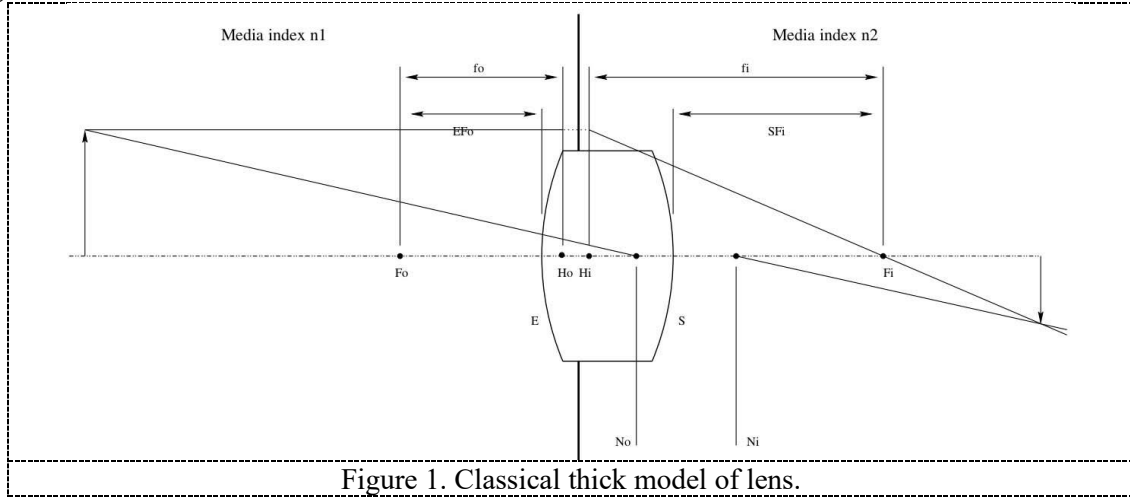


Figure 1. Classical thick model of lens.

The focal length of the camera is determined by the CCD sensor and the optical center. It can be seen in Figure 1 that this distance is equivalent to $N_i F_i$ if the object is at infinity:

$$N_i F_i = N_i H_i + H_i F_i = \frac{n_o - n_i}{k} + \frac{n_i}{k} = \frac{n_o}{k} = f_o \quad (1)$$

Then,

$$f_o = N_i F_i = n_o \frac{r_2}{n_i - n} = n_o \cdot C \quad (2)$$

Where C is a constant. This relationship (2) is our main concern. It can be seen from the equation that the focal length object medium has a direct linear relationship. Because CCD-medium index $n_i = n_{air} = 1$ and r_2 is constant. When the camera is in the air, the refractive index $n_o = n_{air} = 1$ and the focal length of the camera is C . When the camera is underwater, the focal length of the camera is equal to the focal length in the air multiplied by 1.33. We can draw the following two diagrams according to the imaging principle of the camera under the water, as shown in Figure 2. is the light pattern imaged by the camera. So we can try to calibrate the camera based on these relationships.

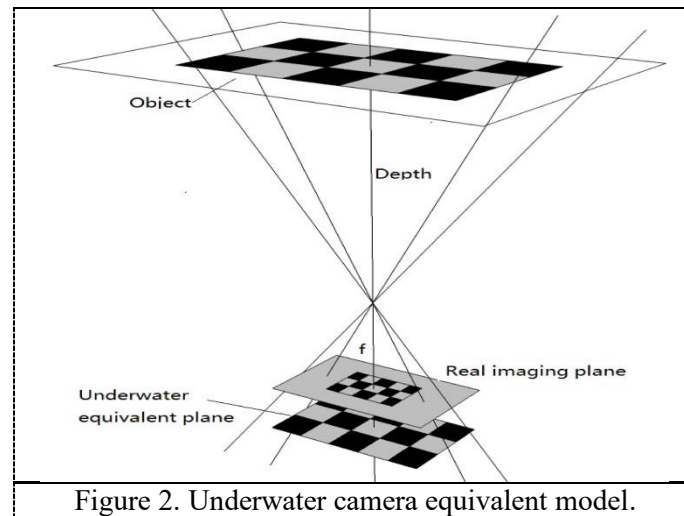


Figure 2. Underwater camera equivalent model.

We can see that for the camera to be underwater, the angle of view becomes smaller, so the same object is not as far away as the camera in the air and the same distance is equivalent to generating pictures at different focal lengths. So the size of the image has changed. So we can use the camera's relationship in different media to calibrate it in the air and use it underwater.

2.2. Binocular Stereo Vision

For a binocular computer vision task, the first thing to do is the calibration. With the calibration, we can get the intrinsic and extrinsic parameters and it has been widely discussed[5]. The intrinsic parameters include the camera focal length f and distortion coefficients. As shown in Figure 3, for any point P in the space projected from the angle of the left camera the image point of the image is P_1 and from the angle of the right camera the image point is P_2 . The position of the P point is only certain, which is the intersection of the ray PP_1 and PP_2 . The distance between the projection centers of the two cameras is the baseline distance b , and the camera focal is f .

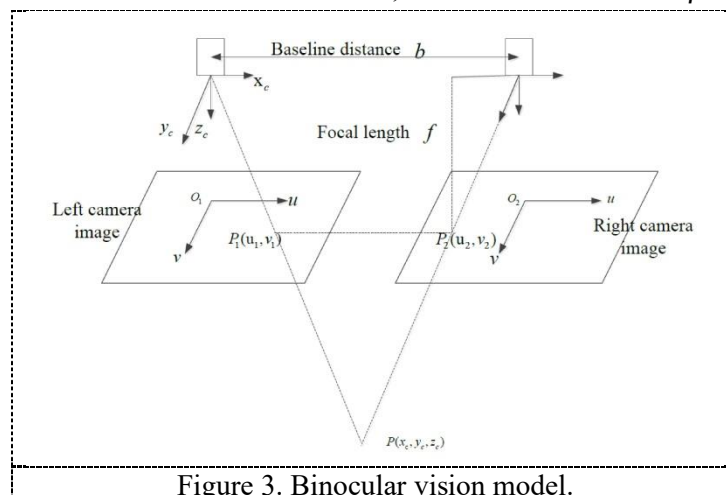


Figure 3. Binocular vision model.

The corresponding coordinates of a point P in the left camera image and the right camera image in the space are P_1 and P_2 respectively. Because the two cameras are on the same plane, Then the point

P has the same vertical coordinates in the camera image, which means $v_1 = v_2$, derived from trigonometric relations:

$$u_1 = f \frac{x_c}{z_c}, \quad u_2 = f \frac{(x_c - b)}{z_c}, \quad v_1 = v_2 = f \frac{y_c}{z_c} \quad (3)$$

Disparity d is defined as the difference between the transverse coordinates of the left and right camera images,

$$d = u_1 - u_2 = \frac{f \cdot b}{z_c} \quad (4)$$

As a result, the coordinates of a point P in the left camera coordinate system can be calculated as follows:

$$z = \frac{b \cdot f}{d} \quad (5)$$

Because the two cameras are on the same horizontal plane, z is the distance between the point P and the camera.

2.3. Stereo matching

The stereo matching is to calculate the disparity d . According to the classification of Scharstein and Szeliski[6], a typical stereo matching algorithm consists of four steps, 1) matching cost calculation. 2) Aggregation of costs, 3) calculation of disparity, and 4) refinement of disparity[7]. In this paper, the SGBM algorithm is used to realize stereo matching. As the semi-global matching algorithm has the advantages of the local matching algorithm and the global matching algorithm.

The SGBM[2] matching algorithm is based on mutual information $MI_{1,2}$, which is defined by the information threshold H_1 and H_2 of two images and their joint information threshold $H_{1,2}$. It is defined as follows

$$MI_{1,2} = H_1 + H_2 - H_{1,2} \quad (6)$$

The information threshold H of a single image is calculated by the probability distribution described by the histogram. The information threshold $H_{1,2}$ of the joint image is calculated by the joint probability distribution of the gray level of the matching image.

3. Experiment and Analysis

In this part, We first calibrated the camera in the air and underwater with the method[5]. And then we used the relationship we got to calculate the parameters of the camera. Finally, we use the SGBM method for stereo matching.

3.1. Calibration in Air

For calibrating a binocular camera in the air. So we use a calibration plate, the length of the square is 2cm, then we verified the experiment according to the feature points and compute the parameters. We took a total of 40 pictures with the left and right cameras in the air. Then, we used matlab to process the images we obtained. For the radial distortion, we choose 3 coefficients and compute the Skew and Tangential Distortion. So we can get the results as shown in Figure 4, Figure 5 and Figure 6.

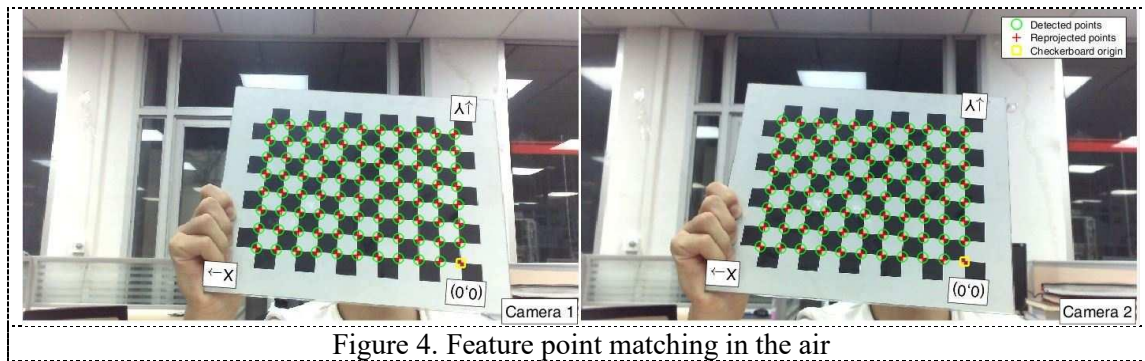


Figure 4. Feature point matching in the air

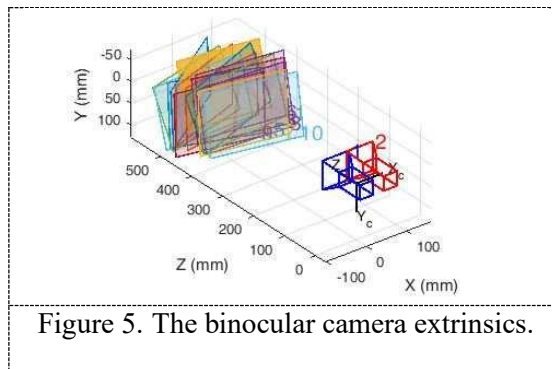


Figure 5. The binocular camera extrinsics.

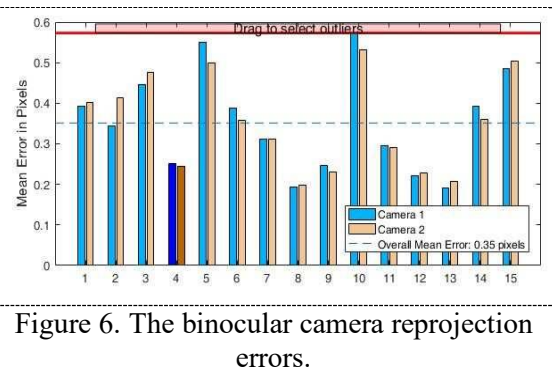


Figure 6. The binocular camera reprojection errors.

We get the internal and external parameters of the binocular camera we have mentioned above as shown in the Table 1.

Table 1. The result of the calibration of the binocular camera in the air.

Parameters	Left camera	Right camera
f_x	1.1369e+03	1.1252e+03
f_y	1.1384e+03	1.1299e+03
u_0	639.2938	661.4008
v_0	369.9685	361.9341

Where f_x and f_y are focal lengths, u_0 and v_0 are pixel coordinates.

3.2. Verification of Underwater Image Calibration

This section contains experiments for calibrating underwater with a binocular camera. We will verify the relationship we obtained above based on the experimental results. In the same way, we packaged the binocular camera in a sealed and transparent box and placed it in water for calibration. We also took 40 photos for calibration, some of which are shown in Figure 7. And we calculated the internal parameters of the binocular camera underwater, as shown in Table 2.

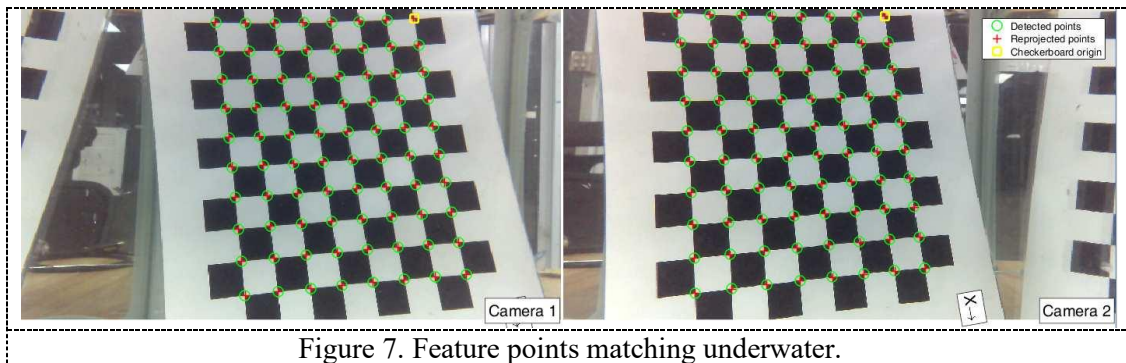


Figure 7. Feature points matching underwater.

Table 2. The result of the calibration of the binocular camera underwater.

Parameters	Left camera	Right camera
f_x	1.5028e+03	1.5018e+03
f_y	1.5077e+03	1.5078e+03
u_0	662.4167	679.6604
v_0	338.2959	315.2423

Table 3. The ratio of the focal length of the binocular camera in water to air.

	f	f_{water}	f_{air}	ratio
Right camera	f_x	1.5018e+03	1.1215e+03	1.3390
	f_y	1.5078e+03	1.1299e+03	1.3344
Left camera	f_x	1.5028e+03	1.1178e+03	1.3444
	f_y	1.5077e+03	1.1192e+03	1.3471

It seems that the theoretical relationship is almost completely satisfied: the distance between the image node and the CCD matrix is multiplied by the water index. Table 3 shows the ratio between the focal lengths of water and air. Considering the focal length uncertainty given by the calibration settings, the ratio is almost 1.333.

3.3. Underwater image preprocessing and stereo matching

We put a box in our transparent glass tank. Two pictures as shown in Figure 8 and Figure 9 which were obtained with our binocular camera. Based on the parameters of the binocular camera we obtained above in the air, we can perform underwater stereo matching.



Figure 8. Picture taken by left camera of the binocular camera.



Figure 9. Picture taken by right camera of the binocular camera.

Then we can use the SGBM algorithm to calculate the disparity. With the disparity, we can draw the disparity map. We use the parameters calibrated in the air to test our ways and the Figure 10 and Figure 11 shows the rectified image and the disparity map.



Figure 10. The rectified image.



Figure 11. The disparity map of the image.

According to the disparity map and the relationship we get, The distance between the object and the camera can be calculated with the equation (5). We place the object 45.6 cm away from the camera. According to the relationship between air and underwater, we use the parameters in the air and get the distance is 45.32 cm which is consistent with our expected results.

4. Conclusions

This work proposed a method with a binocular camera calibration for underwater stereo matching. And experiments showed that our ideas were feasible. We showed an imaging model of an underwater binocular camera and analyzed the underwater imaging model of the camera to obtain the relationship between the underwater pixel coordinate system and the world coordinate system. Besides, we used the SGBM method to perform stereo matching experiments, and calculated the depth information of the image, and obtained satisfactory results. This showed that our work had good guiding significance for underwater applications.

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