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Binocular Vision-based Underwater Ranging Methods

Shuxiang Guo [*1, *3], Shangze Chen[*1, *2], Fagen Liu[1], Xiufen Ye[*1] and Hongbiao Yang [*1, *2]

[*1] College of Automation

Harbin Engineering University
Nangang District, Harbin, Heilongjiang Province, 150001, China

chenshangze@hotmail.com

[*2] Graduate School of Engineering, Kagawa University

[*3] Department of Intelligent Mechanical Systems Engineering
Kagawa University
Takamatsu, Kagawa 761-0396, Japan

guo@eng.kagawa-u.ac.jp

Abstract – **In order to assist the underwater robot working in the underwater environment, underwater ranging method is researched based on the binocular vision. Precise calibration of the binocular vision is the most important. In this paper, a novel underwater binocular vision calibration method for both monocular camera and binocular camera. Then through experiments, the internal and external parameters are obtained. And according to the distortion in the underwater binocular image, the image is rectified and the matching method are conducted, and thus the parallax image is got. Finally, the distance ranging is done and the experiment show the better measure precision.**

Index Terms – Underwater Binocular Vision, Underwater Stereo Calibration, Visual Distance Ranging, Underwater Moving Targets Detection

I. INTRODUCTION

With the development of human economy, land resources have been difficult to satisfy the needs of human beings. Therefore, rich marine resources are urgent to be exploited. How to effectively develop and utilize the ocean resources has become a difficult problem. So the underwater robot technology has more and more research [1]-[3]. Guo Laboratory of Kagawa University works on the underwater spherical robot and has a certain result [4]-[21].

Computer vision technology [22]-[24] is an integral part of the robot system. It holds a dominant position. Many machine vision systems are based on the framework to build [25][26]. Binocular stereo vision system is also based on it. This theoretical framework provides a theoretical basis for binocular stereo vision. Compared with the monocular vision, the binocular vision can provide various information of three-dimensional space, such as ranging [27][28], which can provide more precise information for the control of robot.

As the 'eyes' of the robot, more and more researchers have begun to focus on the research of binocular vision. Underwater binocular vision system is used for underwater robot visual AIDS, helping underwater vehicle for underwater operation. However, due to the particularity of underwater environment, the progress of research for binocular stereo vision underwater is very slow. By contrast, binocular vision is easier to study on land. The precision of underwater calibration algorithm is the most important for the binocular vision.

Monocular camera calibration is the first step of binocular vision calibration. A typical monocular vision calibration method is two-procedure calibration method proposed by Tsai [29]. It can solve most of the parameters through linear equation, and then obtain the rest of the refining parameters through iterative algorithm. However, this algorithm considers only one distortion parameter and cannot solve the problem of distortion effectively. Another is two plane calibration method proposed by Zhengyou Zhang [30]. It can solve the internal parameters of the camera through three different attitude images. But it considers only two radial distortion parameters and does not consider tangential distortion parameter. In view of the camera tangential distortion and radial distortion, mathematical model is set up in this paper.

Traditional binocular vision calibration includes the internal parameters and the rotation and translation matrix. This algorithm is also linear and the error of external parameters is very big. In this paper, we proposed a non-linear algorithm to solve the problem.

The rest of this paper is organized below: At first, there is a study on the underwater calibration for binocular cameras under water. Then we study on the three-dimensional correction of underwater image. Besides, this paper implements various stereo matching algorithm. Then ranging experiment is implemented. The last part is conclusions.

II. UNDERWATER CALIBRATION

A. *The framework of underwater binocular vision system*

The underwater binocular visual ranging system consists of 5 main steps [31][32], as shown in Fig. 1.

The first step is image acquisition. The binocular camera is fixed in a best relative position. And because of the waterproof processing, the image quality is worse than on land. The second step is camera calibration by using two two-dimensional images to get a three-dimensional parameter. And next step is the feature extraction. This is an important step. Through the analysis of different image features, features with strong robustness are determined to be used in matching step. Then it can enhance these features, we preprocess the images by using the methods such as image denoising, contrast enhancement, edge character enhancements. The next step is the image matching. This is the most important and difficult thing to do. Its purpose is to get the corresponding points of three-dimensional space in the binocular camera images. The last step is vision ranging or three-dimensional reconstruction. This is a reverse validation process of calibration.

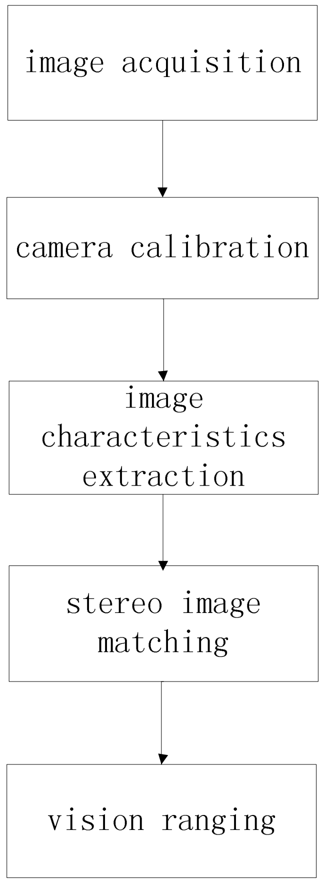


Fig. 1 The framework of underwater binocular vision system

B. Improved underwater calibration algorithm

Camera calibration in the water is more difficult than on land. Although the two cameras are the same, the actual camera parameters will be a little different. Therefore, it is necessary for camera calibration. There are 2 main steps for the binocular calibration process. One is a monocular camera parameter calibration. The other is the position relationship between the two cameras for stereo calibration. In this paper, an improved method is proposed for under water calibration.

The monocular camera projection model is built at first. Then we establish a coordinates system of calibration. The coordinates systems including the world coordinates system "(X_w, Y_w, Z_w)", camera coordinates system "(X_e, Y_e, Z_e)", image physical coordinates system "(x, y)" and the phase coordinate system "(u, v)". The purpose for it is to link the world coordinate system and the phase coordinate system, shown in Fig. 2.

The corresponding relationship between the world coordinates system and the phase coordinate system is shown in the formula (1).

$$Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & 0 & u_0 & 0 \\ 0 & \beta & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R_{3\times3} & t_{3\times1} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} = M_1 M_2 \hat{x}_w = M \hat{x}_w \quad (1)$$

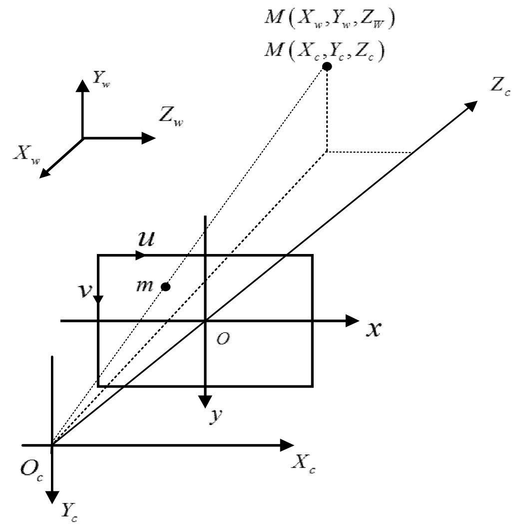


Fig. 2 Coordinates system of calibration

Where "$a = \frac{f}{d_x}$", "$\beta = \frac{f}{d_y}$", M_1 is internal parameters of the camera, M_2 is the external parameter matrix.

The double calibration plane method was proposed by Zhang Zhengyou used two-dimensional checkerboard as the calibration plate. The board image is collected in different viewing angle, so that the 5 internal parameters and 2 radial distortion parameters could be calibrated. In the progress of solving calibration parameters, let the spatial coordinate "$z_w = 0$". And the origin is based on the upper left corner of the calibration plate. Then the Matrix "M" in the formula (1) is transformed into a homography matrix "H". Besides, the rotation matrix "$R = [r_x, r_y]$". Then we can get the formula (2).

$$H = \begin{bmatrix} h_1 & h_2 & h_3 \end{bmatrix} = \lambda M_1 \begin{bmatrix} r_x & r_y & t \end{bmatrix} \quad (2)$$

In this formula, λ is a proportionality coefficient. It can establish the relation between the corner position and pixels on the calibration plate through the matrix "H". It is possible to obtain the parameters of the camera by calculating a plurality of matrices in different fields of view. Then it can obtain a matrix by the maximum likelihood estimation method.

For a single camera's parameters calibrating, Mr. Zhang only considers two radial distortion parameters, but no tangential distortion. On the basis of the Zhang Zhengyou calibration algorithm, tangential distortion parameters are added to make the calibration model more complete.

When the five internal references and all external parameters have been received, the image coordinates can be obtained without distortion at the projection formula (1). And the actual image coordinate is "(u', v')". According to the previous distortion model analysis, two constraint equations can be obtained at any point on the image, as shown in the formula (3).

$$\begin{bmatrix} (u-u_0)r^2 & (u-u_0)r^4 & 2(u-u_0)xy & (u-u_0)(r^2+2x^2) \\ (v-v_0)r^2 & (v-v_0)r^4 & (v-v_0)(r^2+2y^2) & 2(v-v_0)xy \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \end{bmatrix} = \begin{bmatrix} u'-u \\ v'-v \end{bmatrix} \quad (3)$$

For "n" images, each image has "m" detection corners. It can constitute "$2m \times n$" equations, which written in matrix form is "$XD = x$". Using the least squares method as shown in formula (4), 4 distortion parameters can be solved.

$$\begin{cases} D = (k_1, k_2, p_1, p_2) \\ D = (X^T X)^{-1} X^T x \end{cases} \tag{4}$$

Then optimization of all internal parameters and distortion parameters are obtained by using maximum likelihood estimation. If the imaging points are subjected to noise independent and evenly distributed, the maximum likelihood estimate can be obtained from the minimum value of the cost function. As the formula (5) is shown.

$$F = \sum_{i=1}^{n} \sum_{j=1}^{m} \left\| m_{ij} - \widehat{m}_{ij}(M_1, D, R_i, t_i, M_{ij}) \right\|^2 \tag{5}$$

In this formula, M_{ij} is the chessboard corner space coordinate. R_i and t_i are the rotation and translation matrices of the No. i chessboard image. M_1 is the camera internal parameter. And D is the distortion parameter. $\widehat{m}_{ij}$ is the coordinate of the ideal chessboard corners based on the estimated parameters. m_{ij} represents the actual chessboard image corner coordinate. The collected "n", "m" are the number of corners detected in the image. Finally, nonlinear optimization algorithm is used to substitute into the initial camera inside and outside the parameters and distortion parameters and then it repeats iterations until the convergence. Then the minimum value of the cost function "F" can be obtained so that the final internal camera parameters and distortion parameters are obtained.

Binocular camera calibration includes calculating internal parameters in two cameras and determining the rotation and translation matrix between two cameras. It can set the external parameters of left and right cameras in the same coordinate system are "(R_l, T_l)" and "(R_r, T_r)".Then we can get the relationship matrix "$[R \quad T]$" of two cameras, as shown in formula (6).

$$\begin{cases} R = R_r R_l^{-1} \\ T = T_r - R_r R_l^{-1} T_l \end{cases} \tag{6}$$

For "n" pieces of calibration images, we can get "n" pairs of left and right camera external parameters. "n" sets of the stereoscopic calibration parameters can be calculated by the plates are at different positions. The traditional method of solving three-dimensional parameters is to use the mean method, as shown in formula (7).

$$(R,T) = \sum_{i=1}^{n} (R_i, T_i) / n \tag{7}$$

Because this method belongs to the linear method, the timeliness is good. When calibrated under water, there is a large error parameter because of the unclear picture, harsh underwater environment, and some else. The linear method for these larger errors can't be well removed and produce a large error accumulation so that it could affect the calculation accuracy. In this paper, a nonlinear cost function method is proposed to solve the three-dimensional parameters of the camera by using the global optimization algorithm. Then the final three-dimensional parameter is calculated. For some of the larger errors will not produce accumulation, it can well eliminate large errors. Specifically, the distance between the coordinate points of the coordinates of the right imaging plane from the coordinate points in the left imaging plane is calculated from the distance error of the coordinate points corresponding to the right plane. The formula is shown in formula (8).

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \left\| m_{ij}^{R} - m(m_{ij}^{L}, R, T, M_1^{L(R)}, M_2^{L(R)}, D^{L(R)}) \right\|^2 \tag{8}$$

In this formula, m_{ij}^R in the front represents the chessboard corner coordinates on the right view. m_{ij}^R in the rear represents the corner coordinates of the corresponding left view through the back projection to the right view. According to this, it is possible to convert the calibration parameter iterative optimization process into a non-linear minimization problem. The iterative optimization calculation is carried out by bringing the initial calibration value calculated in equation (6) into equation (7). Then it can get the final accurate calibration value. The iterative algorithm used in this paper is the LM algorithm. And finally the global optimal solution can be obtained. With precise stereo calibration parameters, line correction, stereo matching and other research can be carried out.

III. EXPERIMENTS

A. Experiments of Calibration

The binocular cameras are shown in Fig. 3. They are installed in the same bracket and waterproofed so that they can work underwater. Through the improved calibration method, we get the calibration parameters of the binocular camera shown in Table I and stereo calibration parameters shown in Table II.

The calibration error is less than 0.3945 and satisfy the requirement of experiment. In the meantime, we can verify the effectiveness of the calibration results through focuses. We calculate the ratio of underwater focus to land focus of both left camera right camera respectively, we get the ratios 1.3346 and 1.3543, respectively. These results are approach the value of 1.3333 which is the refractive index of water medium relative to air medium.

B. Stereo Rectification of the Underwater Image

After finishing the above work, the binocular camera stereo calibration parameters are obtained. It is possible to rectify the left and right view so that the output image lines are aligned. The process of stereo rectification of the underwater image shown in Fig. 4. An example of calibration is shown in Fig. 4. After the stereo rectification, all the corresponding pixels are on the same horizontal line.

In the process of experiment, we use the checkerboard pattern as a calibration board. The checkerboard pattern has angle points for 9*7. The size of the square is 20*20(mm).

Fig. 3 Waterproof binocular cameras

Table I Left and right camera underwater calibration parameters

	Left camera	Right camera
Internal parameter matrix	$\begin{pmatrix} 605.5 & 0 & 319.5 \\ 0 & 605.5 & 239.5 \\ 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 610.8 & 0 & 319.5 \\ 0 & 610.8 & 239.5 \\ 0 & 0 & 1 \end{pmatrix}$
Effective focal length	$(605.5 \quad 605.5)$	$(610.8 \quad 610.8)$
Reference point	$(319.5 \quad 239.5)$	$(319.5 \quad 239.5)$
Distortion parameter	$(-0.13478 \quad 0.17409 \quad -0.00326 \quad 0.00048)$	$(-0.1901 \quad 0.2320 \quad -0.00264 \quad 0.00039)$

Table II Underwater stereoscopic calibration parameters

Matrix R	$\begin{pmatrix} 0.9977 & 0.0620 & -0.0278 \\ -0.0619 & 0.9981 & 0.0051 \\ 0.0281 & -0.0034 & 0.9996 \end{pmatrix}$
Matrix T	$(100.317 \quad 0.2815 \quad -5.3866)$

The board image is acquired at different angles and we can calibrate 5 internal parameters and two radial distortion parameters [33]. On the basis of this, the tangential distortion parameter is also rectified. This step can acquire the complete calibrated model in order to perform three-dimensional reconstruction so that the robot can get three-dimensional information. Then we use the least square method to estimate the distortion parameters. According to the distortion parameters, the camera's internal and external parameters can make the maximum likelihood estimation. Then the camera's parameters have been optimized.

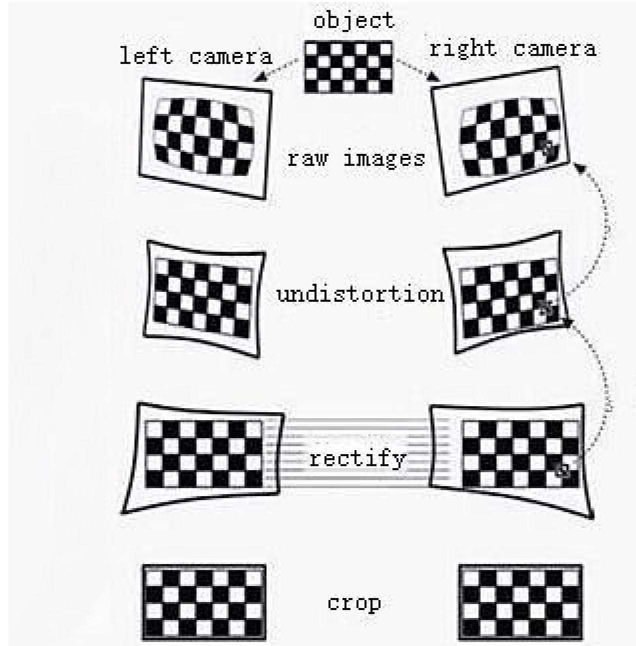
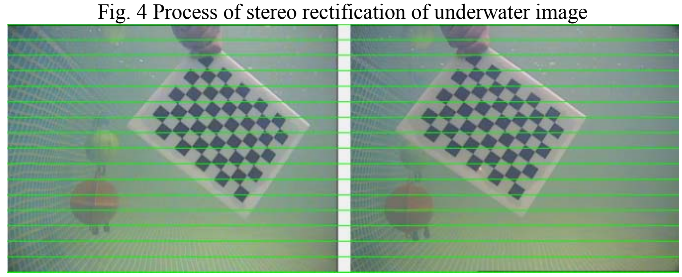
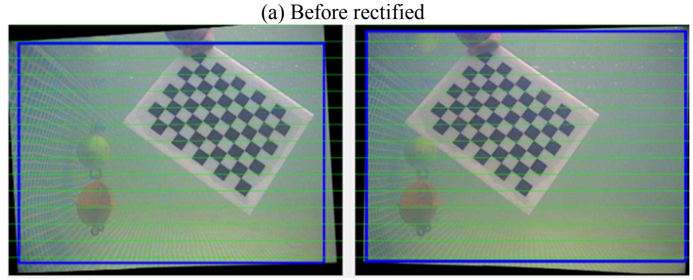


Fig. 4 Process of stereo rectification of underwater image

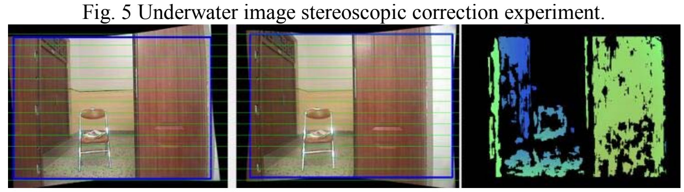


(a) Before rectified

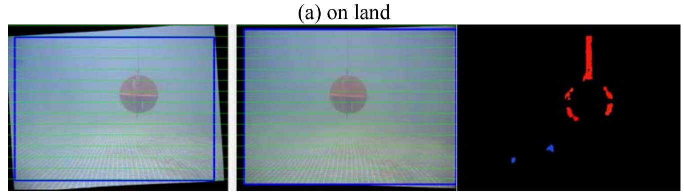


(b) After rectified

Fig. 5 Underwater image stereoscopic correction experiment.



(a) on land



(b) under water

Fig. 6 BM algorithm parallax image.

C. Underwater stereo matching study

The stereo matching is very important in the whole binocular vision system. This study can be divided into direct matching algorithm and indirect matching algorithm [34][35]. Its aim is to find the corresponding pixels in the two images under different perspective. So the underwater stereo matching is the foundation of the binocular visual ranging.

The stereo matching algorithm includes 3 parts. They are Matching constraint, Similarity measure and matching search strategy. In order to ensure the precision of the parallax image, this paper adopts bidirectional matching (BM) algorithm. This method can get accurate matching points. The first step is the image preprocessing. This step can normalize the image brightness and enhance the image texture. Then we use the sum of absolute differences(SAD) to match searching along the horizontal pole line. And finally it's smooth to get rid of the bad matching points. Through the above operation, we can get parallax images on land and under water respectively, as shown in Fig. 6.

This algorithm could get dense parallax images. But it's darker under water than on land. The image is blurred. And the texture feature is less obvious than that on land. So the parallax image is poor quality. But this method gets the dense parallax in the ball part. However, the background region has no useful information. So this method is suitable for the underwater target ranging in this paper.

III. UNDERWATER TARGET RANGING

After finishing the above work, we get the parallax images. Then we can get the three-dimensional depth information of space objects through the calculation of matrix. This paper uses the function "reProjectImageTo3D" from the OpenCV, so that the parallax image can be matrix computed. Then we can get the three-dimensional coordinates of space object.

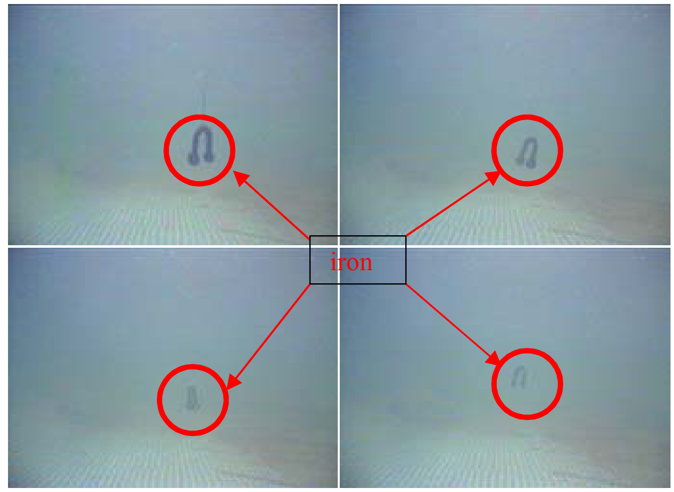
On the basis of the relationship between the target and the camera. It can be divided into the static and dynamic background motion detections. This paper only does research into the static background. And We use the triangle ranging principle for getting the information of spatial point of three-dimensional to calculate the distance.

The error of ranging by iron ranging experiments, as shown in Fig. 7. The results are shown in Table III.

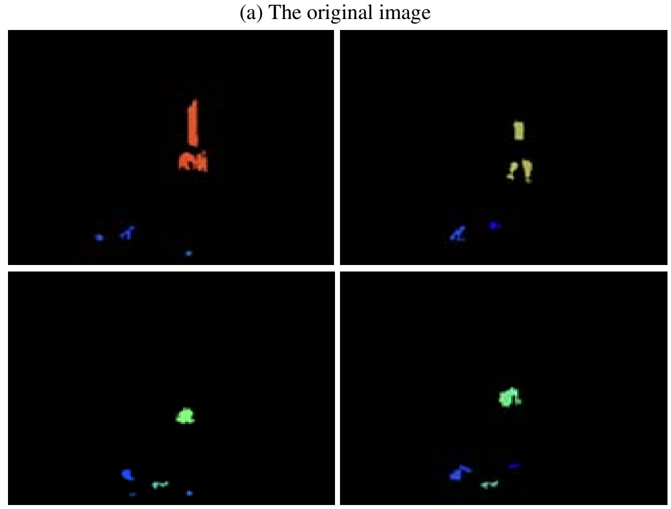
The gray-scale parallax image is transformed into a pseudo-color disparity parallax image. The color turns from red to green, then into blue. This indicates that the object is farther and farther from the camera. The experimental results show that although this method can't achieve the same accuracy as land, the error is less than 5%. The accuracy is high.

IV. CONCLUSIONS

Underwater environment is worse and there exists the strong and weak light. The ranging effect of the binocular stereo vision is very good either under the strong and weak light. It's better than Gaussian mixture model in many aspects. This technology may use for search and rescue work in the future.



(a) The original image



(b) The parallax image

Fig. 7 Underwater iron ranging experiments.

Table III Ranging experiment of iron piece

Actual range (cm)	Measuring range (cm)	Error（%）
94	98	4.3
126	130	3.2
158	163	3.1
190	196	3.2

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