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Research on the calibration technology of an underwater camera based on equivalent focal length

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ABSTRACT

Calibration is one of the most crucial and inevitable processes in vision technology, whose performance can significantly affect the measurement accuracy of the vision system. To compensate for coefficients of water factors, the conventional calibration technology for the underwater camera generally introduces several higher-order distortion coefficients, which, unfortunately, suffer poor stability, low efficiency, as well as computational complexity. To overcome these drawbacks, a newish calibration method based on equivalent focal length is proposed in this paper. The method takes the refraction distortion of water factors as equivalent focal length changing to cause. Applying the invariance principle of linear perspective projection, distortion correction should first be carried out. Subsequently, the internal and external parameters of the camera are calculated by using Zhang's calibration method based on the camera linear model, which simplifies the process of underwater camera calibration. Finally, the experimental results show that the calibration method can effectively improve the accuracy of the underwater camera.

1. Introduction

Cameras can be used as non-contact sensors, and with the development of computer technology, as well as requirements for a high degree of intelligence, visual technology is widely used in various fields. Importantly, calibration is an indispensable step in using visual technology systems. If we want to obtain positional information of an object in space by a visual system, it is necessary to predict some parameters of the camera itself; this parameter acquisition is known as the calibration process, so that the final measurement accuracy of the camera is determined by the result of its calibration.

At the present, commonly used camera calibration methods generally fall into three categories as follows: traditional camera calibration methods, self-calibration methods, and active visual calibration methods [1]. When traditional calibration methods use a calibration plate as a reference object, a system of equations is established by a corresponding relationship of spatial points for the calibration plate, and then a mathematical optimization method is used to solve the equations; finally, the camera's internal and external parameters are obtained. The main calibration methods are as follows: the direct linear transformation method (DLT) [2]; the two-step method based on radial restraint (Tsai two-step method) [3]; the camera biplane model [4]; and Zhang's calibration method [5]. Since Zhang's camera calibration method was presented in 1999, camera calibration methods and theories have matured gradually, and now all camera calibration methods are based on this theory as a basis for improvement. Otkovic I et al used a neural network algorithm for camera calibration [6–9]. Kukelova et al added two constraints to the base matrix of the calibration model, which can improve the speed of the camera calibration process [10,11]. Li Guangle modified Zhang's calibration method based on the vanishing point principle, whereby the LM algorithm was used to simplify Zhang's calibration process, and the experiment showed that the precision of camera calibration was improved [12,13]. Zhao Yuntao et al used the step calibration method based on the geometric characteristics of a ball with a maximal calibration error of 5% [14,15].

From past studies, we already know that the camera calibration method has been studied and improved, according to different application environments and requirements, then various algorithm calibrations appear; however, there is no universal calibration method, and each method has advantages and disadvantages. Therefore, it is necessary to design an appropriate calibration method according to these specific problems; for example, the underwater calibration method cannot be directly applied on land. Furthermore, researches on various calibration methods are mainly to improve the efficiency and robustness of calibration methods at present, and vision calibration

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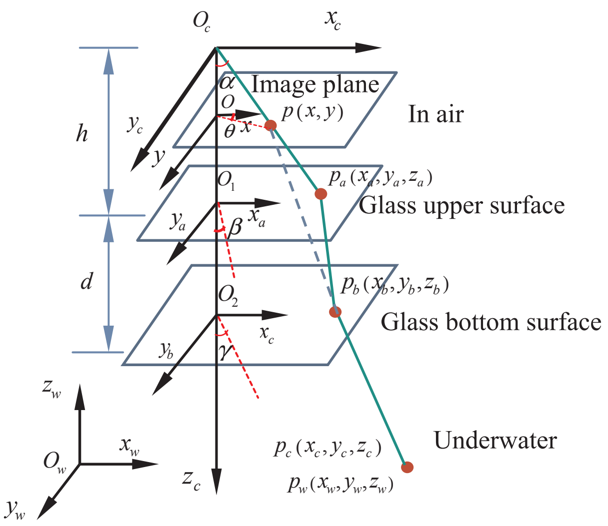


Fig. 1. Light path of imaging principle underwater.

technology is rarely studied for practical application to the underwater environment.

2. Problem description

Since the visual system is to function in an underwater environment, in the process of underwater imaging, the light must pass through water/glass/air/lens, which are a variety of different mediums, to finally reach the image plane for imaging; thus, the refraction phenomenon will occur when the light goes through these different kinds of mediums, as shown in Fig. 1.

To set a target p in three-dimensional (3D) space, $p_w[x_w,y_w,z_w]$ is a coordinate point of 3D space in a world coordinate system, and $p_c[x_c,y_c,z_c]$ is a coordinate point of a camera coordination system. By the law of Snell refraction, light through different kinds of medium will produce different angles of refraction, according to the geometric relations based on the optical path in Fig. 1. The point $p_c[x_c,y_c,z_c]$ in the camera coordinate system can be expressed by:

$$\begin{cases} x_c = [h\tan\alpha + d\tan\beta + (z - h - d)\tan\gamma]\cos\theta \\ y_c = [h\tan\alpha + d\tan\beta + (z - h - d)\tan\gamma]\sin\theta \end{cases} \tag{1}$$

where $\alpha = \arctan\left(\frac{\sqrt{x^2+y^2}}{f}\right)$, $\theta = \arctan\left(\frac{y}{x}\right)$, x and y is a coordination point in the image plane coordination system after point p is refracted underwater, and f is the focal length of the lens.

Applying Snell's law refraction, we can produce the formula:

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_g}{n_a}, \frac{\sin\gamma}{\sin\beta} = \frac{n_g}{n_w} \tag{2}$$

From above formula, we find that:

$$\beta = \arcsin\left(\frac{n_a}{n_g}\sin\alpha\right), \gamma = \arcsin\left(\frac{n_a}{n_w}\sin\alpha\right) \tag{3}$$

where n_a,n_g, and n_w are refractive indices of air, glass, and water, respectively.

According to the results derived above, x_c,y_c and z_c of p point coordinates of the above formula were converted to x and y of the homogeneous transformation matrix to deduce the formula:

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{h/f + (z - h - d)\tan\gamma \times 1/\sqrt{x^2+y^2}} & 0 & 0 \\ 0 & \frac{1}{h/f + (z - h - d)\tan\gamma \times 1/\sqrt{x^2+y^2}} & 0 \\ 0 & 0 & 1/z_c \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \tag{4}$$

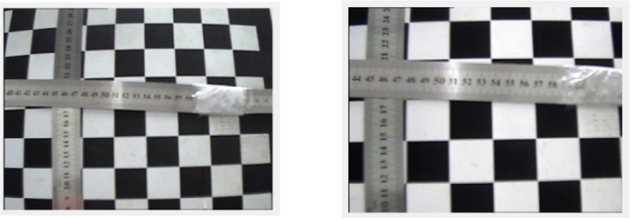
Formula (4) is obtained by transformation between the camera coordinate and image coordinate systems in the underwater environment, and combining the imaging plane coordinate system with the pixel coordinate system on land, as well as the relationship between the world coordinate system and the camera coordinate system, produces a nonlinear model of an underwater camera, which has many unknown parameters and a large number of calculations for calibration.

According to the above underwater camera model, the traditional method of dealing with an underwater camera calibration is taking the water/glass/lens/air combination as a compilation of several lenses, of which the resulting distortion is equivalent to a higher-order distortion compensation correction calibration. Moreover, according to the actual underwater optical path imaging geometric model, the underwater image is converted into a land image, and then the calibration calculation is performed [16–19]. Analysis of these literatures shows that equivalent higher-order distortion compensation can be corrected by introducing higher-order distortion compensation underwater. This processing method will not compensated satisfy such as water medium with a large distortion, which leads to decreased measurement precision, and if the distortion parameter is introduced too much, the stability of the algorithm is decreased. Meanwhile, the underwater image is converted into a corresponding image on land, the land image inverse geometry formed by the actual optical path, and then the conventional water calibration method is used; however, the image conversion process requires large calculations and inverse projection, for which it is very difficult to ensure accuracy. In essence, these methods are converted to the terrestrial environment calibration, which involves a large number of calibration parameters and calculations, increasing the difficulty and complexity of the underwater camera calibration method, which is not conducive for the technology of underwater camera development.

3. Treatment method for influence the water medium

Fig. 2 shows two images obtained by fixing a calibration plate on land and underwater, respectively. These images have the same position and distance conditions of the camera.

As shown in Fig. 2, the imaging range of the target is different between these two images, whereby the imaging range of the underwater target is smaller than that for land imaging. This phenomenon can be regarded as a change in the visual field of the two images, which means that the underwater field of the camera is smaller than that of the land



(a) On land

(b) Underwater

Fig. 2. Comparison of image changing.