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Study on the reconstruction method of stereo vision in glass flume

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ABSTRACT

In three-dimensional reconstruction experiments based on stereo vision theory in a glass flume, there is usually more than one medium in the travel path of the light, such as air, glass and water. These media not only degrade image quality, but also change the light route. Large errors are generated if the effects of these media are ignored. To solve the problems of media effects, a new method of object reconstruction for the glass flume is proposed, based on computer vision theory and laws of refraction. Firstly, the light refraction effects are analyzed and a coordinate correction formula is developed. Secondly, correction parameters are obtained based on a stereo vision method to correct the coordinates of a target point. Finally, model experiments in glass flume are described and the errors are analyzed. The experimental results show that the proposed method is effective in correcting refraction distortion, and improves the accuracy of three-dimensional reconstruction of target points.

1. Introduction

Measurement methods based on computer vision are untouched measurement techniques with high accuracy. These forms of measurement mainly rely on the methods of digital image analysis, which make it suitable for glass flume model experiments. Thus, they have been widely used in the ocean engineering field. Many experiments have been made in glass flumes in recent years – for example, for vision techniques that locate the accurate positions of moving objects, and to study the deformation of structures. These applications include six degrees-of-freedom (6-DOF) motion measurement, particle image velocimetry (PIV) and particle tracking velocimetry (PTV), among others. Many related studies have been reported in the literature [1–7].

However, the media effect is usually ignored in research and applied procedures. This factor is negligible for experiments conducted in air, but is significant for experiments in a glass flume. When cameras outside the flume take photographs of the target objects, the light travels through at least three media: air, water and glass. Since these affect the geometrical relationships of the image, the reconstruction methods differ from those used for experiments in air [8–10]; however, few studies of this problem have been reported.

In some flume experiments, the optical axis of the camera is perpendicular to the glass flume, and refraction is ignored or regarded as optical distortion in the calculations. This approach is usually used in PIV and PTV exiperiments. The approach utilizes the vertical imaging principle and computation is mature in camera calibration, but the measurement result is valid only for a small-scale field.

In other experiments, in order to make camera position flexible, an optical prism is used to correct refraction distortion without changing the calculation process. When measuring objects in this way, different experiments may need different prisms, making the operation very complicated and more costly. Refractive index matching is used for distortion correction in some experiments [11,12], most commonly in microscope-based analysis; due to the cost problem and amount of disturbance, however, this approach is difficult to apply to large-scale measurements and these physical methods may limit the application scope of vision technology.

To date, no appropriate method is available for reconstructing target objects in a glass flume. In this work, we improve the experimental convenience through changing the vision reconstruction algorithms. Firstly, we examine the refraction routes of reconstruction experiments in a flume, then derive the geometrical relationship between the true position and the pseudo-position of an object. A new reconstruction method for flume experiments is also proposed based on stereo vision theory. The last part of the paper describes model experiments designed to evaluate the performance of the proposed algorithm.

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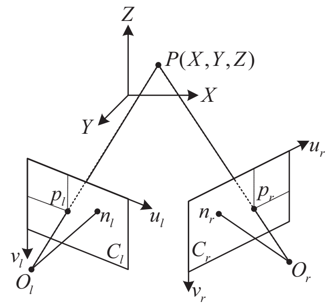

Fig. 1. Reconstruction theory of stereo vision (binocular vision).

2. Reconstruction method based on stereo vision

To derive the 3D coordinates of an object using vision theory, images are captured by two cameras at different viewing angles to the object. In Fig. 1, $P(X, Y, Z)$ is a point in space; subscripts l and r indicate left and right view; p_l and p_r and are image points of P in different image planes; and O_l and O_r are the optical centers of the two cameras. Target P is located at the intersection of projected lines $O_l\,p_l$ and $O_r\,p_r$.

To calculate the coordinates of P, the cameras must first be calibrated to determine the necessary intrinsic and extrinsic parameters [13]. The relationship between the 3D point P and its projection $p(u, v)$ in the image coordinate system is given by

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & \gamma & u_0 & 0 \\ 0 & \beta & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}, \tag{1}$$

where s is an arbitrary scale factor. The first matrix on the right-hand side is the camera intrinsic matrix in which (u_0, v_0) are the coordinates of the principal point; α and β are the scale factors on the image u and v axes; and γ is a parameter describing the skewness of the two image axes. The middle matrix on the right-hand side is the camera extrinsic matrix, in which R and T are the rotation and translation which relate the world coordinate system to the camera coordinate system.

In practice, especially using industrial cameras, γ in Eq. (1) is usually ignored. The camera parameter matrix M is defined as Eq. (2):

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix} = \begin{bmatrix} f/S_x & 0 & u_0 & 0 \\ 0 & f/S_y & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}. \tag{2}$$

In Eq. (2), f is the focal length; S_x and S_y are the pixel dimensions of two axes. For a point pair in different images, the relationship between 2D points and their corresponding 3D points is expressed as

$$\begin{cases} m^l_{11}X+m^l_{12}Y+m^l_{13}Z+m^l_{14} - m^l_{31}u_lX - m^l_{32}u_lY - m^l_{33}u_lZ = u_lm^l_{34} \\ m^l_{21}X+m^l_{22}Y+m^l_{23}Z+m^l_{24} - m^l_{31}v_lX - m^l_{32}v_lY - m^l_{33}v_lZ = v_lm^l_{34} \\ m^r_{11}X+m^r_{12}Y+m^r_{13}Z+m^r_{14} - m^r_{31}u_rX - m^r_{32}u_rY - m^r_{33}u_rZ = u_rm^r_{34} \\ m^r_{21}X+m^r_{22}Y+m^r_{23}Z+m^r_{24} - m^r_{31}v_rX - m^r_{32}v_rY - m^r_{33}v_rZ = v_rm^r_{34} \end{cases}, \tag{3}$$

where l and r are defined as above.

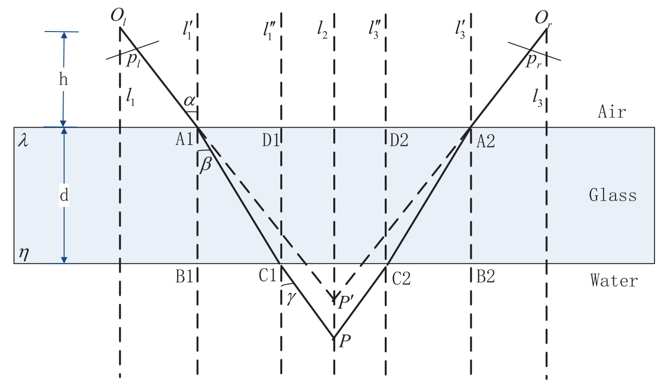

Fig. 2. Imaging light route.

3. Refraction effect of media in a flume

To ensure that the flow field is not disturbed, the cameras must be outside the flume; the image light will then pass through air, glass and water. The light path in the experiment is shown in Fig. 2.

In Fig. 2, O_l is the optical center of the left-hand camera; O_r is the optical center of the right-hand camera; h is the distance between the left-hand optical center and the glass surface of the flume; d is the thickness of the glass; p_l and p_r are the image points of P in the left-hand and right-hand images; P' is the point reconstructed from p_l and p_r; λ and η are the outer and inner surfaces of the glass; A_1, A_2, C_1, C_2 are the intersections of the image light and glass surface; and l_1, l_1', l_1'', l_2, l_3, l_3', l_3'' are lines normal to the glass.

Because of refraction effects, P and P' are not the same points. The refractive indices of air, glass and water are n_{air}, n_{glass} and n_{water}, where $n_{air}(1.0003) < n_{glass}(1.3333) < n_{water}(1.5000)$. Thus P' is closer to the observation position than$P$. In order to determine the true position P, the pseudo-position P' must be modified.

4. Correction method for refraction distortion

Firstly, the glass thickness is assumed to be fixed. A parallel relationship $\lambda//\eta$ is defined in Fig. 2. P and P' are collinear according to their geometrical relationship, which is simply proved as follows:

$\because P \in [O_lA_1B_1C_1]$, $P' \in [O_lA_1B_1C_1]$, $P \in [O_rA_2B_2C_2]$, $P' \in [O_rA_2B_2C_2]$ and $[O_lA_1B_1C_1]\perp\lambda$, $[O_rA_2B_2C_2]\perp\lambda$, $P \in l_2$, $l_2\perp\lambda$ $\therefore P' \in l_2$. So P and P' are collinear in l_2.

To deduce the correction formula, the coordinate system is then defined with the $x-y$ plane on the glass surface. Let $O_l(X_0, Y_0, Z_0)$ be the optical center of left-hand camera; $P(X, Y, Z)$ is the real position of the target; $P'(X_w, Y_w, Z_w)$ is its pseudo-position. In Fig. 2, the relationships $X = X_w$ and $Y = Y_w$ are readily found. In addition, Eq. (4) is deduced from the geometrical relationship in Fig. 2:

$$Z-h-d=\left(\sqrt{(X_w-x_0)^2+(Y_w-y_0)^2}-h\cdot tg\alpha-d\cdot tg\beta\right)\cdot ctg\gamma. \tag{4}$$

Defining the refractive ratios as n_1 and n_2, with $n_1 = \sin\alpha/\sin\beta$, $n_2 = \sin\beta/\sin\gamma$, we can obtain the equations from Eq. (5) to Eq. (7):

$$tg\alpha = \sqrt{(X_w-X_0)^2+(Y_w-Y_0)^2}/(Z_w-Z_0), \tag{5}$$

$$tg\beta = \sin\alpha/\sqrt{n_1^2-\sin^2\alpha}, \tag{6}$$