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Optical-path-difference analysis and compensation for asymmetric binocular catadioptric vision measurement

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ABSTRACT

In order to determine the influence of optical path difference (OPD) in an asymmetric binocular catadioptric system, we analyzed a production law of unequal optical paths and modified a catadioptric stereovision structure. Firstly, the measurement problem caused by the OPD is analyzed based on a traditional asymmetric binocular catadioptric structure. Secondly, the reflective mirror with a shorter optical path is modified to a curved lens to compensate for the OPD. The mathematic model with an aplanatism is established in the traditional asymmetric structure. Finally, a modified design of the traditional prototype is presented depended on a planar mirror and a curved lens. Experimental results show that the demonstrated structure without the OPD is more effective for improving the measurement accuracy.

1. Introduction

With rapid developments of computer vision and stereoscopic imaging technology, stereovision systems have been widely used in various applications for detecting the depth of specific objects in hazardous atmospheres [1–4]. Recently, stereo vision sensors have been divided by type, into traditional binocular measurements [5–7] and catadioptric binocular determinations [8–11]. The applications of traditional binocular systems are limited, owing to their structure and the problem of synchronization of image acquisition with two independent cameras [12]. Compared with the traditional method, catadioptric stereovision technology is considered to be more practical and accurate, because of its small structure required and cost effectiveness. As an alternative to multiple camera techniques, methods based on catadioptric stereovision systems using a single camera have been proposed. Chen et al. [13] proposed a binocular parallax-based single-lens stereo acquisition technique and designed a double-symmetric prism to be placed in front of a single camera. Pan et al. [14] designed a microscopic stereo vision system using a diffraction grating. Lim et al. [15] proposed a simple geometrical ray approach and solved the stereo correspondence problem of the single-lens biprism stereovision system. These designs of stereovision systems can be improved by miniaturizing the prism to reduce cost and occupy less space. However, the whole measurement process is complicated, due to the partially overlapping image. The other catadioptric stereovision method using the mirror reflection has same advantages [16–17]. One of the first use of curved mirrors for stereovision was by Nayar et al., who suggested a wide field of view (FOV) stereo system consisting of a conventional camera pointed at two specular spheres [18]. Gluckman et al. [19] discussed the geometry and calibration of catadioptric stereo systems with two planar mirrors. Zhang et al. [20] described the algorithm in an experiment using the object and its images in a plane mirror. Wu et al. [21] investigated affine epipolar geometry to reduce the number of parameters in fundamental matrix based on a planar catadioptric stereo (PCS) system. Although many researches have been done on the catadioptric stereo system, few attentions have been paid to the analysis of the OPD influence on the asymmetric catadioptric stereo system.

To simplify the design of stereoscopic capturing systems and to avoid OPD influences, we analyzed OPD variations with increasing epipolar angle and OPD influences on the measurement accuracy of the traditional catadioptric stereovision system. In this paper, we present a different way to optimize the model of catadioptric stereovision system and understand the traditional binocular structure and its mathematical model, which will enable the measurement accuracy of the modified structure to become more robust and precise.

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2. Traditional model

2.1. Basic structure

In order to accurately approximate practical measurement processes, we focus on the structure of the traditional catadioptric stereo sensor firstly. Fig. 1 shows the basic geometry of the traditional sensor. The camera is placed point to two planar mirrors and the camera optical axis crosses the intersection D of two mirrors. There are some identifiers in Fig. 1 that need to be defined: o is the origin; C is the camera optical center; V is the real camera, and V_1 and V_2 are the virtual cameras through reflection by planar mirrors l_1 and l_2, respectively. The shaded area in Fig. 1 is the common field range.

According to the measurement principle of the traditional sensor, the size parameters of the sensor must be determined as follows: the working distance of the real camera is $|CD| = d$; the angles between the planar mirrors l_1 and l_2 and the horizontal direction are β and α, respectively. The common field range of the two virtual cameras is W. The parameters mentioned before were influenced by the FOV angle θ of the camera and the intersection angle γ of the two virtual camera optical axes.

From the geometry of the binocular sensor, the relationship of the angles α, β, and γ can be expressed as:

$$\alpha = \beta - \gamma/2, \tag{1}$$

Because the minimax size of two planar mirrors needs to be considered in the FOV of the camera, the size of the two planar mirrors can be derived as:

$$\begin{cases} l_1 = d\sin\theta/\cos(\theta-\beta) \\ l_2 = d\sin\theta/\cos(\theta+\alpha) \end{cases}, \tag{2}$$

Based on the structure of the sensor, the common field angle γ is determined. Then, the common field range W of the two virtual cameras is expressed as:

$$W = \frac{d\sin\theta}{\cos(\theta-\gamma/2) - \sin\theta/2\sin(\gamma/2)}, \tag{3}$$

The initial configuration of the sensor is addressed in Eqs. (1)–(3). Then, we analyzed the OPD problems based on the initial structure and eliminated the OPD influence.

2.2. OPD production law

The principle of the binocular system with a single camera is shown in Fig. 2. The various coordinates in Fig. 2 are defined as follows: $\boldsymbol{o}_1 - \boldsymbol{\mu}_1\boldsymbol{v}_1$ is the image coordinate system of the virtual camera V_1; $\boldsymbol{o}_2 - \boldsymbol{\mu}_2\boldsymbol{v}_2$ is the image coordinate system of the virtual camera V_2; and $\mathbf{O} - \mathbf{xyz}$ is the world coordinate system. The x-axis coincides with the baseline of the two virtual cameras. Given one point P in 3D space, its ideal perspective projections in the image planes of the virtual cameras are $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$. α_1 and α_2 are the intersection angles of the virtual camera optical axes and the baseline. ω_1 and ω_2 are the horizontal projected angles. f is the focal length of the camera.

From the sine theorem, the relationship of the various parameters mentioned above can be described as:

$$\begin{cases} \tan\varphi_1 = v_1\cos\omega_1/f \\ \tan\varphi_2 = v_2\cos\omega_2/f \end{cases}, \quad \begin{cases} \tan\omega_1 = \mu_1/f \\ \tan\omega_2 = \mu_2/f \end{cases}, \tag{4}$$

where the image coordinate $\boldsymbol{P}_1$ in $\boldsymbol{o}_1 - \boldsymbol{\mu}_1\boldsymbol{v}_1$ is denoted by $\boldsymbol{P}_1 = (\boldsymbol{\mu}_1, v_1)$ and the image coordinate $\boldsymbol{P}_2$ in $\boldsymbol{o}_2 - \boldsymbol{\mu}_2\boldsymbol{v}_2$ is denoted by $\boldsymbol{P}_2 = (\mu_2, v_2)$. According to the binocular vision model and the pinhole imaging model, the world coordinate P can be derived as:

$$\begin{cases} x = B\cot(\omega_1+\alpha_1)/[\cot(\omega_1+\alpha_1)+\cot(\omega_2+\alpha_2)] \\ y = zv_1\cos\omega_1/[f\sin(\omega_1+\alpha_1)] \\ z = B/[\cot(\omega_1+\alpha_1)+\cot(\omega_2+\alpha_2)] \end{cases}, \tag{5}$$

Then, the OPD between the two virtual cameras is expressed as:

$$s = n\left[\left(\sqrt{x^2+y^2+z^2} - \sqrt{(B-x)^2+y^2+z^2}\right) + \left(\frac{v_1}{\sin\varphi_1} - \frac{v_2}{\sin\varphi_2}\right)\right], \tag{6}$$

where n is the refractive index of air. Obviously, the OPD based on the reflection of two virtual cameras exists in this stereovision system. The influence of the OPD on real-time measurements will be more apparent in a larger quantity of image data.

In order to analyze the OPD influence on the measurement accuracy, it is necessary to apply the mentioned parameters to predict the measurement accuracy. Here, we use the measurement errors in the x, y, and z directions to express the composite error. Then, the measurement errors in the x, y, and z directions can be derived by using Eq. (5).

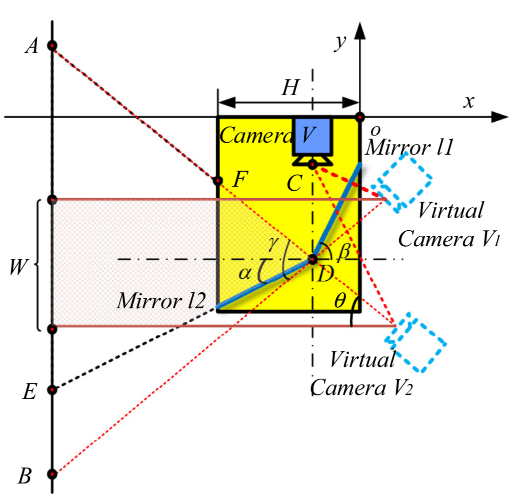

Fig. 1. Geometry of the binocular sensor.

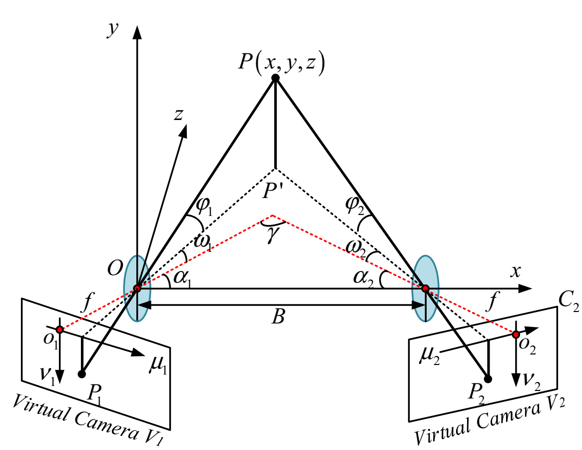

Fig. 2. Principle of the binocular vision with a single camera.