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Distortion correction for the orthogonally-splitting-imaging pose sensor

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ABSTRACT

The orthogonally-splitting-imaging pose sensor utilizes not only large field of view spherical lenses but also two sets of cylindrical ones to realize the high-speed, high-precision and wide-field pose measurement. Notable distortion, however, results from the wide-field lenses at the same time. Therefore, to obtain the best performance of the camera model, a distortion correction method is proposed in this paper, which combines the advantages of the high-stability of the Least Square fittings based on the orthogonal polynomials and the independence of the distortion correction based on the cross-ratio invariability. In this way, the ill-conditioned fitting matrix as well as the iteration and optimization procedures in solving extrinsic and intrinsic parameters can be avoided. Due to the wide fitness of the cross-ratio invariability and the orthogonal polynomials, this distortion correction technique is also suitable to other optical set up with different imaging structure. The experiment results that the corrected grids have superior precision and reliability with their original slopes demonstrate that the distortion model on the basis of orthogonal polynomial is validated and that the distortion correction is effective.

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1. Introduction

In monocular vision measurements targeting at feature points, line array charge coupled devices (CCD) are able to pick image data at higher speed and higher accuracy compared to the area array ones, but their line structure restricts the application merely within one-dimensional measurement [1–3]. To realize three-dimensional measurement, several line CCDs are combined together in recent research.

Xiong et al. utilize an assembled system of two sets of line array CCDs and cylindrical lenses to achieve pose measurement [4]. Ai et al. get the coordinates of three signs of different wavelengths on the target simultaneously via the joined line CCDs system [5,6]. However, in these multiple-line-CCDs measuring systems, feature points should be in the public visual field, since every line camera needs to shoot them from its own view [4–6] as if in the multi-vision. As a result, the Field of View (FOV) of such pose sensor is limited. In addition, their cylindrical lenses are set perpendicularly to the line array CCDs, to stretch the dot spot into a line one that intersects with the line CCD [4–6]. Nonetheless, the extension length of the sign spot is limited, thus making the FOV even smaller ($<40^\circ$).

In order to expand the visual field, this orthogonally-splitting-imaging pose sensor achieves monocular vision with two line CCDs by introducing a splitting prism before two orthogonally arranged sets of cylindrical lenses. Furthermore, the cylindrical lenses are set parallel to the line CCDs to compress the image at full range. In this way, the imaging plane is transformed into a linear one at no cost of FOV. Thus, the monocular vision's advantage of large FOV and line CCD's advantage of high speed and resolution are combined together, and hence the high-speed, high-accuracy and large view measurement can be achieved.

Nevertheless, notable “barrel” distortion at maximum of 6.5% is introduced into this system by the large FOV objective lenses at the same time, whose aperture stop follows the first concave lens. Moreover, cylindrical lenses also bring in significant unidirectional distortion. These distortions lead to false feature extraction and pattern recognition [7]. Therefore, distortion correction is a key requisite for the intrinsic and external parameters' calibration [8] and also a crucial step to achieve high-precision measurement.

Distortion correction is always based on the polynomial mapping from distorted coordinates to the ideal ones. The solving of the distortion parameters, however, is always a successive process of nonlinear optimization combined with other extrinsic and intrinsic parameters [9–13]. Consequently, the best global solution may not be converged due to the stray point's interference [26].

Comparatively, calibrating distortion parameters independently [14] can abandon the consecutive iteration and optimization

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procedures effectively, among which the distortion correction based on the cross-ratio invariability is one of the most widely used methods [7,15]. Nevertheless, when substituting the coordinates of the cross-ratio formula with those denoted by distortion parameters, quadratic equations need to be solved [7] whose computing complexity grows rapidly in proportion to the number of the distortion parameters.

Asari et al. put forward a distortion calibration method based on the Least Square (LS) estimate [16]. Employing the LS fittings can directly lead to the coefficients of the distortion model and thus avert quadratic equations' solving, and extend the application to the Weng's distortion model [17]. However, the fitting matrices will get ill-conditioned when orders of the fitted polynomial are high, making the solutions unstable.

The orthogonal polynomials can avoid the ill-condition problem effectively [18], precluding the divergences of fitting from different directions and meanwhile suppressing the turbulence caused by measuring errors. Ram et al. introduced a model of the finger print ridge orientation based on Legendre Polynomials [27]. Raich et al. proved that the orthogonal polynomials have high stability in the pre-distortion model of Power Amplifier [19].

As for wave front fittings, Zernike polynomials are distinctive due to their orthogonality within a unit circle domain and the precise fitting of various aberrations [20,21]. However, Zernike polynomials are not sufficient to characterize varied distortions out of design, manufacturing and assembling. Besides they are not orthogonal on discrete sampling points, whose LS fittings' normal vector matrices are still ill-conditioned in this situation. Furthermore, Smith et al. presented a formulation in which orthogonal Chebyshev polynomials were applied to determine the parameters of the radical distortion [22] for the distortion correction of discrete sampling points. This method was later used by Stefansic et al. in second-order distortion calibration for laparoscopes [23]. Nonetheless, it is not applicable to the distortion models joined by tangential and prism distortion and can only be utilized for the polar coordinates that are within a unit circle.

Therefore, a method of nonlinear distortion correction based on the orthogonal Laugerre polynomials and the cross-ratio invariability is proposed. First, the combined nonlinear distortion is characterized by the model on the basis of orthogonal Laguerre polynomials. Then, the distortion parameters of the model can be obtained from the LS fittings with the ideal coordinates derived from the cross-ratio invariability and the perspective projection. Due to the high stability of Legendre polynomials in high power fittings as a member of orthogonal polynomials and the independence of cross-ratio invariability restoring the ideal coordinates from distorted ones in LS fittings, the distortion parameters can be stably and accurately solved by preventing the normal vector matrix from getting ill-conditioned, precluding iteration and avoiding solving high order equation. Therefore, this distortion correction method is of high stability, high accuracy and low computational cost. Furthermore, the orthogonal domain of Laguerre polynomials is $[0, +\infty)$, which makes the correction applicable to the Cartesian coordinate system. Besides, the dependence of the horizontal and vertical coordinates expands the orthogonality domain of the model into the ones with cross-terms as that of the Weng.

This paper is organized as follows. In Section 2 the orthogonally-splitting-imaging pose sensor's structure is described as well as its imaging principles. In Section 3 the distortion correction is presented based on the orthogonal polynomials and the cross-ratio invariability. In Section 4 the procedures and results of the distortion correction experiment are reported. Finally in Section 5, the advantages and restrictions of the distortion correction method are summarized.

2. The imaging principles of the orthogonally-splitting-imaging pose sensor

2.1. The optical structure of the pose sensor

In order to enlarge the FOV, the orthogonally-splitting-imaging pose sensor adopts the splitting prism, so that synchronous accesses to the feature points can be given to the orthogonally set line CCDs through the common objective lens, and thus reserves the large FOV of monocular vision. In addition, two-step cylindrical lenses compress the whole image within the scope to

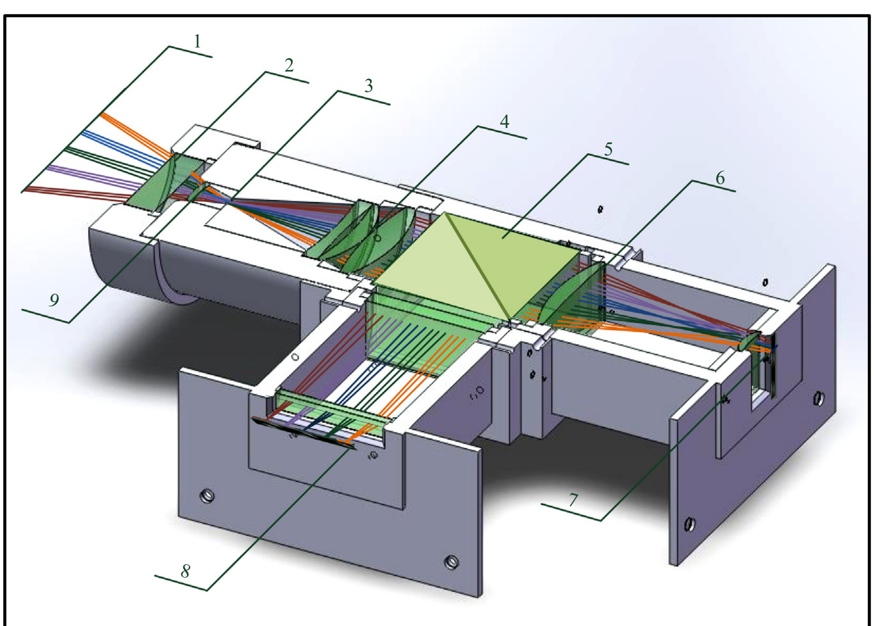

Fig. 1. Schematic diagram of imaging of the orthogonally-splitting-imaging pose sensor, 1. Horizontal LED signs, 2. Filter, 3. Aperture stop, 4,9. Spherical lenses, 5. Splitting prism, 6. Cylindrical lenses, 7. Identical ordinate and 8. Five diverse abscissas.

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