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Complete calibration of a structure-uniform stereovision sensor with free-position planar pattern

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Abstract

We present a novel structure-uniform stereovision sensor for variable 3D inspection tasks. In this paper, the mathematical model of the stereovision sensor is established. A flexible approach to estimate all the primitive parameters of the stereovision sensor with free-position planar pattern is proposed. In this technique, without restriction to the moving of the planar reference object, all the camera parameters with coefficient of lens radial and tangential distortion can be readily calibrated, and based on the 3D measurement model of stereovision sensor, the sensor parameters can be optimized with the feature points constraint algorithm simultaneously. The proposed approach greatly reduces the cost of the calibration equipment, and it is flexible and practical for the vision measurement. It shows that this method has high precision by experiment, and the measured relative error of space length excels 0.3%.

Keywords: Structure-uniform; Stereovision; Calibration; Planar pattern; Free-position; Feature point constraint

1. Introduction

Stereovision is the approach to acquire three-dimensional (3D) geometric information of objects according to two or more perspective images. Stereovision technology has been widely used in the various application of robotics, industrial automation, such as component quality control, dimensional analysis, on-line inspection and object recognition [1,2], due to non-contact, fast measuring speed, moderate accuracy, well flexibility and low cost.

A conventional stereovision sensor consists of two cameras, commonly called passive stereovision. The operation of this kind of stereovision sensor mainly relies on the changes of the light reflection or radiation from the object surfaces, thus it is difficult to detect smooth surfaces of objects, such as metal plates. Chen and Zheng [3] proposed a passive and active stereovision, which adds structured light to detect the smooth surface of the deformed plates. Since 2000, our group has been developing a structure-uniform stereovision sensor, which consists of two cameras and additional feasible projector for choosing, for example, lamp, single structured light stripe, multiple structured light stripes and LCD raster, according to variable measure task. The structure-uniform stereovision sensor has been widely applied in many practical projects [4,5]. For this multifunctional stereovision sensor, how to set up more flexible on-line calibration apparatus and improve metric calibration precision of each camera and camera-pair is the key problem for many vision inspection tasks.

The fundamental measuring method of structure-uniform stereovision, like all other stereovision systems, is stereo method. In general, the approach to calibrate a structure-uniform stereovision sensor includes two stages: camera calibration and sensor calibration. The complete calibration parameters include camera intrinsic parameters (e.g. effective focal length, principle point and lens distortion coefficient), extrinsic parameters (including the 3D position and orientation of two camera frames relative to a certain world coordinate system) and sensor parameters (the relative 3D position and orientation of two camera frames).

In the camera calibration stage, camera parameters are estimated using at least six world points whose 3D coordinates are known and their corresponding image projection points which can be extracted accurately. A popular and practical one is the method developed by Tsai [6] using radial alignment constraint

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(RAC), but in this method, camera initial parameters (e.g. number of sensor elements in the X direction, number of pixels in a line as sampled by the computer) are required and only lens radial distortion is calculated. Zhang proposed a flexible new technique for camera calibration by viewing a plane from the different unknown orientations. This approach is very easy to use and obtains very good accuracy [7].

In the sensor calibration stage, conventional approaches to estimate the vision sensor's model parameters usually use elaborate 3D calibration reference object, such as the patterns with two or three planes orthogonal to each other, or 3D sphere target whose center geometry in 3D space is known with very good precision [8]. For calibration targets with orthogonal planes, two cameras have difficulty observing all feature points which lie on different planes simultaneously. For 3D sphere target, it is easier to take one image to calibrate, but it is difficult to manufacture and maintain because careless impact on it will affect inspection accuracy intensively. Thus, calibration target often requires readjust by CMM or other 3D measuring equipments before used again. Wu [9] proposed the method by using virtual 3D calibration target through 2D one, but target plane must undergo a precisely known translation, and orientation must be perpendicular to the plane. This approach requires a relatively complex calibration procedure.

Besides the methods already mentioned, there are other methods in the literature, such as, a two-step calibration method based on the principle of "vanishing point" of the parallel lines in Ref. [10] and a calibration procedure based on neural network in Ref. [11]. But because all these methods are difficult to satisfy required calibration condition, none of them is suitable for practical on-line calibration, and cannot be widely accepted.

To sum up, the methods of calibrating a stereovision sensor presented in the literature mainly have the following drawbacks:

(1) Some methods require an expensive calibration apparatus and elaborate set-up.
(2) The methods are unsuitable for on-line sensor calibration.

These factors obstruct the improvement of calibration accuracy of stereovision sensor and convenience in 3D metrology application.

In this paper, inspired by the work of Zhang, we propose a novel approach to calibrate complete primitive parameters of the stereovision sensor with free-position planar pattern. The proposed technique only requires two cameras to observe a planar pattern shown at a few (at least two) different orientations. The pattern can be printed on a paper with a high-quality printer and attached to a "reasonable" planar surface, or ray-echoed for a much higher precision. The planar pattern can be moved by hand, and the motion need not be known. What is more, the captured images of the target can be used for camera calibration and sensor calibration successively. According to optimizing algorithm based on feature points constraint presented in the paper, we can estimate all the sensor parameters conveniently only with a few images.

The paper is organized as follows. Section 2 introduces the mathematical model of the structure-uniform stereovision sensor. The model includes the perspective projection model of the camera and the 3D measurement model of the sensor. Section 3 describes the procedure of calibrating the sensor. This procedure includes camera calibration, sensor calibration and parameters optimizing. Section 4 provides the experimental results. Real data are used to validate the proposed technique.

2. Mathematical model of the structure-uniform stereovision sensor

2.1. Camera model

Fig. 1 shows the perspective projection model of the camera in the structure-uniform stereovision sensor. Note that o_n is the center of the camera image plane π_i, o_c is the projection center of the camera and z_c axis is the optical axis of the camera lens. The relative coordinate frames are defined as follows: $o_w x_w y_w z_w$ is the 3D world coordinate frame, $o_c x_c y_c z_c$ is the 3D camera coordinate frame and $o_u x_u y_u$ is 2D image plane coordinate frame.

Given one point P_w in 3D space, its homogeneous coordinate in $o_w x_w y_w z_w$ is denoted by $\tilde{P}_w = (\,x_w \quad y_w \quad z_w \quad 1\,)^T$. P_n is the ideal projection of P_w in the camera image plane, while P_d is the real projection because of lens distortion. In the same way, we can use $\tilde{p}_u = (\,x_u \quad y_u \quad 1\,)^T$ to denote P_n's homogeneous coordinate in $o_u x_u y_u$.

According to the pinhole perspective projection theory of camera, the relationship between a 3D point and its image projection can be given by

$$s\tilde{p}_u = A[\,R \quad T\,]\tilde{P}_w \tag{1}$$

where

$$A = \begin{bmatrix} f_x & 0 & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

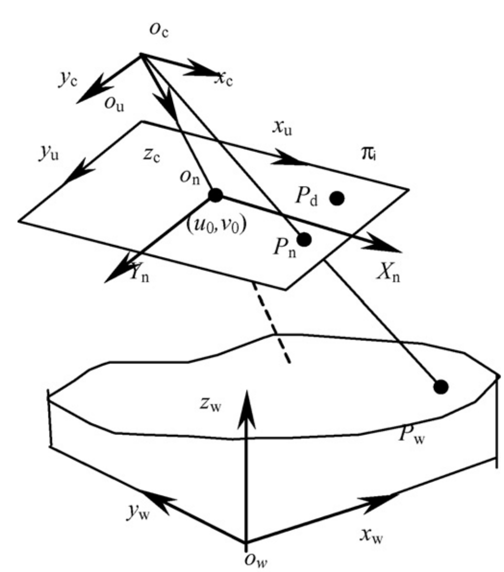

Fig. 1. Perspective projection model of camera in the structure-uniform stereovision sensor.