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Simultaneous calibration of the intrinsic and extrinsic parameters of structured-light sensors

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ABSTRACT

A novel approach for simultaneously calibrating the intrinsic and extrinsic parameters of structured-light sensors is presented in this paper. A planar target etched with grid lines is adopted to generate calibration points. By intersecting the laser plane with the grid lines on the target some co-linear points are formed, and their 3-D coordinates are computed according to the rule of cross-ratio invariance. For obtaining non-colinear points in the laser plane, the sensor is located at several different positions by the moving of coordinate measuring machine (CMM). However, the co-linear points corresponding to different CMM positions locate at different coordinate frame. In order to establish conjugate pairs to calibrate the sensor, all of the generated points in the laser plane are transformed into the CMM machine coordinate frame. Then using the 3D points in this coordinate frame a 2D coordinate frame is established with determined direction vectors, i.e., the extrinsic parameters are calibrated. By transforming the 3D points in the CMM machine coordinate frame into the 2D coordinate frame, conjugate pairs for calibrating the intrinsic parameters are established. Experimental studies show that the planar target is simple, and it can be manufactured with high accuracy. The calibrating process is facilitating, and the calibration result possesses high accuracy.

1. Introduction

In recent years, structured light sensors have been widely used in quality control and reverse engineering [1–5]. This sensor has two types of working modes. One working mode is scanning measurement [6–8]. The sensor is usually integrated with coordinate measuring machines (CMMs), CNC machines or other scanning devices to collect data cloud on a part for reverse engineering. Another mode is online inspection [9–11]. The sensor is fixed on a device, and the part is measured when it passes through the working range of the sensor. The dimension to be inspected usually includes diameter and thickness, for example, the diameter of a cable or a steel pipe, the thickness of a steel or wood board.

A structured-light sensor is basically composed of a CCD camera and a line laser projector, according to the working principle of laser triangulation. When the laser plane is projected on a part, the CCD camera captures the image with the modulated light stripe. If the sensor is calibrated, the 2D data in the laser plane could be obtained from the image. This calibrating procedure is called "intrinsic calibration". The aim of intrinsic calibration is to determine the mapping relationship between the 2D computer image plane and the laser plane, meanwhile establish a 2D coordinate frame in the laser plane.

When the sensor is mounted on a CMM to implement 3D scanning, the data point directly obtained possesses 2D coordinate in the laser plane, which should be converted into 3D data in the CMM machine coordinate frame. The procedure for identifying the transformation from 2D coordinate frame in the laser plane to 3D CMM machine coordinate frame is "extrinsic calibration".

The studies on structured-light sensors mainly focus on intrinsic calibration to determine the relationship between the laser plane and the image plane [11–14]. By contrast, only several researchers [15–17] have paid their attentions on extrinsic calibration, and successfully solved the extrinsic calibration problem when mounting the structured light sensor on a CMM or a CNC machine tools.

Traditionally intrinsic and extrinsic calibrations are two separate steps. They are fulfilled usually in different conditions with different equipments. For some commercial sensors, the intrinsic calibration are carried out by the manufacture, only the extrinsic calibration needs to be done by the customers when the sensor is mounted on a 3D scanning device.

When calibrating the extrinsic parameters, the intrinsic parameters are usually considered as stable values. In practice, the intrinsic parameters are likely to vary after the sensor is used for a long time, since they can be influenced by many factors, such as ambient temperature, shaking etc. In order to solve this problem Santolaria [18] proposed a one-step intrinsic and extrinsic

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calibration method. He adopted a 3D target manufactured with some non-coplanar characteristic points, and the world coordinate frame is directly established on the 3D target. The laser plane intersects the 3D target, and some non-colinear calibration points are formed in the world coordinate frame. Thus the “intrinsic calibration” and “extrinsic calibration” can be simultaneously done using these points. Since the final measuring result is in CMM machine frame, the transformation from the world coordinate frame to CMM global frame is derived after the position and orientation of the target in CMM machine frame have been measured by using a trigger probe. In this method, the CCD camera and the sensor share the same coordinate frame, the camera model and the sensor model are easy to be established, while the manufacture of 3D target is difficult, and it is hard to ensure high accuracy. On the other hand, by adopting a contact probe to identify the target orientation in the CMM global frame, the calibration process is inconvenient and not facilitating.

In this study, a planar target is adopted to simultaneously calibrate the intrinsic and extrinsic parameters of structured light sensors. As shown in Fig. 1, the structure of the target is simple, and easy to be manufactured with high accuracy. In the process of calibrating, the target is placed on the worktable of the CMM without any special adjustment. When the laser plane projects on the target, a laser line is formed. It intersects with the grid lines on the target, and several co-linear points are created. If the sensor is located at different positions, more non-colinear points can be obtained in the laser plane. They are taken as calibration points for simultaneously calibrating the intrinsic and extrinsic parameters of structured-light sensors. The specific description of this approach is given as follows:

In Section 2, the camera is modeled and calibrated to identify the transformation between the world coordinate frame and the camera coordinate frame. In Section 3 the model of the structured light sensor is created. The intrinsic model is the mapping relationship between the laser plane and the image plane. The extrinsic model is the transformation from the 2-D coordinate frame in the laser plane to the CMM machine coordinate frame. In Section 4 the method for determining calibration points is given. When the laser plane projects on the planar target, it intersects with the grid lines on the target and some co-linear points are formed. The 3D coordinates of the intersected points in the world coordinate frame are computed according to the rule of cross-ratio invariance. The co-linear points obtained at different sensor positions are taken as calibration points. All of them are transformed into the CMM machine coordinate frame. In Section 5, the extrinsic parameters are solved by establishing a 2D coordinate frame using the 3D data points in the laser plane, also in the CMM machine coordinate frame. The conjugate pairs for solving the intrinsic parameters are created by transforming the 3D points in the CMM machine coordinate frame into 2D data points in the established 2D coordinate frame. Experimental results are given in Section 6.

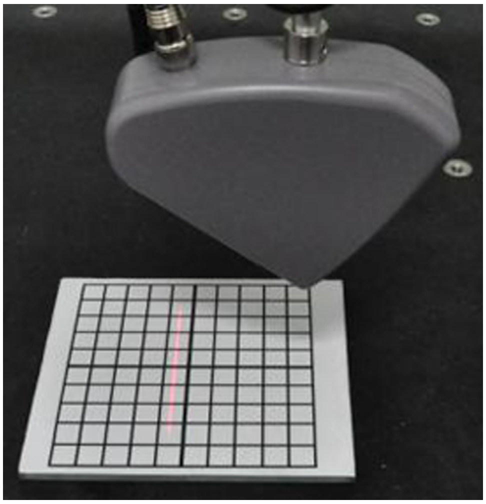

Fig. 1. The planar target for intrinsic and extrinsic calibrating of the sensor.

2. Camera modeling and calibrating

In this section, the camera model is established, the transformation from the camera coordinate frame to the world coordinate frame is determined, and the lens distortion is corrected. A planar target is adopted to calibrate the camera, it is also used to obtain calibration points for simultaneously calibrating the intrinsic and extrinsic parameters of the sensor in Section 4.

2.1. Camera modeling

The modeling of the camera is performed according to the perspective projection principle [16], as shown in Fig. 2. Because of lens distortion, the image would be distorted and that would lead to measurement errors. There are two types of lens distortion: radial distortion and tangential distortion. Since the radial distortion is the main factor that affects the measurement accuracy, we only take it into consideration when establishing the camera model.

Note that $o_w x_w y_w z_w$ is the 3D world coordinate frame. $O'XY$ is the CCD array plane coordinate frame, O' is the intersection of the optical axis and the CCD array plane. $o_c x_c y_c z_c$ is the 3D camera coordinate frame, where o_c is the projection center of the camera, z_c axis is the optical axis of the camera lens, x_c and y_c are parallel to X and Y, respectively. P is a point in $o_c x_c y_c z_c$ or $o_w x_w y_w z_w$. Its correspondence in $O'XY$ should be $P_u(X, Y)$, but the actual corresponding point is $P_d(X_d, Y_d)$ due to the lens distortion. f is the effective focal length. $o''uv$ is the computer image coordinate frame, o'' is the origin of the image, u,v axes are parallel to X,Y respectively, the unit of u axis and v axis is pixel. Let (u_0, v_0) be the coordinate of O' in $o''uv$, here (u_0, v_0) is the principal point. The transformation from $o_w x_w y_w z_w$ to $o''uv$ is derived through the following process.

According to perspective projection, the transformation from $o_c x_c y_c z_c$ to $O'XY$ is

$$\rho \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \tag{1}$$

where ρ is a scale factor.

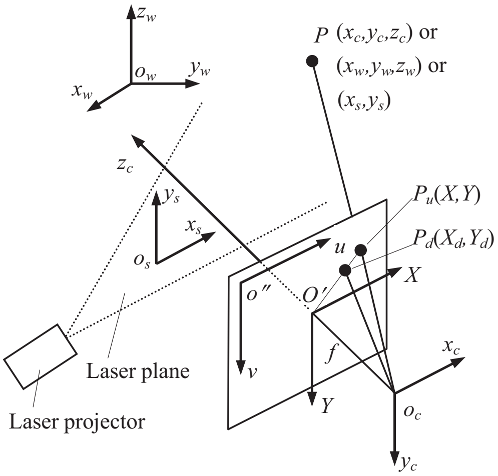

Fig. 2. Principle of perspective projection and camera model.