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The Research on Calibration Methods of Dual-CCD Laser Three-dimensional Human Face Scanning System

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ABSTRACT

In this paper, on the basis of considering the performance advantages of two-step method, we combines the stereo matching of binocular stereo vision with active laser scanning to calibrate the system. Above all, we select a reference camera coordinate system as the world coordinate system and unity the coordinates of two CCD cameras. And then obtain the new perspective projection matrix (*PPM*) of each camera after the epipolar rectification. By those, the corresponding epipolar equation of two cameras can be defined. So by utilizing the trigonometric parallax method, we can measure the space point position after distortion correction and achieve stereo matching calibration between two image points. Experiments verify that this method can improve accuracy and system stability is guaranteed. The stereo matching calibration has a simple process with low-cost, and simplifies regular maintenance work. It can acquire 3D coordinates only by planar checkerboard calibration without the need of designing specific standard target or using electronic theodolite. It is found that during the experiment two-step calibration error and lens distortion lead to the stratification of point cloud data. The proposed calibration method which combining active line laser scanning and binocular stereo vision has the both advantages of them. It has more flexible applicability. Theory analysis and experiment shows the method is reasonable.

Key words: Calibration, Binocular stereo matching, Line structured-light, 3D scanning

1. INTRODUCTION

Three-dimensional (3D) digital technology develop rapidly, the results of these research are widely used in the field of human digital, 3D surface detection, mold design and reverse engineering. Wherein, Human face 3D visualization is an important prerequisite for face image analysis, such as the facial feature detection and face recognition. Among numerous 3D visualization technologies, active 3D data acquisition method is that

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projecting light on the surface of the object to be measured by the light source projector, corresponding to the image information collected by CCD (or CMOS) camera, and be transmitted to the processing computer[1][2]. Thus we can use software algorithms based on the principle of triangulation or time-of-flight of light [3] for the calculation and processing of 3D information. Compared with other systems, active vision measurement system has the advantages of high matching efficiency, high accuracy, small errors, and simple principle. Therefore in this article, we adopt an active line laser light human face scanning system.

Calibration method for multi-sensor line laser light system generally consists of two steps, local calibration and global calibration. The purpose of the calibration is to establish the relationship between the two-dimensional image coordinates collected by computer and the 3D world coordinates of the object to be measured. Once this relationship is established, the two-dimensional image can be collected by the computer to restore the 3D information of the object to be measured. Therefore, calibration is the premise and basis of the vision measurement system for 3D space.

Camera calibration technology has been development well. More frequent use is the camera perspective transformation matrix calibration method, nonlinear optimization calibration method [4], multi-stage method, neural network method [5] and self-calibration method[6]. Among them, multi-stage method resolves the conflict between calibration speed and calibration accuracy well. This method uses the geometric relationships in the imaging process to find the part of the parameters, and then use the parameters obtained first to solve the other parameters. Tsai two-stage calibration method [7] and Zhang Zhengyou plane calibration method [8] is that such methods.

Global calibration should unify the measurement data of each vision sensor into a general world coordinate system, that is, it is to determine the position and orientation of each vision sensor coordinate system relative to the entire world coordinate system. Mainly the following three commonly mehods are used as global calibration method[9] : the uniform method for the coordinates of the same name, the uniform method for intermediary coordinate, and the unique method for world coordinate.

Although the traditional two-steps method can calibrate preferably, it also has some drawbacks. First of all, the sensor consisting of camera and laser is generally driven by the mechanical structure to have a one-direction movement, thence two-dimensional coordinates (X_w, Y_w) in the world coordinate are obtained based on the calibration, while coordinate Z_w based on the mechanical scanning. Apparently, the coordinates Z_w of the method is easily influenced by adjustment status of light band and position accuracy of the translation stage. In order to avoid the world coordinate error caused by the tilt, the light plane and the direction of movement should be strictly vertical. In fact, the manual levelness correction of laser is difficult to meet this requirement. Second, the global calibration generally need to design a specific precision calibration target, such as filaments target, serrated target[10], ceramic gauge block target and so on. Additionally, it sometimes need coordinate theodolite. These greatly increase the cost and cumbersome of the subsequent maintenance work. Finally, due to unavoidable errors existing in the process of the actual 3D data acquisition, the 3D point cloud data of two cameras can’t be fully point-to-point matching. It requires extra algorithm to achieve data fusion that make multi-point cloud layers together as a single layer point cloud in the subsequent data processing.This article will combine binocular stereo vision principle with the active line laser system calibration technique [11].

2. CAMERA MODEL

2.1 Pinhole camera model

As shown in Fig.1, a pinhole camera is modeled. Make optical center *o* as the origin of camera coordinate system *o-xyz*. Axis *x*, *y* are parallel to the image plane *K*, with axis *z* being perpendicular. The intersecting point of axis *z* and *K* is the principal point *O* of camera. Then make *O* as the origin of image plane coordinate system *O-XY*, Axis *X* is parallel to the lateral pixel array, and axis *Y* is parallel to the longitudinal array pixel. The distance between *o* and *O* is effective focal length *f*. O = [C_x, C_y] is given by the computer image pixel coordinate system O_f-X_fY_f.

Let $[X_w\ Y_w\ Z_w]^T$ be the world coordinates of a 3D point *M*, M'=[$X_w\ Y_w\ Z_w\ 1]^T$ be the homogeneous world coordinates of it, and M_m =[$X_f\ Y_f$]^T be the computer image pixel coordinates, M_m'=[$X_f\ Y_f\ 1]^T$ be the homogeneous computer image pixel coordinate coordinates. According to the theory of Euclidean Transformation, the ideal projection transformation under ideal pinhole camera model and the relationship between the computer image coordinate system and the image plane of the physical coordinate system, so:

$$z\begin{bmatrix}X_f\\Y_f\\1\end{bmatrix}=\begin{bmatrix}S_x&0&C_x\\0&S_y&C_y\\0&0&1\end{bmatrix}\begin{bmatrix}f&0&0&0\\0&f&0&0\\0&0&1&0\end{bmatrix}\begin{bmatrix}R&T\\O^T&1\end{bmatrix}\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix}=A\begin{bmatrix}R&T\end{bmatrix}\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix} \tag{1}$$

The S_x and S_y are the effective numbers of pixels per millimeter along the axes *X* and *Y* respectively. [C_x, C_y] are the coordinates of the principal point, given by the intersection of the optical axis with the image plane. *R* is a 3×3 rotation matrix, and its column or row vectors are orthogonal, *T* is a 3×1 translation vector, *O* is a zero matrix.

The above formula can also be written as

$$z\cdot M_m = P\cdot M' \tag{2}$$

Where *P* is the meaning of perspective projection matrix (*PPM*), *z* is scale factor, at the same time.

$$A=\begin{bmatrix}S_xf&0&C_x\\0&S_yf&C_y\\0&0&1\end{bmatrix}$$

(3)

A is the camera intrinsic parameters matrix.

Ideal pinhole model can satisfy the relation of similar triangles, however, the actual lens can't. The camera optical system has assembly errors and the impact of the optical distortion should be considered. Radial distortion, tangential distortion and thin prism distortion are three major distortion error types.

Radial distortions are caused mainly by the shape of the lens defects. The distortion is symmetric about the main optical axis of the lens. Tangential distortions are the results from the inconsistency between the optical center and the geometric center. Optical axis' centers of each lens can't be strictly collinear. In fact, the introductions of excessive distortion parameters are often not only fail to improve the accuracy, but also cause the instability of the solution. So we only consider the radial distortion.

The camera radial distortion can be expressed as

$$\begin{cases}\delta_r(x,y) = x(k_1r^2 + k_2r^4 + k_3r^6 + \cdots) \\ \delta_r(x,y) = y(k_1r^2 + k_2r^4 + k_3r^6 + \cdots)\end{cases} \tag{4}$$

Wherein $r^2=x^2+y^2$. Because k_3 and higher-order terms are very small for the imaging distortion, we only care about k_1 and k_2.

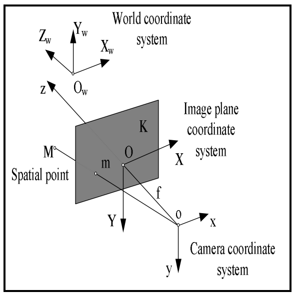


Fig.1 The relations of the coordinate system

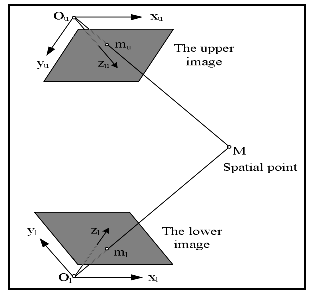


Fig.2 Binocular stereo vision model

2.2 Binocular stereo vision model

In Binocular stereo vision model, as shown in Fig.2, known respectively from the two cameras' *PPM*s are P_{up}, P_{low}

$$P_{up} = \begin{bmatrix} p_{u11} & p_{u12} & p_{u13} & p_{u14} \\ p_{u21} & p_{u22} & p_{u23} & p_{u24} \\ p_{u31} & p_{u32} & p_{u33} & p_{u34} \end{bmatrix} \quad P_{low} = \begin{bmatrix} p_{l11} & p_{l12} & p_{l13} & p_{l14} \\ p_{l21} & p_{l22} & p_{l23} & p_{l24} \\ p_{l31} & p_{l32} & p_{l33} & p_{l34} \end{bmatrix} \tag{5}$$

Thus four linear equations about X_w, Y_w, Z_w have been obtained from the computer image pixel coordinates [X_{fu} Y_{fu}], [X_{fl} Y_{fl}] of the upper and the lower camera

$$\begin{cases}(X_{fu}p_{u31} - p_{u11})X_w + (X_{fu}p_{u32} - p_{u12})Y_w + (X_{fu}p_{u33} - p_{u13})Z_w = p_{u14} - X_{fu}p_{u34} \\ (Y_{fu}p_{u31} - p_{u21})X_w + (Y_{fu}p_{u32} - p_{u22})Y_w + (Y_{fu}p_{u33} - p_{u23})Z_w = p_{u24} - Y_{fu}p_{u34}\end{cases} \tag{6}$$

$$\begin{cases}(X_{fl}p_{l31} - p_{l11})X_w + (X_{fl}p_{l32} - p_{l12})Y_w + (X_{fl}p_{l33} - p_{l13})Z_w = p_{l14} - X_{fl}p_{l34} \\ (Y_{fl}p_{l31} - p_{l21})X_w + (Y_{fl}p_{l32} - p_{l22})Y_w + (Y_{fl}p_{l33} - p_{l23})Z_w = p_{l24} - Y_{fl}p_{l34}\end{cases} \tag{7}$$

The geometric meaning of (6) and (7) is the lines of O_um_u 和 O_lm_l in Fig.2. Because M = [X_w Y_w Z_w] is the intersection point of O_um_u and O_lm_l, M must meet equations of (6) and (7) at the same time. So we calculate the world coordinate [X_w Y_w Z_w].

3. Two-steps Calibration

3.1 System structure improvement

A new system was established with Fig.3. The camera stationary in these system and the line laser projector is driven by mechanical structure to scan from top to bottom. As shown in Fig.4, a cylinder line was captured by the line laser scanner, while utilizing the principle that epipolar line (l_u and l_l) and the laser stripe curves intersect to determine the match between the points (M_{up} and M_{low}) of two cameras' images.

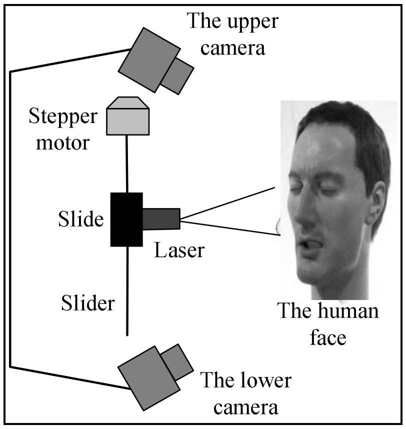


Fig.3 The new scanning systems

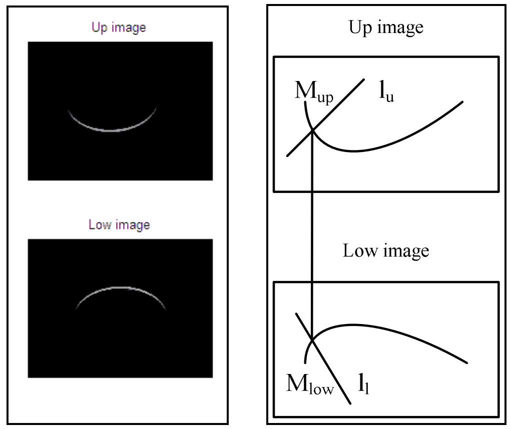


Fig.4 The conjugate points of selection principle

In our two-step calibration based on the new active line laser scanning system, the main procedures are just as shown in flowchart Fig.5, where we select the upper camera coordinate system as the world coordinate, and transform the lower camera coordinate system into it through the relative rotation matrix and translation matrix. Then we can get the two original *PPM*s. Epipolar rectification generates the new *PPM*s on base of the original ones. Above all, the whole calibration is done.

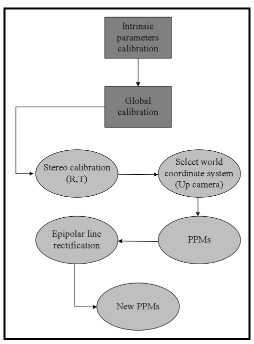


Fig.5 The main procedures of the calibration

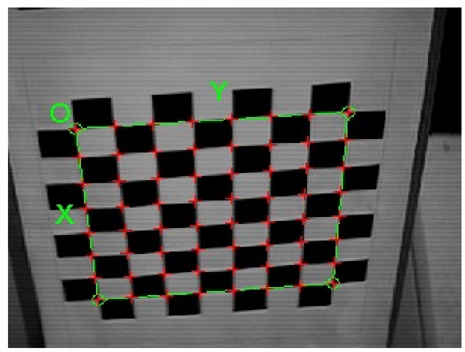


Fig.6 The planar checkerboard calibration target

3.2 Intrinsic parameters calibration

In this article, Zhang's plane calibration method was adapted to acquire the intrinsic parameters of cameras, such as radial distortion coefficient k_1 and k_2, focal length f_x and f_y, optical center coordinates C_x and C_y. As shown in Fig.6, a black and white planar checkerboard has been printed. Its number is 9×9 and grid size is 20mm×20mm.

3.3 Global calibration

In the global calibration based on binocular stereo vision, firstly, select a CCD camera coordinate system as world coordinate system. Secondly, calculate the positional relationship between two CCD camera coordinate systems. Finally, using the Epipolar rectification, two camera coordinate systems are coplanar and perpendicular to the polar plane.

3.3.1 Epipolar constraint

As shown in Fig.7, the two binocular stereo vision cameras are angled placement in space. Let O_u and O_l be the optical center of the upper and lower cameras, respectively. The connection between O_u and O_l is called baseline. Project the spatial point M onto the both image planes. Then projection points m_u and m_l constitute a conjugate pair. If m_u in the upper image has been given, its conjugate point m_l must be constrained to lie on a line in the lower image[12]. The line called the epipolar line $e_l m_l$ of m_u is the intersection of plane π and lower image plane, wherein π defined by M and baseline is known as the epipolar plane.

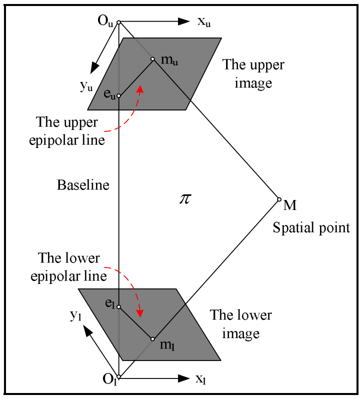


Fig.7 Epipolar constraint

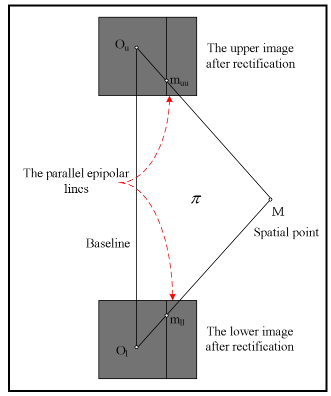


Fig.8 Epipolar rectification

3.3.2 Epipolar rectification

Due to the complexity of the contour of the human face, the intersection of the epipolar line and the laser stripe is not unique. Therefore, we use the epipolar rectification method[13] to ensure the stability of the intersection, while simplifying the follow-up match, and having a match acceleration.

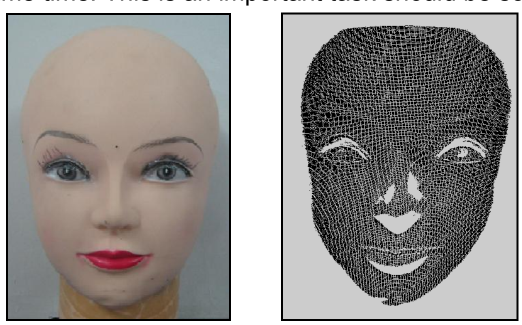
The new projection matrices are achieved after rectification. Image processing can result in the following, as shown in Fig.8. The image coordinate of the space point M in upper camera is m_{uu}= [X_1 Y_1], and in lower camera is m_{ll}=[X_1 Y_1] (i.e., the two points are one-to-one corresponding), i.e. the corresponding epipolar line of m_{uu} in the lower image turns out to be x=X_1. This eliminates the need for solving the epipolar equation. We can obtain the matching points pair just by the image line scanning to determine the intersection point of the epipolar line and laser stripe.

There are many methods to implement epipolar rectification[14][15]. In order to minimize the distortion effects, we have adopted the principle of Bouguet rectification algorithm[16]. By means of dual-camera stereo calibration results, rotating the two camera rotation matrices of the respective half reversely, then resulting in the two cameras facing in the same direction. Next, make the axis y parallel to the translation vectors of two cameras. Because the epipoles are at infinity, the epipolar lines must be parallel to each other. Thus, we minimize the rotation angle between the cameras. Finally, try to keep the characteristics of pre-correction image, while calculate the new parameters after two cameras rectification.

4. Experimental results

The proposed scanning system uses JOINHOPE MC_30 frame grabber in conjunction with Mintron MTV-03K80AHE monochrome board cameras and 8mm lens. At first step, apply Zhang Zheng-you checkerboard calibration method, and the camera intrinsic parameters calibration results are obtained. Then, the upper camera coordinate system was set as the world coordinate system and the *PPM* of upper camera can be calculated. According to the rotation matrix R and translation vector T, the *PPM* of lower camera can be calculated. After the epipolar rectification, the relative rotation matrix R turn into an identity 3×3 matrix R_rect, and the second component of the vector T is not equal to zero, which means the image coordinate of lower camera just have a translation along axis y with respect to the image coordinate of upper camera.

Then the active line laser scanning system is used to scan a human face model, just as shown in Fig.9(a). Fig.9 (b) represents the points cloud that produced by the new system. The Fig.9(b) doesn't have this problem of double layers data owing to the parallax-based stereo matching. So the new active line laser scanning system has a more clear scanning effect and is excellent in practice. The holes in points cloud owing to the mismatch of image plane points in two cameras are concentrated in complex contour, i.e. the junction of cheeks and nose, the orbital depression. The reason of this is two cameras can't take photos of the block places on human face at the same time. This is an important task should be solved in the future study



(a) (b)

Fig.10 The human face model and its points clouds.

(a) The human face model; (b) The points cloud of new scanning system

5. CONCLUSION

In this article, uisng two stationary cameras and a motive laser, we combine active line structured-light scanning calibration method with binocular stereo vision. The calibration procedure includes two steps of intrinsic parameters calibration and global calibration. The global calibration use epipolar rectification to reduce the rate of mismatch successfully. Theory analysis and experiment shows the approach is reasonable.

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