Optik 126 (2015) 2458–2463

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

The circular mark projection error compensation in camera calibration

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ARTICLE INFO

Article history:
Received 27 April 2014
Accepted 4 June 2015

Keywords:
Visual measurement
Camera calibration
Center location
Error compensation
Perspective projection

ABSTRACT

For center deviation of space circular mark in the perspective projection transformation process, a novel method is proposed in this paper to locate the real projection center precisely based on the theory of analytic geometry and spatial perspective. First, we analyze the spatial circle error of perspective projection transforms generated and gives relevant basic principles. Then the detailed implementation of the algorithm and the specific steps are presented. Finally through the experiments verify the effectiveness of the method. Simulation and experimental results indicate that this method can achieve the actual projection point precise positioning of the space circular target. The algorithm does not require additional complex constraints and has good robustness; therefore it has a wide range of practical engineering application value.

1. Introduction

Camera calibration is one of the key technologies in the field of pattern recognition, vision measurement and machine vision. Planar target is widely used for calibration because of its simple production. Accurate coordinates the real image information of space target is very important for the widely used calibration method now, such as Zhang method [1] and Tsai two-step [2].

Circular sign as functional target is universally applicated in computer vision as its easy identification, strong anti-noise ability and other characteristics [3,4]. However, targets often degenerate into an oval in a circular projection transformation. So, the imaged center of a spatial circle and the center of the projection ellipse did not coincide actually. Therefore, center positioning errors existed [5]. Currently, known factors to cause this phenomenon are: the lens distortion [6,7], edge detection algorithm error[8–10], fitting algorithm error[11,12], perspective projection transforms the center deviation[13,14], etc. Xing [15] and other people, who obtained the imaged centers of concentric circles based on the theory of perspective projection and spatial analytic geometry. First, this method needed to determine the centers of two projected ellipses, and then obtained the real imaged centers by cross-ratio, but the radii information was necessary and the slight errors of centers of projected ellipses could significantly impact the final result. Literature [16] mentioned in concentric circles as the goal, the use of concentric circles for solving linear infinity, thus solving the exact center position, but two simultaneous quadratic curves does not intersect to solve infinite straight line, increasing the amount and complexity of computing solving; Kim et al. derived an improved method in literature [17] to find the position of the imaged centers by rank 1 constraint without radii information, but the algorithm was complex. The approach [18] presented by Heikkila utilized an iterative procedure to correct the imaged center of a circle, which is very useful for camera calibration; however, the priori conditions of knowing camera's parameters also narrow down its applications in other fields. An efficient method proposed in Literature [19] to detect the image of the common center of two concentric circles. Based on the theories that concentric circles are symmetric and straight line is projective invariant, the method pointed out that the imaged center lay on the line passing through the intersection points of tangent lines. Therefore, the optimal result is the intersection point of such lines. But this method required knowledge of epipolar constraint and the algorithm was complicated.

A simple and efficient method to accurately locate imaged centers is introduced in this paper. The method also gives way to compensate the lens distortion. Furthermore, the projection center can be obtained without knowing any camera parameters or other complex auxiliary constraints; moreover, the topology of imaged centers can be determined to calibrate a camera automatically depending on the compensated circles. The procedures of our method are quite simple and no iterative computation is involved and easy to be implemented.

2. Center projection error and compensation

Perspective pinhole imaging model is illustrated in Fig. 1. The space objects plane of the circular logo is π_1, π_2 is camera imaging

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http://dx.doi.org/10.1016/j.ijleo.2015.06.017
0030-4026/

plane. $O_c - X_cY_cZ_c$ is the camera coordinate system. Space circle becomes oval through a perspective projection on the camera image plane π_2. In the camera imaging plane, assumed that there is an axis AB through the ellipse center, which midpoint is the fitting center of ellipse. Connecting O_cA, O_cB intersect the space circular plane π_1 at C, D two points. Obviously, the intersections are located on the edge of the space circular plane.

Hypothesis 1. If the line CD is not the diameter of the space circle, the circle center in plane π_1 is not on the CD and the center of the projection is not on the AB in the image plane, so that the imaged center of a spatial circle and the center of the projection ellipse did not coincide.

Hypothesis 2. If the line CD is the diameter of the space circle which is the line AB corresponding to the object plane. So the point O_1 is the center point of the space circle and O_2 is the point of intersection of O_cO_1 and AB. When the object plane and the image plane of the camera parallel to each other, then, there is $AB||CD$. In accordance with the triangle parallel relationship, there are $\frac{O_cO_2}{O_cO_1} = \frac{AO_2}{CO_1}$, $\frac{O_cO_2}{O_cO_1} = \frac{O_2B}{O_1D}$, thus $\frac{O_2B}{O_1D} = \frac{AO_2}{CO_1}$, and because $AO_2 = O_2B$, for this reason, there is no center bias. If not present $AB||CD$, there is $AO_2 \neq O_2B$. At the center of the ellipse fitting is O_2', there must be $AO_2' = O_2'B$, so that O_2 is not overlaps with O_2', resulting in center deviations in the image.

After the space circle through a perspective projection transforms degenerate into elliptic, the fitting center (x_0, y_0) and the real projection center [20] $\left(x_0', y_0'\right)$ are

$$x_0 = \frac{2\left(n^2 + p^2 - \eta_i^2 e^2\right)\left(2mw + 2oq - 2\eta_i^2 df\right) - \left(2mn + 2op - 2de\eta_i^2\right)\left(2nw + 2pq - 2\eta_i^2 ef\right)}{\left(2mn + 2op - 2de\eta_i^2\right)^2 - 4\left(m^2 + o^2 - \eta_i^2 d^2\right)\left(n^2 + p^2 - \eta_i^2 e^2\right)}$$
$$y_0 = \frac{2\left(m^2 + o^2 - \eta_i^2 d^2\right)\left(2nw + 2pq - 2\eta_i^2 ef\right) - \left(2mn + 2op - 2de\eta_i^2\right)\left(2mw + 2oq - 2\eta_i^2 df\right)}{\left(2mn + 2op - 2de\eta_i^2\right)^2 - 4\left(m^2 + o^2 - \eta_i^2 d^2\right)\left(n^2 + p^2 - \eta_i^2 e^2\right)} \quad (1)$$

$$x_0' = \frac{nq - wp}{mp - no}, \quad y_0' = \frac{ow - mq}{mp - no} \quad (2)$$

wherein $a = \left(r_8t_y - r_5t_z\right)$, $b = (r_2t_z - r_8t_x)$, $c = \left(r_5t_x - r_2t_y\right)$, $d = (r_5r_7 - r_4r_8)$, $e = (r_1r_8 - r_2r_7)$, $f = (r_2r_4 - r_1r_5)$, $h = \left(r_7t_y - r_4t_z\right)$, $j = (r_1t_z - r_7t_x)$, $k = \left(r_4t_x - r_1t_y\right)$, $m = (a - X_id)$, $n = (b - X_ie)$, $w = (c - X_if)$, $o = (h + Y_id)$, $p = (j + Y_ie)$, $q = (k + Y_if)$. Among them, X_w, Y_w are the edges of the circle point coordinates, X, Y are the center coordinates in the world coordinate system, η_i as the radius of the circle in the world space, $r_i\,(i = 1, \ldots, 9)$ namely the camera rotation and translation parameters.

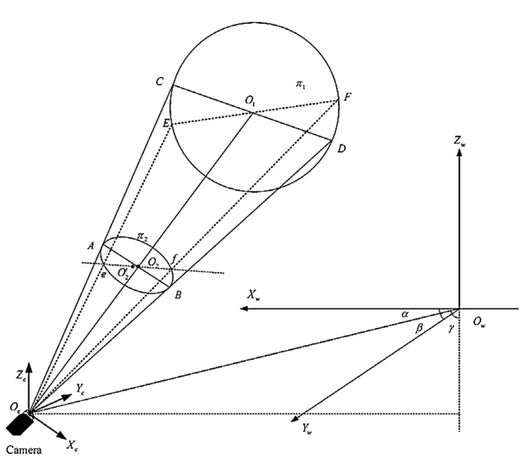

Fig. 1. The perspective projection transformation. α, β, γ denotes the rotation angle of camera around x, y, z axis.

If the camera imaging plane and the space objects plane parallel to each other, there are $x_0 = x_0'$ and $y_0 = y_0'$. When the camera imaging plane is not parallel to the space object plane, there are $x_0 \neq x_0'$ and $y_0 \neq y_0'$. At this time, the two points consisting of a line on the camera imaging plane, the slope of the line is

$$k = \frac{y_0' - y_0}{x_0' - x_0} \quad (3)$$

Take Eqs. (1) and (2) into Eq. (3), there is

$$k = \frac{(mp - no)(em - nd)(dw - mf) + (oe - pd)(dq - of)(mp - no) - (me - dn)^2(ow - mq) - (eo - dp)^2(ow - mq)}{(me - nd)(nf - ew)(mp - no) + (oe - pd)(pf - eq)(mp - no) - (me - dn)^2(nq - wp) - (eo - pd)^2(nq - wp)} \quad (4)$$

From the above equation shows that the slope has nothing to do with the radius of the circle. Therefore, the following conclusion can be drawn.

2.1. Conclusion

Round in space, after perspective projection transforms, the image center by ellipse fitting and the image geometric center of the ellipse is located on a straight line and the straight line through the real projection center of the space circle by perspective projection transformation in the image.

With Section 2.1, we use the sub-pixel edge detection [21] to obtain the accurate edge information from the image after the space circular mark projected. First, the Canny algorithm is used to search all the edges in the calibration image to obtain a single pixel wide edge of the closure assembly. Then the gradient amplitude as a weight is used to calculate the location and weights along the gradient direction to make the edge position sub-pixel correction. There is $\delta d = \sum_{i-1}^{n} g_i d_i / \sum_{i=1}^{n} g_i$, which d_i is the distance of a pixel along the gradient direction and the detected edge point, and g_i is the gradient amplitude; Finally detect oval from the set of edge by using roundness standards, and use the other prior information to remove the edge is not in conformity with the conditions such as elliptical long axis, short axis and fitting circle and so on.

Edge coordinates are processed to obtain the two coordinates of the farthest distance in the elliptical edges which the midpoint is the geometric center of the ellipse in the imaging plane. Then determine the distance of the geometric center between with the fitting center. If the distance less than a set value, take the midpoint of the two centers as a "real" center coordinates. If the two center distance greater than the set value, so, we connect these two centers to compose a straight line. The straight line intersects the ellipse in the imaging plane at $e_{\text{image}}(u_e, v_e)$ and $f_{\text{image}}\left(u_f, v_f\right)$. Assuming that the center point in the image of real projection point coordinates is $O_{\text{image}}(u_o, v_o)$, by the invariant linear and cross ratio under projective transformation, we can obviously get the equation

$$\begin{cases} \dfrac{u_o - u_e}{u_f - u_e} = \dfrac{R}{2R} \\ \dfrac{v_o - v_f}{v_f - v_e} = \dfrac{R}{2R} \end{cases} \Rightarrow \begin{cases} u_o = \dfrac{u_e + u_f}{2} \\ v_o = \dfrac{v_e + v_f}{2} \end{cases} \quad (5)$$