MULTI-IMAGE BASED CAMERA CALIBRATION WITHOUT CONTROL POINTS

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PS WG V/1

KEY WORDS: Camera calibration, Close range photogrammetry, Threedimensional reconstruction, Architecture photogrammetry, Bundle adjustment

ABSTRACT:

In recent years, many researches focus on building 3D object model in the fields of computer vision and photogrammetry, and camera calibration accordingly become the key problem. In this paper, the characteristic and shortage of the theory about calibration with vanishing points are exploited. The error was analyzed which is resulted from calibration based on vanishing points. Furthermore, a novel approach for camera calibration utilizing vanishing points in multi images is proposed. This approach overcame the demerit of the theory mentioned above; therefore the resulting precision of interior and exterior orientation parameters was improved.

1. INTRODUCTION

The research regarding obtaining 3D information of objects in nature from 2D images is always a hotspot in the fields of computer vision and photogrammetry, and the key problem is whether interior orientation parameters, which determine the geometry relationship between 2D images and 3D objects, can be obtained accurately. The process of obtaining interior orientation parameters of camera is in terms of camera calibration. For camera calibration the simplest imaging geometry model—linear imaging model of camera is commonly adopted. It is essential that the camera was calibrated before 3D object reconstruction.

In the field of photogrammetry, there are many conventional methods for camera calibrating such as Optical Laboratory Calibration, Test Range Calibration, On the Job Calibration and Stellar Calibration etc. the characteristic of these methods is high precision and demanding of the surveying job with high precision. However, most of them need place a number of reference objects in the front of camera, it makes the operation procedure not flexible, and in many special environments, there are no reference objects or test range can be used. With the rapid popularization and development of digital camera, many researchers try to solve this problem with a novel calibrating method without reference objects. For some applications the accuracy of camera calibration need not to be very high, and sometimes the focal length of camera is even various with shooting, thus it can't be calibrated beforehand. Therefore, the camera calibrating method without reference objects—calibration based on vanishing points is applied broadly.

2. THEORY AND ADJUSTMENT MODEL UTILIZING VANISHING POINTS OF SINGLE IMAGE

Under the perspective projection, lines, which are parallel in space, will converge to a point in the image plane, this point called vanishing point. Therefore, the surface image of objects taken by camera provide rich geometric line information (such as the parallel and perpendicular outlines of the building surface), the camera calibration can be fulfilled by fully utilizing vanishing points.

2.1 Single-view calibration with vanishing points

Many studies about camera calibration are based on vanishing points. Prof. Heuvel in Delft University was engaged in the study of Architectural Photogrammetry, where he calibrated camera using vanishing points [5]. He mainly calibrated interior orientation parameters of camera utilizing the image with three-point perspective, accordingly line photogrametry was used to solve the problem of 3D model reconstruction. Roberto Cipolla in University of Cambridge used strict geometrically intuitive condition of object (parallelism and orthogonality) to calibrate the intrinsic and extrinsic orientation parameters of the cameras and to recover Euclidean models of the scene from only two object images taking from arbitrary positions [6].

Schuster et al investigated the usefulness of vanishing points for steering(navigating) a robot, the objective is to steer a mobile robot based on the vanishing points of parallel lines in its environment [7]. Tsai employed a hexagon as the calibration target to generate a vanishing line of the ground plane from its projected image, and calibrated parameters include the orientation, the position, and the focal length of a camera [9]. Prof. Nevatia in University of Southern California calibrated the camera by utilizing the vanishing line in level plane and the vanishing point in perpendicular in order to analyze people's motion [8]; from the viewpoints of photogrammetry, [4] proposed an adjustment model of vanishing point that views line information in images as observation, thereby realized modeling only with single image. Its geometric model is shown as Fig.1:

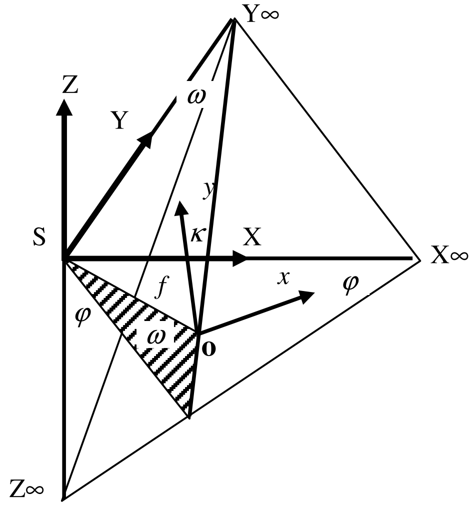

Figure 1. The relationship between vanishing points and orientation parameters

Suppose vanishing points in three orthogonal directions in one image respectively are $X\infty, Y\infty, Z\infty$, i.e. three-point perspective, and S denotes the perspective center. According to Fig.1, The principal point lies at the orthocentre of the triangle formed by the vanishing points.. The focal length f is:

$$f = \sqrt{(x_{X\infty} \cdot x_{Y\infty} + y_{X\infty} \cdot y_{Y\infty})} \tag{1}$$

Three exterior angle parameters are:

$$\begin{aligned} \tan\varphi &= \sqrt{f^2 + x_{Z\infty}^2 + y_{Z\infty}^2} \Big/ \sqrt{f^2 + x_{X\infty}^2 + y_{X\infty}^2} \\ \tan\omega &= f \Big/ \sqrt{x_{Y\infty}^2 + y_{Y\infty}^2} \\ \tan\kappa &= x_{Y\infty} \big/ y_{Y\infty} \end{aligned} \tag{2}$$

2.2 Adjustment model

Vanishing point is the key factor of calibrating because the parameters being calibrated are all the functions of vanishing points. Many methods can obtain vanishing points: in 1983 Barnard first proposed the expression of vanishing point based on Gaussian sphere representation [11], on the basis of this method, E. Lutton obtained vanishing point through Hough Transform [12]; Canadian John C.H.Leung discriminated the true vanishing points from points which naturally arise as the mutual intersection of many lines in the image utilizing the invariable property of vanishing points in two images [13]. In this paper an adjustment model between image lines and vanishing points is formulated to calibrate camera (detailed in [4]).

Supposing that one group of parallel lines in one-image crosses in vanishing point V, ij is one of those lines (Fig.2). Then three points i, j, V needs the condition of collinearity, if the coordinates of vanishing points (x_V, y_V) is unknown, thus we can build indirect observation adjustment model with unknown (formula 3):

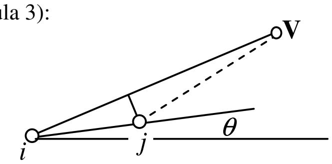

Figure 2. The definition of vanishing points

$$\begin{aligned} &(y_V - y_j)v_{xi} + (x_j - x_V)v_{yi} + (y_i - y_V)v_{xj} \\ &+ (x_V - x_i)v_{yj} + (y_j - y_i)dx_V + (x_i - x_j)dy_V + L_{i0} = 0 \\ &L_{i0} = -(x_j - x_i)(y_V - y_i) + (y_j - y_i)(x_V - x_i) \end{aligned} \tag{3}$$

When the angle between straight line and the horizontal $\theta < 45°$, formula 3 can be approximated by:

$$\begin{aligned} &(x_j - x_V)v_{yi} + (x_V - x_i)v_{yj} + (y_j - y_i)dx_V \\ &+ (x_i - x_j)dy_V + L_{i0} = 0 \end{aligned} \tag{4}$$

When the angle between straight line and the horizontal $\theta > 45°$, formula 3 can be approximated by:

$$\begin{aligned} &(y_V - y_j)v_{xi} + (y_i - y_V)v_{xj} + (y_j - y_i)dx_V \\ &+ (x_i - x_j)dy_V + L_{i0} = 0 \end{aligned} \tag{5}$$

Although many existing methods have the common feature that is based on single view. In next section we will, according to simulation, analyze errors of interior parameters calibrated by vanishing points of single view.

3. ERROR ANALYSIS

Single-view calibration using vanishing points is feasible theoretically. However, practical application indicates that this method only can do week calibration. Because generally the focus length is evaluated accurately but the principal point is not so precise [10]. Thus, a feasible assumption is that the principal point lies at the center of the image, which is a simple approximation [6].

From cube images of multi angle views simulated by computer (shown as Fig. 3), we can analyze the error trend of interior parameters calibrated by single-view method with vanishing points. The length of the cube is 50m, there are 11 straight lines in each direction. Given that the focal length of camera is 1510(pixel), and the principal point lies at the center of the image. In Fig. 3, there A is the angle between level projection of shooting aspect and direction of X; ν is the angle between shooting aspect and vertical direction. Assume that the standard error of observation σ0 is 0.1pixel, and view the error of parameters calibrated as error criterion.

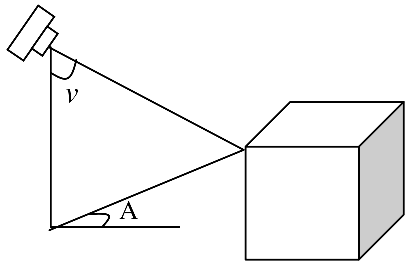

Figure 3. The sketch map of simulation

1) In simulation, firstly only when the value of angle v changes, we observe the extent of error of the principal point and the focal length influenced by v, Fig. 4 illustrates the error trend of the principal point and the focal length when v ranges from $20^{o}-70^{o}$ in the case of $A=45^{o}$.

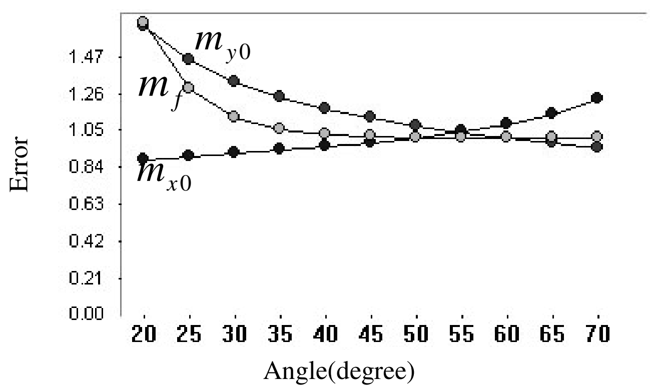

Figure 4. The error curve of f and (x0, y0) obtained when the angle v changed

The experiment above shows: when the angle v increases, the error of the focal length m_f becomes little, namely the precision of f becomes high. But the three error curves trend stable when the angle v is in the range from 40^{o} to 70^{o}; the error of x_0 m_{x0} becomes larger along with increasing the angle v, and the error of y_0 m_{y0} becomes contrariwise. Anyhow the errors of the focal length and the principal point are profoundly influenced by the shooting angle v.

2) Only when the focal length f changes, we observe the extent of error of the principal point and the focal length influenced by f, Fig. 5 illustrates the error trend of the principal point and the focal length when f ranges from $1510-4010$ in the case of $A=v=45^{o}$.

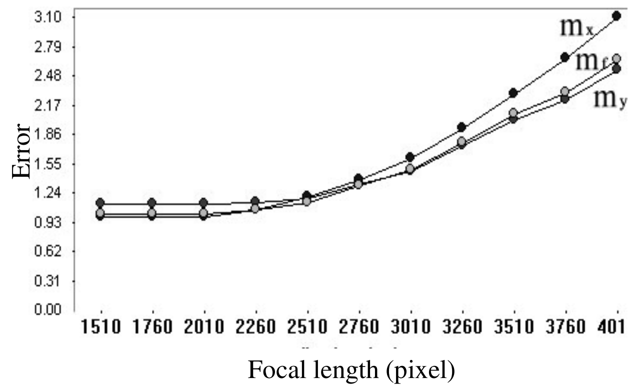

Figure 5. The error curve of f and (x0, y0) obtained when the focus length changed

3) Finally, only when the angle A changes, we observe the extent of error of the principal point and the focal length influenced by A, Fig. 6 illustrates the error trend of the principal point and the focal length when A ranges from $20^{o}-70^{o}$ in the case of $v=45^{o}$.

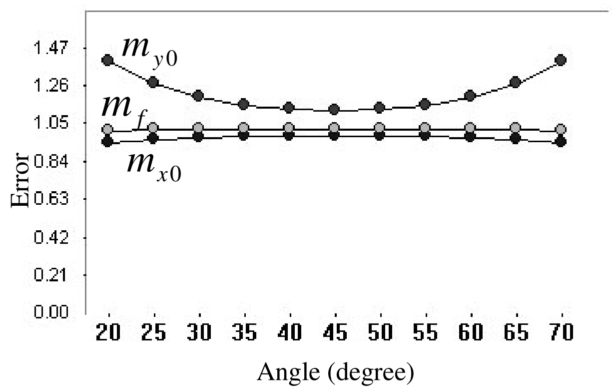

Figure 6. The error curve of f and (x0, y0) obtained when the angle A changed

The experiment indicates: the angle A influences little on the errors of the focal length and x_0, but influences much on the error of y_0, from experiment (3) we can see when $A=45^{o}$, the higher precision can be obtained. However, in practice it is not easy to obtain the optimal shooting angle, thus the precision of calibrated parameter based on single-view calibration is unstable. Aiming at the shortage of this method of camera calibration, we propose the calibrating method based on multi orientations and multi views.

4. MULTI-VIEW CALIBRATION WITH VANISHING POINTS

In single-view calibration utilizing vanishing points, the exterior orientation parameters of camera are not obvious in the model of calibration, therefore they are irrelevant with interior orientation parameters. Accordingly, the view of angle has a great impact on the accuracy of interior orientation parameters. According to error analysis above, we propose the idea that formulate interior and exterior orientation parameters into the adjustment model, and then calibrate by multi views rotating around the object. This method can restrain the error existing in single-view calibration.

Orientation parameters are the function of vanishing points, on the other hand, vanishing points are also the function of orientation parameters. Fig. 7 is illustrated as plane scenograph of Fig. 1.

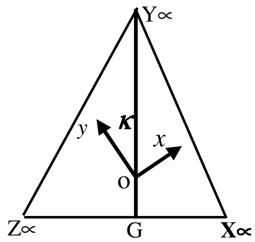

Figure 7. Plane scenograph

Linking with Fig. 1, we can obtain the functional relationship between exterior angle orientation parameters and vanishing points:

$$
\begin{aligned}
x_{X\infty} &= GX\infty \cos\kappa - oG\sin\kappa \\
&= f\cot\varphi\sec\omega\cos\kappa - f\tan\omega\sin\kappa \\
y_{X\infty} &= -GX\infty\sin\kappa - oG\cos\kappa \\
&= -f\cot\varphi\sec\omega\sin\kappa - f\tan\omega\cos\kappa \\
x_{Y\infty} &= OY\infty\sin\kappa = f\cot\omega\sin\kappa \\
y_{Y\infty} &= OY\infty\cos\kappa = f\cot\omega\cos\kappa \\
x_{Z\infty} &= -GZ\infty\cos\kappa - oG\sin\kappa \\
&= -f\tan\varphi\sec\omega\cos\kappa - f\tan\omega\sin\kappa \\
y_{Z\infty} &= GZ\infty\sin\kappa - oG\cos\kappa \\
&= f\tan\varphi\sec\omega\sin\kappa - f\tan\omega\cos\kappa
\end{aligned} \tag{6}
$$

The computation of vanishing points is not the aim of calibration, it just links straight lines of image to calibrating parameters. Therefore, vanishing point shouldn't be viewed as unknown in adjustment model. Linearizing formula (6),

$$
\begin{bmatrix} dx_{X\infty} \\ dy_{X\infty} \\ dx_{Y\infty} \\ dy_{Y\infty} \\ dx_{Z\infty} \\ dy_{Z\infty} \end{bmatrix}
=
\begin{bmatrix}
a_{11} & 1 & 0 & a_{14} & a_{15} & a_{16} \\
a_{21} & 0 & 1 & a_{24} & a_{25} & a_{26} \\
a_{31} & 1 & 0 & a_{34} & a_{35} & a_{36} \\
a_{41} & 0 & 1 & 0 & a_{45} & a_{46} \\
a_{51} & 1 & 0 & a_{54} & a_{55} & a_{56} \\
a_{61} & 0 & 1 & a_{64} & a_{65} & a_{66}
\end{bmatrix}
\begin{bmatrix} df \\ dx_0 \\ dy_0 \\ d\varphi \\ d\omega \\ d\kappa \end{bmatrix} \tag{7}
$$

$$
\begin{aligned}
a_{11} &= \cot\varphi\sec\omega\cos\kappa - \tan\omega\sin\kappa \\
a_{14} &= -f\csc^2\varphi\sec\omega\cos\kappa \\
a_{15} &= f\cot\varphi\tan\omega\sec\omega\cos\kappa - f\sec^2\omega\sin\kappa \\
a_{16} &= -f\cot\varphi\sec\omega\sin\kappa - f\tan\omega\cos\kappa \\
a_{21} &= -\cot\varphi\sec\omega\sin\kappa - \tan\omega\cos\kappa \\
a_{24} &= f\csc^2\varphi\sec\omega\sin\kappa \\
a_{25} &= -f\cot\varphi\tan\omega\sec\omega\sin\kappa - f\sec^2\omega\cos\kappa \\
a_{26} &= -f\cot\varphi\sec\omega\cos\kappa + f\tan\omega\sin\kappa \\
a_{31} &= \cot\omega\sin\kappa \qquad a_{35} = -f\csc^2\omega\sin\kappa \\
a_{36} &= f\cot\omega\cos\kappa \qquad a_{41} = \cot\omega\cos\kappa \\
a_{45} &= -f\csc^2\omega\cos\kappa \qquad a_{46} = f\cot\omega\sin\kappa \\
a_{51} &= -\tan\varphi\sec\omega\cos\kappa - \tan\omega\sin\kappa \\
a_{54} &= -f\sec^2\varphi\sec\omega\cos\kappa \\
a_{55} &= -f\tan\varphi\tan\omega\sec\omega\cos\kappa - f\sec^2\omega\sin\kappa \\
a_{56} &= f\tan\varphi\sec\omega\sin\kappa - f\tan\omega\cos\kappa \\
a_{61} &= \tan\varphi\sec\omega\sin\kappa - \tan\omega\cos\kappa \\
a_{64} &= f\sec^2\varphi\sec\omega\sin\kappa \\
a_{65} &= f\tan\varphi\tan\omega\sec\omega\sin\kappa - f\sec^2\omega\cos\kappa \\
a_{66} &= f\tan\varphi\sec\omega\cos\kappa + f\tan\omega\sin\kappa
\end{aligned}
$$

Put formula (7) into formula (3), thus, an adjustment model, where straight lines are directly relevant to calibrating parameters. Take $X\infty$ as example, get formula (8)(functions of $Y\infty, Z\infty$ are the same with function of $X\infty$):

$$
\begin{aligned}
&(y_V - y_j)v_{xi} + (x_j - x_V)v_{yi} \\
&+ (y_i - y_V)v_{xj} + (x_V - x_i)v_{yj} \\
&+ (a_{11}y_{ji} + a_{21}x_{ij})df + (a_{12}y_{ji} + a_{22}x_{ij})dx_0 \\
&+ (a_{13}y_{ji} + a_{23}x_{ij})dy_0 + (a_{14}y_{ji} + a_{24}x_{ij})d\varphi \\
&+ (a_{15}y_{ji} + a_{25}x_{ij})d\omega + (a_{16}y_{ji} + a_{26}x_{ij})d\kappa \\
&+ L_{i0} = 0 \\
&y_{ji} = y_j - y_i; \quad x_{ij} = x_i - x_j \\
&L_i = x_{ij}(y_V - y_i) + y_{ji}(x_V - x_i)
\end{aligned}
$$

(8)

To evaluate the error of the parameters calibrated by bundle adjustment based on multi images, we also can carry out the experiment of simulation (the parameters of experiment are the same as section 2.2). Differing from the simulation in section 2, four images are gathered with the mode rotating the angle κ every other 90^o, then all the data in the four images is formulated in the uniform mathematical model. The errors of the principal point and the focal length calibrated are shown as Fig. 8. Only when the angle v changes, no matter what the value v is, m_{x0} and m_{y0} are equal, the angle has little influence on the errors of the principal point and the focal length. And comparing Fig. 8 with Fig. 4, we can see that in the same condition of the angle, the calibrated precision based on multi-view is much higher than that based on single-view. (Note that the coordinate systems of Fig.8 and Fig.4 are in the same scale and two curves of m_{x0} and m_{y0} in fig.8 overlapped basically with each other.

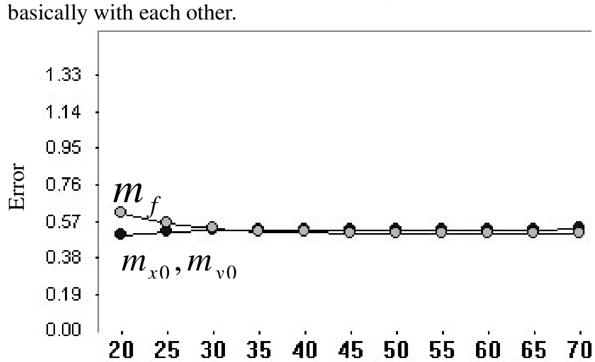

Figure 8. The error curve of f and (x0, y0) obtained when the angle v changed with multi-image

5. PRACTICAL DATA ANALYSIS

In practical calibrating test we use the Rollei d30 metric camera with known intrinsic parameters with image size 1280*1024(pixel). Its focal length is 1510 and the principal point is (670,492), note that the unit of the values above is pixel, and the coordinates of principal point locates in the coordinate system whose origin is left-top point of the image.

In calibrating experiment, four images are taken by the way of rotating to the corner of one building. (See Fig. (9)- (12)). First single-view calibrations based on vanishing points to the four images are respectively fulfilled (the results of calibration are listed in column 2-5 of Chart 1), simultaneously, the multi-view calibration uniting all of the four images is also done (the results of calibration are listed in the 6th column of Chart 1).

Figure 9. The original image (0^o)

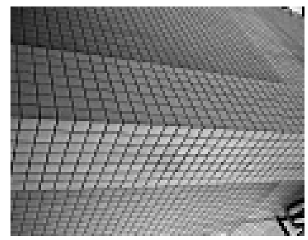

Figure 10. The original image (90^o)

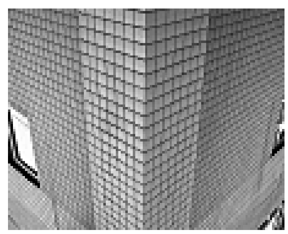

Figure 11. The original image (180^o)

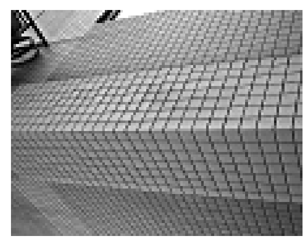

Figure 12. The original image (270^o)

As experiment is shown, in single-view calibration test, the calibrated principal point of camera is not stable; however, the calibrated interior parameters in multi-view calibration test are all better than those in single-view.

	Fig. 9	Fig. 10	Fig. 11	Fig. 12	Four images
f	1505.943050	1500.504439	1498.446842	1521.269439	1508.759933
x_0	633.089894	657.699167	677.716904	699.061394	665.803436
y_0	498.767641	458.748016	526.335161	493.018644	494.034017

Table 2. The result comparison with single-image and multi-image calibration

6. CONCLUSION

This paper, through a series of experiments, analyzed and evaluated the error of interior parameters of camera calibrated utilizing the method of vanishing point of single-view, and then we can conclude, the error of interior parameters calibrated with the method of vanishing point of single-view is greatly influenced by the factors of angle view, focal length etc. Thereby, we proposed a calibrating method of vanishing points based on multi orientations and multi views. Compared with single-view calibration, multi-view calibration has the characteristic as below: 1) put interior and exterior orientation parameters of camera together directly into the model of calibration. Through vanishing points, direct functional model between calibrated parameters and observations (image lines) is formulated. Sequentially, interior and exterior parameters are united to adjust computation, and then exterior angle orientation parameters adjusted (namely camera pose) can be used to build 3D object model. 2) the result is not influenced by shooting angle. Under the system of $A-\nu-\kappa$, when A,ν range from $20^{\circ}-70^{\circ}$, the error of interior parameters changes little; 3) the error of calibrated parameters has been improved greatly. Therefore, this camera calibration method with vanishing points of multi-image has the special advantage that other methods don't exist. In the case of no high-precision test range, this calibration method mentioned in this paper has good prospects aiming at applying in calibration of common zoom digital camera.

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