A new linear algorithm for calibrating central catadioptric cameras

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1. Introduction

Many computer vision applications, such as robot navigation, surveillance, teleconferencing, and virtual reality, require imaging a large field of view (FOV). One effective way to enhance the FOV is to combine mirrors with conventional cameras, which is called a catadioptric imaging system. Until now, many catadioptric imaging systems have been designed [1–3]. These systems can be separated into central class or non-central class by considering whether they have a unique viewpoint or not [4,5]. A single viewpoint is highly desirable due to its superior and useful geometric properties [6,7]. Baker and Nayar [4] presented the entire central class of catadioptric systems with a single traditional camera and a single mirror. They introduced that a central catadioptric system can be built by setting a parabolic mirror in front of an orthographic camera, or a hyperbolic, elliptical, planar mirror in front of a perspective camera, where the single viewpoint constraint can be fulfilled via a careful alignment of the mirror and the camera. Since then, the geometry and calibration of central catadioptric cameras attracted special attentions [5–16]. This paper aims at the calibration of central catadioptric cameras using line images.

In [5,8], Geyer and Daniilidis used a single view of two sets of parallel lines or a single view of three lines to calibrate a parabolic catadioptric camera. They proposed a unified sphere model for describing catadioptric cameras in Ref. [9]. Then, under this model, some works for calibrating central catadioptric cameras were performed in Refs. [6,10,11,16]. For example, Ying and Hu [10] applied the projection of a line or a sphere to calibrate central catadioptric cameras. This method cannot determine the focal length when the mirror parameter is unknown. Recently, Barreto and Araújo [6] studied the projective invariant properties of line images and showed that any central catadioptric camera can be fully calibrated from an image of three or more lines. This method includes three steps: Firstly, the principal point is determined by using the intersections of three or more line images. Then, the image of the absolute conic is estimated from the intersections of the polar lines of the estimated principal point with respect to line images, i.e. from the images of circular points. Lastly, the mirror parameter is determined through cross ratio invariants of line images.

In this paper, we present a novel approach for calibrating central catadioptric cameras from images of space lines under a single view. We firstly derive the projections of points under a central catadioptric camera and then establish a set of linear constraints on the catadioptric parameters from line images. The linear constraints permit us to calibrate any central catadioptric camera using three or more lines without prior information on the camera. In this approach, the step to estimate the principal point is the same as that in the literature [5,6,8,9]. The main contributions of this work are in that: (1) the method is linear; (2) all the camera parameters except for the principal point can be estimated simultaneously; (3) the method is suitable for all kinds of central catadioptric cameras. Compared with Ref. [10], this method can estimate focal length and mirror parameter simultaneously. Compared with Ref. [6], this method does not need to compute images of circular points, the locus of the line at infinity, and cross ratios, etc. Experimental results show the method is more robust and of higher accuracy.
Section 2 reviews the unified model given by Geyer and Daniilidis. The projection of points under this model is described in Section 3. Then in Section 4, the linear constraints on the catadioptric parameters and the calibration algorithm from line images are established. Experimental results are reported in Section 5, and followed are some conclusions in Section 6.

2. Central catadioptric camera

Geyer and Daniilidis [9] showed that the central catadioptric imaging process is equivalent to the following two-step mapping by a sphere (see Fig. 1):

1. Under the viewing sphere coordinate system O-xyz, a 3D point \( X = [x, y, z]^T \) is projected to a point \( X' \) on the unit sphere centered at the viewpoint \( O \) by \( X' = [x/r, y/r, z/r]^T, \ r = ||X|| \).

2. The point \( X' \) on the viewing sphere is projected to a point \( m \) on the image plane \( II \) by a pinhole camera through the perspective center \( C \). The image plane is perpendicular to the line going through the viewpoints \( O \) and \( O' \). This image plane \( II \) is also called the catadioptric image plane.

In this camera system, the optical axis of the pinhole camera is the line \( OC \). And thus, the principal point, denoted as \( p = [u_0, v_0, 1]^T \), is the intersection of the line \( OC' \) with the image plane \( II \). The distance point from \( O \) to \( OC' \), \( \zeta = [O - OC'] \), is called the mirror parameter. The values of \( \zeta \) are different with the mirror kinds being different. The mirror is a paraboloid if \( \zeta = 1 \), an ellipsoid or a hyperboloid if \( 0 < \zeta < 1 \), and a plane if \( \zeta = 0 \). The details can be found in Ref. [9]. In this paper, we always assume \( 0 < \zeta \leq 1 \), i.e. we do not consider the case of plane mirror.

Let the intrinsic parameter matrix of the pinhole camera be

\[
K = \begin{bmatrix}
f_u & s & u_0 \\
0 & f_v & v_0 \\
0 & 0 & 1
\end{bmatrix},
\]

(1)

where \( f_u, f_v \) are the scale factors along the image axes, \( p = [u_0, v_0, 1]^T \) is the principal point, and \( s \) is the parameter describing the skew of the two image axes. Then under the viewing sphere coordinate system O-xyz, a space point \( X \) is projected to its catadioptric image by

\[
m = \lambda [I, [\zeta e]'] \frac{X/||X||}{1} = \lambda K (X/||X|| + [\zeta e],
\]

(2)

with \( \lambda \) being a scalar, \( I \) the 3 \( \times \) 3 identical matrix, and \( e = [0, 0, 1]^T \).

For calibrating catadioptric cameras, there are totally six parameters \([f_u, f_v, s, u_0, v_0, \zeta] \) to be determined.

3. Projections of points

Proposition 1. Let \( m \) be the catadioptric image of a space point \( X \). Then under the pinhole coordinate system \( O^F - x^F y^F z^F \), the projection of the point \( X \) on the viewing sphere can be expressed as

\[
X^I = \frac{\sqrt{1 + \sqrt{1 + \frac{m^T m}{m^T \beta m}}}}{m^T \beta m} K^{-1} m,
\]

(3)

where \( \beta = (1 - \zeta^2)/\zeta^2, \ m = K^{-T} K^{-1} \).

In the case of paraboloid mirror, Eq. (3) can be simplified as

\[
X^I = \frac{2}{m^T \beta m} K^{-1} m.
\]

(4)

Proof. Let \( X^I \) be the projection of space point \( X \) on the viewing sphere under the pinhole camera system \( O^F - x^F y^F z^F \). By Eq. (2), we know

\[
X^I = \lambda K^{-1} m,
\]

\[
||\lambda K^{-1} m - \zeta e|| = 1.
\]

This is equivalent into

\[
m^T \beta m - 2 \zeta \lambda || \zeta e \|
\]

\[
\zeta^2 \beta e e = 1.
\]

(7)

Since \( e^T K^{-1} m = 1 \) and \( e^T e = 1 \), this equation is simplified as

\[
m^T \beta m - 2 \zeta \lambda + \zeta^2 - 1 = 0.
\]

(8)

By solving the equation, there is

\[
\lambda = \frac{\zeta (1 + \sqrt{1 + m^T \beta m})}{m^T \beta m}.
\]

(9)

Moreover, because any visible space point should be in front of the camera, \( \lambda > 0 \), we obtain

\[
\zeta = \frac{\zeta (1 + \sqrt{1 + m^T \beta m})}{m^T \beta m}.
\]

(10)

Hence by Eq. (5), we have

\[
X^I = \lambda K^{-1} m = \frac{\zeta (1 + \sqrt{1 + m^T \beta m})}{m^T \beta m} K^{-1} m.
\]

(11)

When the mirror is a paraboloid, there are \( \zeta = 1 \) and \( \zeta = 0 \). Therefore, Eq. (4) holds true too. □

Definition 1. \( \{m, m'\} \) is called a pair of antipodal image points if they could be images of two end points of a diameter of the viewing sphere.

Proposition 2. If \( \{m, m'\} \) is a pair of antipodal image points under a central catadioptric camera, we have

\[
\frac{1 + \sqrt{1 + m^T \beta m}}{m^T \beta m} m + \frac{1 + \sqrt{1 + m'^T \beta m'}}{m'^T \beta m'} m' = 2p.
\]

(12)

Consequently,

\[
(m \times m')^T p = 0.
\]

(13)

In the case of paraboloid mirror, Eq. (12) is simplified as

\[
\frac{1}{m^T \beta m} m + \frac{1}{m'^T \beta m'} m' = p.
\]

(14)
Proof. Let \( \{X^i, X^s\} \) be the endpoints of a diameter of a sphere whose image points are \( \{m, m'\} \). Since \( O \) is their middle point, there is
\[
X^s + X^s = 2O. \tag{15}
\]
By Proposition 1, we have
\[
X^s = \frac{\zeta(1 + \sqrt{1 + m^T\hat{em}})}{m^T\hat{em}} K^{-1} m,
\]
\[
X^s = \frac{\zeta(1 + \sqrt{1 + m'^T\hat{em}'}K^{-1} m'}. \tag{16}
\]
Under the pinhole camera system, the coordinate of \( O \) is \( \zeta e \). Substituting \( O = \zeta e \), Eqs. (16) and (17) into Eq. (15), we obtain
\[
1 + \sqrt{1 + m^T\hat{em}} - \sqrt{1 + m'^T\hat{em}'} = 2e.
\]  
From this equation and \( Ke = p \), Eq. (12) is obtained. Then, Eq. (13) or (14) is naturally true. □

4. Constraints and algorithm from lines

The catadioptric image of a space line is a conic, which is the image of a great circle on the viewing sphere under the pinhole camera (see Fig. 1). Since any two great circles on the viewing sphere have only two intersecting points, the catadioptric images of two lines have also only two real intersecting points. Hence, by Proposition 2, we have the following proposition, which is also shown in the literature [5, 6, 8, 9].

Proposition 3. Let \( C_i \) be the catadioptric images of \( N \) space lines, and \( \{m_{ij}, m'_{ij}\} \) be the two real intersecting points of \( \{C_i, C_j\} \), \( 1 \leq i < j \leq N \), then, we have the linear constraints on the principal point:
\[
\{m_{ij} \times m'_{ij}\}T p = 0, \quad 1 \leq i < j \leq N. \tag{19}
\]
By Proposition 3, we can linearly determine the principal point from three line images. After determining the principal point, we translate the origin of the image plane to the principal point by
\[
T_p = \begin{bmatrix}
1 & 0 & -u_0 \\
0 & 1 & -v_0 \\
0 & 0 & 1
\end{bmatrix}. \tag{20}
\]
Also, the whole image is transformed by \( \tilde{m} = T_p m \). Under the new coordinate system, the image of the absolute conic can be expressed as \( \hat{a} = K^{-1}\hat{K}^{-1} \), where \( K = T_p K \), which only depends on the skew \( s \) and the two scale factors \( f_s, f_p \). The following proposition gives the linear constraints on \( \{\hat{a} = K^{-1}\hat{K}^{-1}, \tau = (1 - \zeta^2)/\zeta^2\} \).

Proposition 4. For a pair of antipodal image points \( \{\tilde{m}, \tilde{m}'\} \), there is
\[
\begin{cases}
a^T \hat{m} = 2, \\
a^T \hat{m}' = 2.
\end{cases} \tag{21}
\]
where \( [a, a']^T = 2[\hat{m}, \hat{m}]^T o \), \( o^T \) denotes the generalized inverse, and \( o = [0, 0, 1]^T \) is the homogeneous coordinates of the original in the new image plane. In the case of paraboloid mirror, Eq. (21) is simplified as
\[
\begin{cases}
a^T \hat{m} = 2, \\
a^T \hat{m}' = 2.
\end{cases} \tag{22}
\]
Proof. By the translation \( T_p \) on the image, we have
\[
m = T_p^{-1} \tilde{m}, \quad m' = T_p^{-1} \tilde{m}'. \tag{23}
\]
Substituting them into Eq. (12), we obtain
\[
1 + \sqrt{1 + m^T\hat{em}} + 1 + \sqrt{1 + m'^T\hat{em}'} = 2o.
\]  
Let
\[
\begin{cases}
1 + \sqrt{1 + m^T\hat{em}} = a, \\
1 + \sqrt{1 + m'^T\hat{em}'} = a'.
\end{cases} \tag{24}
\]
Eq. (24) is that
\[
am + a' \hat{m}' = 2o. \tag{26}
\]
Because \( \{\hat{m}, \hat{m}'\} \) are two different points on the image plane, \( \text{rank}(\hat{m}, \hat{m}') = 2 \). Thus by applying the generalized inverse \( \{\hat{m}, \hat{m}'\}^T \) to Eq. (26) we get
\[
[a, a'] = 2[\hat{m}, \hat{m}]^T = 0. \tag{27}
\]
Now, \( a, a' \) are regarded as known scales. From Eq. (25), there is
\[
\begin{cases}
\sqrt{1 + m^T\hat{em}} = am^T\hat{e}m - 1, \\
\sqrt{1 + m'^T\hat{em}'} = am'^T\hat{e}m' - 1.
\end{cases} \tag{28}
\]
Simplifying these equations with \( m^T\hat{e}m \neq 0 \) and \( m'^T\hat{e}m' \neq 0 \) generates Eq. (21).

In the case of paraboloid mirror, by \( \tau = 0 \), \( a \neq 0 \), and \( a' \neq 0 \), we have Eq. (22). □

Proposition 5. The two constraints in Eq. (21) are equivalent, namely, there is only one independent constraint in Eq. (21) on \( \hat{a} \) and \( \tau \).

Proof. Assume \( \tilde{m} = [x, y, 1]^T, \tilde{m}' = [x', y', 1]^T \), then Eq. (26) is
\[
\begin{cases}
ax + a'x' = 0, \\
yv + a'y' = 0.
\end{cases} \tag{29}
\]
Solving this system gives
\[
\begin{cases}
a = 2 - a', \quad x = \frac{-a'x}{2 - a'}, \quad y = \frac{-a'y}{2 - a'} \quad \text{or} \quad \\
a' = 2 - a, \quad x' = \frac{-ax}{2 - a}, \quad y' = \frac{-ay}{2 - a}.
\end{cases} \tag{30}
\]
Substituting the coordinates \( \tilde{m} = [x, y, 1]^T, \tilde{m}' = [x', y', 1]^T \) into Eq. (21), we obtain
\[
\begin{cases}
a^2x^2\tilde{e}_{11} + 2axy\tilde{e}_{12} + a^2y^2\tilde{e}_{22} - \tau = 2a - a^2, \\
a^2x'^2\tilde{e}_{11} + 2ax'y'\tilde{e}_{12} + a^2y'^2\tilde{e}_{22} - \tau = 2a' - a'^2.
\end{cases} \tag{31}
\]
We obtain the second equation of (31) if we substitute Eq. (30) into the first equation of (31). And we obtain the first equation of (31) if we substitute Eq. (30) into the second equation of (31). It follows that the two equations of (21) are not independent. □
pairs of antipodal points from each of the three line images can give \(\{\hat{\theta}, \zeta\}\) fully. Using more pairs could boost the calibration’s stability.

An outline of our algorithm for calibrating central catadioptric cameras is summarized as follows:

Step 1: Compute the principal point \(\mathbf{p}\) by the linear constraints (19).

Step 2: Randomly choose points on each line image, and determine their antipodal points by the computed principal point \(\mathbf{p}\).

Step 3: Compute the matrix \(\hat{\theta}\) and the parameter \(\zeta\) by the linear constraints (21).

Step 4: Compute the scale factors \(s\) and skew factor \(f_s, f_v\) from \(\hat{\theta}^{-1}\) by using Cholesky decomposition and compute the mirror parameter by \(\zeta = 1/\sqrt{1 + \tau}\).

In this algorithm, the step to estimate the principal point is the same as that in the literature [5,6,8,9]. The significant differences are as follows: In Ref. [6], firstly the parameter matrix \(\hat{\theta}\) is estimated from the images of circular points, and then the mirror parameter \(\zeta\) is determined by using the cross ratio invariants. While, in our new algorithm, the parameters \(\{\hat{\theta}, \zeta\}\) can be estimated simultaneously, and it is unnecessary to compute the images of circular points and the cross ratios. Such differences make our method more robust and accurate, which is also validated by experimental results.

5. Experimental results

Generally, calibrations based on lines are sensitive to the estimation errors of the conic curves. In this section, we report the sensitivity analysis of the proposed algorithm (referred to as CLP) and the experiments using real images. As our work is closely related with Ref. [6] (referred to as CP), we also show its result.

![Graphs showing sensitivity analysis](image)

Fig. 2. The graphics show the sensitivity to errors on the conic curves of calibration with different kinds of mirrors: (a)–(c) the conic curves are translated, respectively, for \(\zeta = 0.8, 0.9, 1.0\). In (c), the lines with different colors are nearly same. (d)–(f) the conic curves are rotated, respectively, for \(\zeta = 0.8, 0.9, 1.0\). (g)–(i) changing the eccentricity of the conic curves, respectively, for \(\zeta = 0.8, 0.9, 1.0\).

5.1. Sensitivity analysis

The intrinsic parameters of the simulated catadioptric cameras are \([f_u, f_v, s, u_0, v_0] = [500, 400, 0.512, 384]\) and the mirror shape parameter \(\zeta\) is set to 0.8, 0.9, 1.0, respectively. Synthetic images of a random set of three space lines are generated from three great circles on the viewing sphere. In order to evaluate the stability of CLP, we distort the catadioptric projections of each line. The camera is calibrated using distorted images of the three lines by CLP and CP, respectively, where the conic curves are fitted by DLT (direct linear transformation). The estimation results are compared with the ground truth, and the RMS relative error of each parameter is computed over 100 trails. The experimental results are shown in Fig. 2, where clpfu, clpfv, clps (cfpu, cpfv, cps) denote the scale factors and the mirror parameter estimated by CLP (CP). From Fig. 2a to c, each conic curve is independently translated by a random 2D vector. The translation direction is generated from a uniform distribution, while the amplitude is chosen from a Gaussian distribution with zero mean and standard deviation (horizontal axis in the graphics). From Fig. 2d to f, each conic curve is independently rotated around the image center by an angle \(\theta\), while from Fig. 2g to i, the distortion is caused by a change in percentage \(\varepsilon\) on the eccentricity of each conic curve. Both \(\theta\) and \(\varepsilon\) are randomly generated from a Gaussian distribution with zero mean. From Fig. 2, we can see that the accuracy of the calibration is degraded gracefully with respect to the distortion level. For paracatadioptric case with translation, as shown in Fig. 2c, all the parameters estimated by the two methods are nearly same. For paracatadioptric case with rotation, as shown in Fig. 2i, all the parameters estimated by the two methods are very close. Except for these, all the other figures show that CLP is more robust than CP, which supports our conjectures in Section 4.
5.2. Experiments with real data

With paracatadioptric camera: Fig. 3 (a) shows an image downloaded from http://mail.isr.uc.pt/~carloss/software/software.htm, which was captured by an uncalibrated paracatadioptric camera [6]. The FOV is 180° [12]. The used conic curves that several lines in the scene are projected to are shown in the figure (blue curves), and the image points used for curve fitting are manually selected by using the software presented in this website. Generally, only a small segment of the conic curve corresponding to the catadioptric projection of a line is visible in catadioptric images due to the partial occlusion. It is very difficult to estimate the conic curve correctly. The conic fitting algorithm proposed in Ref. [12] has solved this problem for the paracatadioptric camera. It is used to estimate the conic curves in this experiment. Using every three or four of the four curves, we calibrate the camera by CLP and CP, respectively. The calibration results are shown in Table 1, where CLP3 and CP3 (CLP4 and CP4) denote the algorithms using three (four) lines of CLP and CP, respectively. Later in Table 2, these notations are the same meanings. From the table, we see that the two methods perform comparably. The comparison of FOV shows that CLP is better.

With hypercatadioptric camera: Five images of a stick with six control points were taken by a perspective camera with a hyperbolic mirror. This mirror is designed by the Center for Machine Perception, Czech Technical University, its FOV is 217.2°, and the eccentricity of the hyperbolic mirror is 1.302, corresponding to \( \frac{1}{af} = 0.966 \).

Fig. 3 (b) shows one of the five images. The image resolution is of 2048 × 1536 pixels. For each image, the six points (shown in the image) are manually selected. Using every three or four of the five conic curves, the camera is calibrated through CLP and CP, where the
conic curves are fitted by using the six control points with DLT. The results are shown in Table 2. Since the estimation of the conic curves by DLT is not well, every parameter except for principal point estimated by CLP and CP are much different. From the comparisons of FOV and the mirror parameter \( \xi \), we can see the estimations by CLP are closer to the real values.

We have performed a number of experiments with simulated and real data. The experimental results show that CLP can improve the calibration’s robustness. Some of the reasons are as follows: the computation of CLP is very simple. It estimates the camera parameters from image points of spatial lines linearly and directly. It does not need several complex computations such as computing the images of circular points, computing the locus of the line at infinity, computing the cross ratios, and so on. As a result, the calibration by CLP is more robust to errors of conic estimations. The calibration by CP needs to compute the images of circular points, to compute the locus of the line at infinity, and to compute the cross ratios, which uses the estimated conic curve more than once.

6. Conclusions

In this paper, we firstly introduced the projection of points on the viewing sphere under a central catadioptric camera. Then using the projection of points, we established a set of linear constraints on the catadioptric parameters from line images. The linear constraints permit us to linearly calibrate any central catadioptric camera without prior knowledge on the camera. In the proposed algorithm, the principal point is estimated by the same way as that in the literature. While, different from the way in the literature, all the other camera parameters including mirror parameter are estimated simultaneously. Extensive experiments show that the proposed approach can improve the calibration’s robustness.

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References


Table 1
Calibration results from Fig. 3(a)

<table>
<thead>
<tr>
<th></th>
<th>( f_u )</th>
<th>( f_v )</th>
<th>( u_0 )</th>
<th>( v_0 )</th>
<th>FOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLP3</td>
<td>374.2 ± 45.7</td>
<td>363.5 ± 44.2</td>
<td>-6.2 ± 0.78</td>
<td>511.2 ± 12.8</td>
<td>395.5 ± 39.9</td>
</tr>
<tr>
<td>CP3</td>
<td>373.1 ± 45.7</td>
<td>363.3 ± 44.5</td>
<td>-6.5 ± 0.8</td>
<td>511.2 ± 12.8</td>
<td>395.5 ± 39.9</td>
</tr>
<tr>
<td>CLP4</td>
<td>387.4</td>
<td>375.8</td>
<td>-7.2</td>
<td>511.1</td>
<td>393.7</td>
</tr>
<tr>
<td>CP4</td>
<td>385.2</td>
<td>375.1</td>
<td>-6.8</td>
<td>511.1</td>
<td>393.7</td>
</tr>
</tbody>
</table>

Table 2
Calibration results from Fig. 3(b)

<table>
<thead>
<tr>
<th></th>
<th>( f_u )</th>
<th>( f_v )</th>
<th>( u_0 )</th>
<th>( v_0 )</th>
<th>( \xi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLP3</td>
<td>527.1 ± 15.1</td>
<td>541.1 ± 14.6</td>
<td>-28.0 ± 21.1</td>
<td>995.4 ± 13</td>
<td>704.7 ± 11</td>
</tr>
<tr>
<td>CP3</td>
<td>383.7 ± 10.2</td>
<td>397.4 ± 12.2</td>
<td>12.8 ± 0.9</td>
<td>995.4 ± 13</td>
<td>704.7 ± 11</td>
</tr>
<tr>
<td>CLP4</td>
<td>545.1 ± 41.2</td>
<td>564.9 ± 48.2</td>
<td>-41.1 ± 26.2</td>
<td>1031.4 ± 35</td>
<td>745.3 ± 33</td>
</tr>
<tr>
<td>CP4</td>
<td>383.0 ± 8.6</td>
<td>396.4 ± 9.6</td>
<td>-2.5 ± 2.7</td>
<td>1031.4 ± 35</td>
<td>745.3 ± 33</td>
</tr>
</tbody>
</table>

Fig. 3. The used images by (a) paracatadioptric camera; (b) hypercatadioptric camera.

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