A Unified Camera Calibration Using Geometry and Blur of Feature Points

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Abstract

Although a lot of camera calibration methods have been proposed so far, most of them deal with the pinhole camera model, which neglects the defocus effects introduced by real lens systems. In this paper, we present a unified camera calibration method which determines both internal and external camera parameters from several blurred edges detected in a single image. First, we show the calibration procedure using our thin lens based camera model. Then, we describe how to determine the position and the width of blurred features in an image. Experiments have been done with real images and those results have shown the validity of our method.

1. Introduction

Camera calibration is an important issue in both computer vision and computer graphics. Therefore, a lot of work has been done to obtain camera parameters from real images. One of the most famous calibration methods was proposed by Tsai [16]. This method uses a target that has several feature points of known position. Zhang proposed a similar method for a restricted case when the target is a plane surface[17]. Another approach called “self-calibration” was proposed[12, 10]. This calibration method uses objects in the images, so it doesn’t need any special targets. Since these methods are based on the pinhole camera model, defocus effects made by real lens systems are not considered. Fig. 1 shows an example of a captured image taken by a real lens system. Because of the blur caused by the defocus effect, it is difficult to determine the positions of the feature points.

In the research of depth from focusing[7, 14, 2, 5] and depth from iris[13, 4, 15], a lot of camera models were proposed to deal with the defocus effect. On the other hand, in the research of depth from zooming[11, 9, 8], the depth was estimated using the pinhole camera model. Recently, we reported another approach to depth recovery based on the defocus analysis by zooming[1], and proposed a new camera model which describes the mutual relationship between zoom, focus and iris parameters[3]. In our previous work, the internal camera parameters, i.e. focal length and lens aperture, were calibrated from a set of images taken by varying camera parameters.

In this paper, we propose a new camera calibration method which takes into account both geometric information of the feature points and the defocus information of edges in an image. We first show the thin lens camera model which enables us to analyze the image blur as well as the perspective projection by the lens. Then, we show the detail of our calibration method. Our calibration method determines both internal and external camera parameters simultaneously from the width of blur and the position of the feature points. In the experiments section, we have performed the camera calibration using our method, and we have evaluated the accuracy of the calibration result.

Figure 1. An image of a calibration target taken by a real lens system.
2. Camera Calibration

2.1. Camera Model

Figure 2 shows the thin lens based camera model which describes the mutual relationship between zoom, focus and iris parameters[3]. In the figure, $w$ is an effective focal length which is defined as a distance between the lens center $O$ and the image plane, $d$ is an effective lens diameter, $U$ is a focused distance, and $s$ is the distance of the object. The parameter $c$ is defined as a distance between the frontal position of the actual zoom lens $R$ and the lens center $O$.

2.2. Geometric Information

Let the world coordinate $(X_w, Y_w, Z_w)$, and let the camera coordinate $(x, y, z)$ of a point $P$, as shown in Figure 3. The relationship between these coordinates is represented by using the rotation matrix $R$ and the translation vector $T$ as follows.

$$
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix} = R \begin{bmatrix}
x_w \\
y_w \\
z_w
\end{bmatrix} + T
$$

(1)

$$
R = \begin{bmatrix}
r_1 & r_2 & r_3 \\
r_4 & r_5 & r_6 \\
r_7 & r_8 & r_9
\end{bmatrix}, \quad T = \begin{bmatrix}
T_x \\
T_y \\
T_z
\end{bmatrix}
$$

(2)

where $r_i (1 \leq i \leq 9)$ are elements of the rotation matrix $R$, and $T_x, T_y, T_z$ are elements of the translation vector $T$.

The perspective projection from the camera coordinate $(x, y, z)$ to the image coordinate $(u, v)$ is represented as follows.

$$
u = w \frac{x}{z}, \quad v = w \frac{y}{z}
$$

(3)

where $w$ is an effective focal length. The pixel position $(X, Y)$ is calculated using image coordinate $(u, v)$, image center $(C_x, C_y)$, and pixel size $(d_x, d_y)$.

$$
X = C_x + \frac{u}{d_x}Y = C_y + \frac{v}{d_y}
$$

(4)

The relationship between the pixel position $(X, Y)$ of the point $P$ and the world coordinate $(X_w, Y_w, Z_w)$ is represented by the following equations.

$$
X = C_x + \frac{w}{d_x}r_1X_w + \frac{w}{d_x}r_2Y_w + \frac{w}{d_x}r_3Z_w + T_x + \frac{w}{d_x}r_7X_w + \frac{w}{d_x}r_8Y_w + \frac{w}{d_x}r_9Z_w + T_z
$$

(5)

$$
Y = C_y + \frac{w}{d_y}r_4X_w + \frac{w}{d_y}r_5Y_w + \frac{w}{d_y}r_6Z_w + T_y + \frac{w}{d_y}r_7X_w + \frac{w}{d_y}r_8Y_w + \frac{w}{d_y}r_9Z_w + T_z
$$

(6)

2.3. Width of Blur

The width of blur $b$ of the object is a function of $d$, $w$, $c$, $U$, and $s$, as shown in figure 2. From the geometric relationship of these parameters, $b$ can be written as follows[3].

$$
b = wd \left| \frac{1}{s+c} - \frac{1}{U+c} \right|
$$

(7)

Since the origin of the camera coordinate $O_c$ in figure 3 is corresponding to the lens center $O$ in figure 2, $z$ equals $s+c$ in the equation (7). We define the focused distance $U'$ from $O_c$ as $U' = U+c$, and obtained the following equation.

$$
b = wd \left| \frac{1}{r_7X_w + r_8Y_w + r_9Z_w + T_z} - \frac{1}{U'} \right|
$$

(8)

2.4. Calibration Using Geometry and Blur

By minimizing $E$ in the following equation, we can estimate the camera parameters such as $R$, $T$, $w$, $d$, and $U'$.

$$
E = \sum_{i=1}^{n} \left\{ \left( X_i - \hat{X_i} \right)^2 + \left( Y_i - \hat{Y_i} \right)^2 + \left( b_i - \hat{b_i} \right)^2 \right\}
$$

(9)
where \( n \) is the number of feature points, \( \hat{X}_i, \hat{Y}_i \) are image coordinates of the feature point \( P_i \), and \( \hat{b}_i \) is the blur width at the feature point obtained from the image. If we don’t take into account the blur effect which is expressed by the width of blur \( b \), the equation (9) is the same as Tsai’s calibration method.

### 2.5. Position and Width of Blur from Image

We show the procedure to determine the position \((X,Y)\) of the feature point and the width of blur \( b \). When a stepping edge is defocused, the brightness along a perpendicular line of the edge is represented by the following equation [3],

\[
g(u) = \frac{1}{2} + \frac{1}{\pi} \left( u \sqrt{1 - u^2} + \arcsin u \right)
\]

where the brightness range is normalized between 0 and 1. The width of the blurred edge is determined by fitting this brightness function to the brightness profile across the blurred edge, as shown in figure 4. The position of the edge point is obtained by calculating the half point of the blurred edge. If the edge is slanted, the width of blur \( b' \) is calculated as follows.

\[
b' = b \times \cos \theta
\]

where \( b \) is the width of blur using the horizontal scan line, \( \theta \) is the angle between the edge and the vertical scan line.

Because a feature point is a intersection of edges, it is difficult to determine the position of the point by fitting the brightness profile. So we determine the edge point and the width of blur along each horizontal and vertical line, and calculate the position of the feature point and the width of blur by interpolating the values on the edges as shown in figure 5. Figure 5 (a) shows edge points along the edge. A feature point is determined by fitting a line to the edge points along the edge, as shown in figure 5 (b). From the width of blur at the edge points in figure 5 (c), the width of blur at the feature point is calculated as shown in figure 5 (d).

### 3. Experimental Results

We have performed some experiments with real images and have evaluated the accuracy of the calibration result. The real images are taken by using a CCD video camera (SONY XC–007) with a zoom lens (Canon J16×9.5B4R-AS). The resolution of the images is 512×480 pixels. Figure 6 (a) is a real image of a calibration target which has 25 feature points, and figure 6 (b) is the generated image using the camera parameters obtained by the camera calibration. We use the accumulation buffer algorithm[6] to generate images. Figure 6 (c) shows the difference between the position of the feature points obtained from a real image and the position calculated by using 3D position of the feature points and camera parameters. The average position error of feature points was 0.58 pixels and that maximum error was 1.70 pixels. Figure 7 (a) shows brightness profiles of the real image and the generated image along the horizontal line at \( Y = 240 \). Figure 7 (b) shows the width of blur along the second edge from the right. As shown in Figure 7, both the brightness profile and the blur profile are quite similar. From these basic experiments, we found that the error was small enough to use for an image synthesis.

### 4. Conclusion

This paper has presented a novel camera calibration method that takes into account both geometric information and the width of blur in an image. The experimental results have demonstrated the validity of our camera calibration method and have also shown its applicability to the image synthesis.
Figure 6. Error evaluation of feature points.

Figure 7. Comparison of real and generated images.

References