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# The location and identification of concentric circles in automatic camera calibration

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ABSTRACT

In order to eliminate user's interaction, a new method based on concentric circles pattern is proposed to calibrate a camera automatically and accurately. Firstly, the imaged centers of concentric circles are located using the principles of cross-ratio and pole–polar; secondly, different centers are identified by cross-ratio; finally, the topology of imaged centers is established to calibrate the camera automatically. The effectiveness and accuracy of the method is demonstrated by experiments with simulated and real images. It is shown that this method has high robustness and precision, can be efficiently used in many applications.

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## 1. Introduction

Camera calibration is one of the key technologies in the fields of pattern recognition, machine vision and visual measurement [1–3]. For traditional camera calibration approaches, i.e., those using calibration targets, the calibration accuracy depends on the accuracy of target extraction from the image of calibration pattern. Thus, it is important to accurately determinate the image coordinates. Since the proposition of Zhang's method [4], plane-based camera calibrations have become the most popular ones. To those methods, the correspondences between spatial feature targets and their projections on image are necessary to calculate the parameters of the camera, therefore, both locations and topology of the projections are required.

The merits with high-recognition and anti-noise of circle make it attractive for computer vision as a feature target [5], but the correspondences between targets and their projections are often difficult to be known. Literatures [7,8] pointed out that the imaged center of a spatial circle and the center of the projection ellipse did not coincide actually. In recent years, many approaches were addressed to locate the real imaged center. Because a single circle had less geometric constraints, most of these methods were based on concentric circles. The approach [7] 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. Literature [9] introduced a new projective invariant that the imaged centers always lay on the line defined by the two ellipse centers. This method is quite simple, but the physical models of concentric circles should be known. Kim et al. derived an improved method in literature [10] to find the position of the imaged centers by rank 1 constraint without radii information, but the algorithm was complex. Abad et al. [11] proposed a new method using the prior knowledge that the imaged center of a circle is always enclosed in its projected ellipse, so a circle of radius zero should project onto the imaged center in the limitation. This method was quite novel and a good result could be obtained. Literature [12] obtained the imaged centers of concentric circles based on the theory of perspective projection and spatial analytic geometry. This method needed to determine the centers of two projected ellipses firstly, 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. Jiang et al. [13] introduced a geometric method to detect the real imaged center using iterative method to converge to imaged centers and optimizing the centers by homological constraints. This method does not need to know the camera parameters and metric information of concentric circles, but its efficiency and stability need to be verified due to the use of iterative methods. Literature [16] presented an efficient method 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

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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 automatic application in camera calibration was not mentioned in that paper. In conclusions, these methods are subject to certain limitations in practical applications; moreover, most of them have not put sufficient efforts on the automatic identification of targets for the practice of camera calibration. Up to now, in order to determine the correspondences, some methods need a few appropriate user's interactions [4], but reduce the automaton of camera calibration; others need a special pattern attaching with additional markers [6] which damage the integrity and simplicity of the pattern.

In order to overcome the above defects, a simple and efficient method to accurately locate imaged centers is introduced in this paper. The methods mentioned above and our approach are all based on conventional image processing for target determination; thus, the main differences are mainly in how to locate the accurate imaged centers from these targets. The procedures of our method are quite simple and no iterative computation is involved; furthermore, the projection center can be obtained without knowing any camera parameters or the metric information of concentric circles; moreover, the topology of imaged centers can be determined to calibrate a camera automatically depending on the geometric constraints of concentric circles. The main properties of our method can be summarized as follows:

- Locate the real imaged centers of spatial circles accurately.
- Identify different features targets automatically.
- The physical models of concentric circles are not necessary for location or just the proportion of inner and outer radii should be known when identification is needed.
- Any information about intrinsic or extrinsic parameters of a camera is not required.
- Only simple linear computation is involved.
- It can be applied for the calibration of both camera and system architecture.

The rest of this paper is organized as follows: the basic principles of the method with detection and location of the features are expressed in Section 2. Section 3 presents the new method to identify different features to construct the topology. The new methods are experimented and summarized in Section 4. A short conclusion is given in Section 5.

## 2. Location of imaged centers

### 2.1. The basic theory

The basic theory involved in the method presented in this paper will be described simply.

#### 2.1.1. The matrix form of ellipse

The common expression of 2-D ellipse is $ax^2+by^2+cxy+dx+ey+f=0$, so the equivalent matrix form can be expressed as

$$\mathbf{p}^T E\mathbf{p}=0, \tag{1}$$

where, $E=\begin{bmatrix} a & c/2 & d/2 \\ c/2 & b & e/2 \\ d/2 & e/2 & f \end{bmatrix}, \quad \mathbf{p}=\begin{bmatrix} x & y & 1 \end{bmatrix}^T.$

#### 2.1.2. The harmonic conjugated points

If $\mathbf{P}_a$,$\mathbf{P}_{a'}$,$\mathbf{P}_m$and$\mathbf{P}$ are four collinear points and satisfy $\{\mathbf{P}_a,\mathbf{P}_{a'},\mathbf{P}_m,\mathbf{P}\}=-1$, where $\{\cdot\}$ indicates the cross-ratio function, then $\mathbf{P}_a$ and $\mathbf{P}_{a'}$are called the harmonic conjugated points with respect to $\mathbf{P}_m$and $\mathbf{P}$, especially, if $\mathbf{P}_m$ is the midpoint of $\mathbf{P}_a$ and$\mathbf{P}_{a'}$, then $\mathbf{P}$ will be the point at infinity.

#### 2.1.3. The pole–polar relationship

If $\mathbf{I}_o$ is the imaged center of a spatial circle, $\mathbf{l}_\infty$is the intersection line (vanishing line) of the spatial circle plane with the plane at infinity, $E$is the projection ***conic*** of the spatial circle, then the following formula can be obtained [14]

$$s\mathbf{l}_\infty=E\times\mathbf{I}_o, \tag{2}$$

where $s$ is a constant factor.

### 2.2. The imaged center

Until now the algorithms of ellipse extraction are widely available and mature, so we will not put much attention on extracting ellipses but on locating the imaged centers. We extract the ellipses using the canny detector and fit the contours in ellipses by the least square method (LSM); the two ellipses are considered as the projections of a pair of concentric circles if the distance of their centers is less than the threshold value.

#### 2.2.1. Determination of vanishing points

In space, a pair of concentric circles are shown in Fig. 1. $\mathbf{P}_a$ and $\mathbf{P}_{a'}$are two points of the outer circle crossed by a line, $\mathbf{P}_b$ and $\mathbf{P}_{b'}$are points of the inner circle crossed by the same line. $\mathbf{P}_m$ is the common midpoint of the segments $\overline{\mathbf{P}_a\mathbf{P}_{a'}}$ and $\overline{\mathbf{P}_b\mathbf{P}_{b'}}$. $\mathbf{P}_\infty$ (vanishing point) is the infinite point on the line. From Section 2.1 we have two equations $\{\mathbf{P}_a,\mathbf{P}_{a'};\mathbf{P}_m,\mathbf{P}_\infty\}=\{\mathbf{P}_b,\mathbf{P}_{b'};\mathbf{P}_m,\mathbf{P}_\infty\}=-1$.

Fig. 2 shows the projections of the pair of concentric circles in Fig. 1. Elements with the same subscripts are the projections of corresponding ones, such as $\mathbf{I}_a$is the projection of $\mathbf{P}_a$. Since the cross-ratio is projective invariant, we have two equations

$$\{\mathbf{I}_a,\mathbf{I}_{a'};\mathbf{I}_m,\mathbf{I}_\infty\}=\{\mathbf{I}_b,\mathbf{I}_{b'};\mathbf{I}_m,\mathbf{I}_\infty\}=-1, \tag{3}$$

where$\mathbf{I}_a$, $\mathbf{I}_{a'}$, $\mathbf{I}_b$ and $\mathbf{I}_{b'}$can be determined by solving equations of the line and ellipses. $\mathbf{I}_m$ and $\mathbf{I}_\infty$are one of the two pair solutions of the 2nd-order polynomial from Eq. (3). According to the fact that $\mathbf{I}_m$ lies inside the segment $\overline{\mathbf{I}_b\mathbf{I}_{b'}}$, the right solution pair can be chosen, i.e. $\mathbf{I}_m$ and $\mathbf{I}_\infty$ can be determined.

#### 2.2.2. Determination of vanishing line

As described in Section 2.2.1., $N$ vanishing points can be computed and denoted as $\mathbf{I}_\infty^i$ $(i=1,\ldots,N)$. Ideally, all the vanishing points should be on the common line (vanishing line). The vanishing line can be obtained using LSM whose objective function is the sum of the squared Euclidean distances from vanishing points to the vanishing line, i.e.

$$f(\mathbf{x})=\sum_{i=1}^{N}d^2, \tag{4}$$

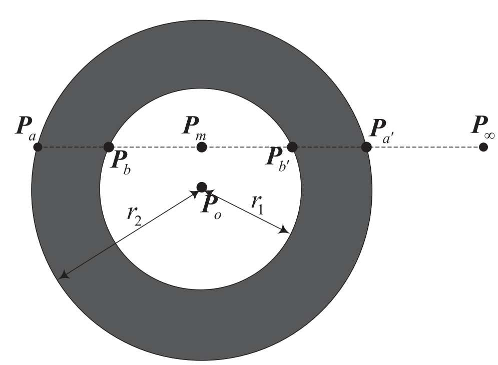


**Fig. 1.** The segment of concentric circles crossed with line.

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