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General fusion frame of circles and points in vision pose estimation

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ABSTRACT

A general fusion frame of circles and points in vision pose estimation is addressed. We present a very simple formula to solve camera pose with a single circle, and then develop a general fusion method to integrate solved poses of circles and points. Two steps including initial guess and non-linear optimization are used for vision pose estimation. Different situations such as one circle one point, circles with same rotation center axis and circles with different rotation center axis are discussed for initial guess. After that, a novel unified reprojection error for circles and points is defined to determine the optimal pose solution. Experiments with real images are carried out to validate the proposed method, and results show that the method is valid and high-accuracy available.

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1. Introduction

Pose estimation is an essential step in many machine vision and photogrammetric applications including robotics, 3D reconstruction, and MAV landing [1]. Points, lines and circles are basic geometric shapes of objects around us. The well-known perspective-n-point (PnP) problem [2,3] is to find the pose of an object from the image of several points at known location on it. Lines are very similar with points in perspective transformation, and pose estimation based on lines is also commonly used [4,5]. Circular features are another kind of patterns in man-made objects. Under perspective geometry, a projected circle appears as an ellipse in the imaging plane, and the 3D position of the circle can be extracted from single image using the inverse projection model of the calibrated camera. Camera calibration with circles is a commonly used method in computer vision [6–10].

However, two possible pose solutions can be recovered under normal circumstances when employing a single circle [11,12]. The duality problem in pose estimation of a single circle should be solved with external constraint, such as another circle, new points or lines. Stereo vision used in [13,14] is another way to solve the duality of circular pose estimation. Researchers have developed many approaches to determine monocular vision pose with circles. [15] presents a direct and analytical pose estimation algorithm using a single circle with two special diameters. [16] uses distinguishable points on a circle instead of circular edge line. A single straight line is used as the external feature in [17]. Intersection angle of two line are another external features used in [18]. Points, such as two non-coplanar point in [19], discriminable circle center in [20], are also enough to determine an unique pose with a circle. Using more circles, such as two concentric circles in [21],

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two coplanar circles in [22], three circles with same rotation center axis in [23], parallel circles in [24], and two orthogonal circles in [25], is another effective way to solve the duality problem.

In this paper, we propose a general fusion frame of circles and points in vision pose estimation. Unlike the existed method using the geometry constraint to solve the duality problem in particular cases, a general frame to fuse circles and points including all situations such as one circle one point, two or more circles, and other situations, is addressed. A very simple formula to solve single circular vision pose is presented, and non-linear optimization after initial guess is applied. And then, a novel unified reprojection error for circles and points is defined to determine the optimal pose solution.

This paper is organized as follows. Section 2 briefly introduces some notations and basic equations in computer vision, and provides a very simple formula to solve the pose determination problem based on a single circle. After that, the general fusion frame of circles and points in vision pose estimation problem is proposed in Section 3. The results of experiments with real images are shown in Section 4. Finally, the conclude is presented in Section 5.

2. Perspective geometry and circular projection

2.1. Camera projection model

Let $\tilde{\boldsymbol{x}} = (x, y, z, 1)^T$ be the 3D homogeneous coordinates of a world 3D point $\boldsymbol{x} \in \mathbb{R}^3$, and $\tilde{\boldsymbol{m}} = (u, v, 1)^T$ be the homogeneous coordinates of its projection in the image plane. Under perspective geometry, the projection relationship can be described as:

$$z_c\tilde{\boldsymbol{m}} = \boldsymbol{K}\boldsymbol{X}_c = \boldsymbol{K}[\boldsymbol{R}, \boldsymbol{t}]\tilde{\boldsymbol{x}} \tag{1}$$

where $\boldsymbol{X}_c = (x_c, y_c, z_c)^T$ is the 3D coordinates of $(\mathbf{x})$ in camera frame. $\boldsymbol{K}$ is the camera intrinsic matrix. $[\boldsymbol{R}, \boldsymbol{t}]$ is the camera extrinsic matrix, where $\boldsymbol{R} = [\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{r}_3]$ means the rotation matrix, and $\boldsymbol{t}$ means the translation vector from the world frame to the camera frame.

2.2. Projection of a circle

Without loss of generality, we may assume the world space is restricted to its $x-y$ plane, which means $z = 0$. Then a point $\boldsymbol{x} = (x, y, 0)^T$ on a circle $\boldsymbol{C}$ will satisfy the following equation:

$$\tilde{\boldsymbol{x}}_p^T\boldsymbol{P}\tilde{\boldsymbol{x}}_p = 0 \, with \, \boldsymbol{P} = \begin{bmatrix} 1 & 0 & -x_0 \\ 0 & 1 & -y_0 \\ -x_0 & -y_0 & x_0^2 + y_0^2 - r^2 \end{bmatrix} \tag{2}$$

where $\tilde{\boldsymbol{x}}_p = (x, y, 1)^T$, $(x_0, y_0)^T$ is the center of $\boldsymbol{C}$, and r is the radius. Substituting $z = 0$ into Eq. (1), then we can get

$$\tilde{\boldsymbol{x}}_p = z_c\boldsymbol{H}^{-1}\tilde{\boldsymbol{m}} \, with \, \boldsymbol{H} = \boldsymbol{K}[\boldsymbol{r}_1, \boldsymbol{r}_2, \boldsymbol{t}] \tag{3}$$

With Eqs. (2) and (3), the equation of projected ellipse $\boldsymbol{E}$ of circle $\boldsymbol{C}$ can be derived as

$$\tilde{\boldsymbol{m}}^T\boldsymbol{Q}\tilde{\boldsymbol{m}} = 0 \, with \, \boldsymbol{Q} = \mu\boldsymbol{H}^{-T}\boldsymbol{P}\boldsymbol{H}^{-1} \tag{4}$$

where μ is a non-zero factor.

2.3. Scene recovery from a circle

Using the intrinsic matrix $\boldsymbol{K}$ for the calibrated camera, we may get the equation coefficient matrix of the normalized imaging ellipse for the circle $\boldsymbol{C}$ as $\bar{\boldsymbol{Q}} = \boldsymbol{K}^T\boldsymbol{Q}\boldsymbol{K}$. If $\bar{\boldsymbol{Q}}$ is diagonalized as $\bar{\boldsymbol{Q}} = \boldsymbol{V} \cdot diag(\lambda_1, \lambda_2, \lambda_3) \cdot \boldsymbol{V}^T$ where $\lambda_1 \geq \lambda_2 \geq \lambda_3$, and $\boldsymbol{V} = [\boldsymbol{v}_1, \boldsymbol{v}_2, \boldsymbol{v}_3]$ is made up of the eigenvectors of $\bar{\boldsymbol{Q}}$, then according to [23], the position vector b of the center of $\boldsymbol{C}$ and the norm vector $\boldsymbol{n}$ of the circle plane in the camera frame can be solved as follows:

$$\begin{aligned} \boldsymbol{b} &= -\omega_1 r\sqrt{-\frac{\lambda_3(\lambda_1-\lambda_2)}{\lambda_1(\lambda_1-\lambda_3)}}\boldsymbol{v}_1 + \omega_2 r\sqrt{-\frac{\lambda_1(\lambda_3-\lambda_2)}{\lambda_3(\lambda_3-\lambda_1)}}\boldsymbol{v}_3 \\ \boldsymbol{n} &= \omega_1\sqrt{-\frac{\lambda_1-\lambda_2}{\lambda_1-\lambda_3}}\boldsymbol{v}_1 + \omega_2\sqrt{-\frac{\lambda_3-\lambda_2}{\lambda_3-\lambda_1}}\boldsymbol{v}_3 \end{aligned} \tag{5}$$

where $\omega_1 = \pm 1$, $\omega_2 = \pm 1$. Four solutions can be obtained, and two can be excluded when considering $\boldsymbol{e}_3^T\boldsymbol{b} > 0$ where $\boldsymbol{e}_3 = (0, 0, 1)^T$ in the actual situation.

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