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Method for fundamental matrix estimation combined with feature lines

Fan Zhou [a,*], Can Zhong [b], Qi Zheng [c]

[a] College of Information Engineering, Shanghai Maritime University, Shanghai, China
[b] Beijing Institute of Space Mechanics & Electricity, Beijing, China
[c] National Engineering Research Center for Multimedia Software, Wuhan University, Wuhan, China

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ABSTRACT

Fundamental matrix estimation has been studied extensively in the area of computer vision and previously proposed techniques include those that only use feature points. In this study, we propose a new technique for calculating the fundamental matrix combined with feature lines, which is based on the epipolar geometry of horizontal and vertical feature lines. First, a method for parameterizing the fundamental matrix is introduced, where the camera orientation elements and relative orientation elements are used as the parameters of the fundamental matrix, and the equivalent relationships are deduced based on the horizontal and vertical feature lines. Next, the feature lines are used as the interior points by the RANSAC algorithm to search for the optimal feature point subset, before determining the weight of each factor using the M-estimators algorithm and building a unified adjustment model to estimate the fundamental matrix. The experimental results obtained using simulated images and real images demonstrate that the proposed approach is feasible in practice and it can greatly reduce the dependency on feature points in the traditional method, while the introduction of feature lines can improve the accuracy and stability of the results to some extent.

1. Introduction

The estimation of three-dimensional (3D) information from images is an important problem in computer vision. At present, many approaches are available to accomplish this task, which can be classified into stratified reconstruction and direct reconstruction [1]. The first approach is based on a previous camera calibration but it cannot be used in active systems because of its lack of flexibility, where the intrinsic and extrinsic parameters of the camera need to be fixed [2]. The second approach is based on either the Euclidean reconstruction [3] or the epipolar geometry [4]. However, the approaches based on Euclidean reconstruction require a priori knowledge of the scene [5], such as the projective basis and invariants, whereas the epipolar geometry is based only on point correspondences. Thus, the latter method has been studied widely during the last decades [6–8].

The epipolar geometry is the intrinsic projective geometry between two views [1], which is independent of the scene structure, and it depends only on the cameras' internal parameters and relative pose [4]. The fundamental matrix is an algebraic representation of the epipolar geometry, thus, the projective reconstruction of the scene or object can be inferred from it. In other words, the epipolar geometry can be expressed fully in terms of the fundamental matrix. Therefore, it is a required step for applications such as camera calibration [9], self-calibration [10,11], projective reconstruction [12], 3D reconstruction [12,13], object matching and tracking [11,14,15], attitude estimation [16], and 3D measurements [17].

An application of scene reconstruction using epipolar geometry was first published by Longuet-Higgins [12]. Subsequently, great efforts have been made to improve this method. At present, the commonly used methods can be divided into linear methods [4,12], iterative methods [18], and robust methods [19–21]. Linear methods perform well if the points are well located in the image and the corresponding problem has been solved previously; Iterative methods can cope with some Gaussian noise in the localization of points, but they are inefficient in the presence of outliers; Robust methods can cope with discrepancies in the localization of points and false matching [2]. Therefore, robust methods have more widespread practical applications.

Armangué and Salvi surveyed 19 of the most widely used techniques for computing the fundamental matrix [2]. Fathy et al. also summarized and compared the accuracy and efficiency of the different error criteria, which are used to compute the fundamental matrix [22]. The methods used to calculate the fundamental matrix

* Corresponding author at: NO. 1550 Haigang Av., Shanghai, China.
Tel.: +86 13671892160; fax: +86 2138282823.
E-mail address: carter1zf1@126.com (F. Zhou).

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appear to have been adequate. In recent years, however, researchers have begun to study the application of fundamental matrix estimation in some special cases. For example, Yang et al. proposed a novel technique for estimating the fundamental matrix based on least absolute deviation [23]. Zhang computed the fundamental matrix in the presence of radial lens distortion [24]. Steger proposed a method for estimating the fundamental matrix in conditions of pure translation and radial distortion [25]. Additional computational time is required by real-time applications, especially video data analysis with numerous frames per second. Thus, efforts have been made recently to facilitate the automated computation of the fundamental matrix for vision-based construction site applications [26]. Overall, these methods can be summarized as special cases of calculating the fundamental matrix.

The methods mentioned above all use models based on feature points, but there may be few feature points or the distribution of feature points may not be appropriate in some cases, which means that ideal results may not be obtained in these situations. The processing of stereo pairs during imaging includes straight lines, curves, vanishing points, and absolute conics, in addition to feature points. These feature objects also contain the epipolar geometry relationship during imaging. However, the fundamental matrix is derived from the feature points and other feature objects cannot be included in the calculation process. Therefore, if the utilization of these feature objects could be increased, it may be possible to reduce the dependency of the fundamental matrix estimation on the feature points, which could also expand the application scope of the fundamental matrix.

A new method for fundamental matrix estimation is proposed in this study, which is based on the epipolar geometry of the horizontal and vertical lines. First, a method for parameterizing the fundamental matrix is introduced and the equivalent relationships are deduced based on the horizontal and vertical line. The feature lines are then used as the interior points by the RANSAC algorithm [27], before determining the weight of each factor with M-estimators algorithm [21] and building the final unified adjustment model. This method reduces the dependency of the traditional calculation method on the feature points, so it is suitable for cases where there are few feature points but the feature lines are present. In addition, the geometrical characteristics of feature lines are more obvious than those of feature points, so the proposed method has high positioning accuracy and a lower possibility of false matching. Therefore, the introduction of feature lines can also improve the accuracy and stability of the final result.

The rest of the paper is organized as follows. After briefly introducing the parameterization of the fundamental matrix in Section 2, we describe the new approach of estimating the fundamental matrix in Section 3, and the experimental results are presented in Section 4. Finally, some conclusions are provided in Section 5.

2. Parameterization of the fundamental matrix

Epipolar geometry exists between any stereo-camera systems. Algebraically, the epipolar constraint can be expressed using the fundamental matrix as follows:

$$\boldsymbol{m}^{\mathrm{T}}\boldsymbol{F}\boldsymbol{m}' = 0 \tag{1}$$

where $\boldsymbol{F}$ is the fundamental matrix, which is a 3×3 singular matrix of rank 2 that is defined by a scale factor, and $\boldsymbol{m}$ and $\boldsymbol{m}'$ are the homogeneous coordinates of the point correspondences. To ensure its singularity, there are several possible parameterizations for $\boldsymbol{F}$ [1]. To calculate $\boldsymbol{F}$ using feature lines, a method of parameterization based on the relationship between the camera

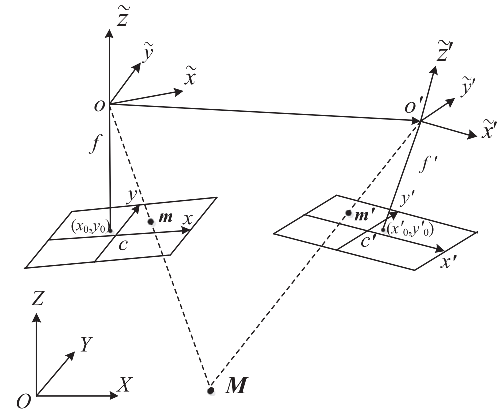

Fig. 1. Analytical geometry of two stereo images.

orientation elements, the relative orientation elements, and the elements of $\boldsymbol{F}$ is proposed.

As shown in Fig. 1, two stereo images are situated within the 3D global coordinate system O-XYZ. The 2D image coordinates system c-xy and the 3D image space coordinates system $o-\tilde{x}\tilde{y}\tilde{z}$ are local to the image on the left. The orientation of $o-\tilde{x}\tilde{y}\tilde{z}$ in the 3D global coordinates system O-XYZ is captured by an orthonormal rotation matrix $\boldsymbol{R}$, which is defined by three successive rotation angles α, β, γ around O-X, O-Y, O-Z:

$$\boldsymbol{R} = \boldsymbol{R}_\alpha \boldsymbol{R}_\beta \boldsymbol{R}_\gamma = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Suppose that an object point $\boldsymbol{M}=(X,Y,Z)$ in O-XYZ is projected onto an image point $\boldsymbol{m}(x,y)$ in the 2D image coordinates system, $\tilde{\boldsymbol{m}}$ is the 3D image space coordinate and $\overline{\boldsymbol{m}}$ is the auxiliary image space coordinate (the auxiliary image space coordinate system $o-\overline{xyz}$ is definite, with origin o, and the orthogonal axes are labelled $\overline{xyz}$, where the orientation of its axes are the same as O-XYZ). Then, we have:

$$\overline{\boldsymbol{m}} = \boldsymbol{R}\tilde{\boldsymbol{m}} = \boldsymbol{R}\boldsymbol{\Omega}\boldsymbol{m} \tag{3}$$

$$\boldsymbol{m} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}, \quad \boldsymbol{\Omega} = \begin{bmatrix} 1 & 0 & -x_0 \\ 0 & 1 & -y_0 \\ 0 & 0 & -f \end{bmatrix}, \quad \boldsymbol{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{4}$$

where (x_0, y_0, f) are the elements of the interior orientation. Similarly, the symbols related to the image on the right are marked with a prime symbol ($'$). In the same manner, the image coordinate of $\boldsymbol{M}$ in the right image is $\boldsymbol{m}'$, the 3D image space coordinate is $\tilde{\boldsymbol{m}}'$, and the auxiliary image space coordinate is $\overline{\boldsymbol{m}}'$. Then, we have:

$$\overline{\boldsymbol{m}}' = \boldsymbol{R}'\tilde{\boldsymbol{m}}' = \boldsymbol{R}'\boldsymbol{\Omega}'\boldsymbol{m}' \tag{5}$$

$$\boldsymbol{m}' = \begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix}, \quad \boldsymbol{\Omega}' = \begin{bmatrix} 1 & 0 & -x'_0 \\ 0 & 1 & -y'_0 \\ 0 & 0 & -f' \end{bmatrix}, \quad \boldsymbol{R}' = \begin{bmatrix} r'_{11} & r'_{12} & r'_{13} \\ r'_{21} & r'_{22} & r'_{23} \\ r'_{31} & r'_{32} & r'_{33} \end{bmatrix} \tag{6}$$

Let $\boldsymbol{B}$ denote the baseline vector of oo'. Clearly, the five points o, m, o', m', M are coplanar, which can be captured by using a cross-product of the three vectors that is equal to zero:

$$\overline{\boldsymbol{m}}^{\mathrm{T}}(\boldsymbol{B} \times \overline{\boldsymbol{m}}') = \overline{\boldsymbol{m}}^{\mathrm{T}}[\boldsymbol{B}]_\times \overline{\boldsymbol{m}}' = 0 \tag{7}$$

Using the notations and relations defined by Eqs. (3) and (5), we obtain:

$$\boldsymbol{m}^{\mathrm{T}}\boldsymbol{\Omega}^{\mathrm{T}}\boldsymbol{R}^{\mathrm{T}}[\boldsymbol{B}]_\times \boldsymbol{R}'\boldsymbol{\Omega}'\boldsymbol{m}' = 0 \tag{8}$$