TRINOCULAR STEREO IMAGE RECTIFICATION IN CLOSED-FORM ONLY USING FUNDAMENTAL MATRICES

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ABSTRACT

Trinocular stereo image rectification is a process to transform a set of three images into a new set so that the epipolar lines in the transformed images have the same direction as the image row or column and matching epipolar lines in different images have the same row or column indices to enable an efficient and reliable dense stereo matching. In this paper we propose a new closed-form method to rectify three-view stereo images just using fundamental matrices. The algorithm involves only direct and purely geometric transformation processes. No iteration or optimization process is involved in our method. Real images have been used for testing purposes, and accurate results have been obtained using our algorithm.

Index Terms— Trinocular stereo images, rectification, closed-form, fundamental matrix, epipole

1. INTRODUCTION

Stereo image rectification is an important step for three dimensional scene analyzes. The rectification process transforms the input images into new ones with epipolar lines being along the horizontal and vertical axes and matching epipolar lines from different images having the same row or column indices. For stereo matching, image rectification can increase both the reliability and the speed of disparity estimation. Stereo rectification usually requires calibrated camera parameters or parameters of uncalibrated cameras in the form of fundamental matrices; and most algorithms require the initial feature matching points as part of inputs.

There are articles on two-view image rectification using known calibrated camera parameters [1, 2]. There are also a large number of algorithms developed for uncalibrated two-view cases. Some of these methods use a direct sampling approach based on the epipolar geometry [3, 4, 5]. Some algorithms require the fundamental matrix and matching points information to obtain the rectifying matrices [6, 7, 8]. Another class of algorithms for two-view cases are the estimation of the rectifying matrices directly from image matching points [9, 10]. Two-view rectification methods without using the image matching points but only using the fundamental matrix are also developed in [11, 12, 13, 14, 15].

Below are researches on three-view image rectification. Ayache and Hansen presented a technique for calibrating and rectifying a pair or triplet of images with estimated camera matrix [16]. A similar method for efficient rectification for trinocular stereo vision was given in [17]. Shao and Fraser also developed a rectification method for calibrated trinocular cameras [18]. Laganière and Kangni presented a projective rectification method for image triplets [19]. Zhang et al. proposed a linear method for trinocular rectification for accurate stereoscopic matching [20]. Sun presented several methods, such as rotation and skew, affine transformation, and vanishing points methods, for rectifying the reference image and then applying matching transformations for rectifying the rest of the image triplets [21].

In this paper, we propose a new closed-form algorithm for rectifying three uncalibrated images when only a pair of fundamental matrices are used and no iterative parameter optimization step is involved. All the steps that we use only involve geometric or perspective transformation. Because our algorithm only uses the fundamental matrices for rectification, it is especially useful when the fundamental matrices are estimated without the use of matching points as in [22], or when the fundamental matrices are obtained from a trilinear tensor which can be obtained from matching lines, not points.

2. RECTIFYING TRINOCULAR IMAGES

2.1. Obtaining Fundamental Matrices

With trinocular images, it has been shown in [23] that the point correspondence constraint among the three views is expressed by the trilinear tensor. It has also been shown that the fundamental matrices which govern the epipolar geometry between any two views of the three can be obtained from the trilinear tensor. The fundamental matrices can also be estimated directly from image matching points between any two views of the three [24]. Once the fundamental matrices among the three views are available, they can then be used for rectification purposes.

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2.2. Projection Matrices for the Reference Image

With the three images in the image triplet, we use "left", "right" and "top" to represent each image. The left image is also the reference image. Given the epipolar geometry defined by the fundamental matrix $\mathbf{F}_{12}$ between the left and right images, a pair of epipoles $\mathbf{e}_{12}$ and $\mathbf{e}_{21}$ in these two images can be obtained by solving $\mathbf{F}_{12}\mathbf{e}_{12} = 0$ and $\mathbf{e}_{21}^T\mathbf{F}_{12} = 0$ using a singular value decomposition method. Similarly with $\mathbf{F}_{13}$ for the left and top images, a pair of epipoles $\mathbf{e}_{13}$ and $\mathbf{e}_{31}$ can also be obtained. $\mathbf{e}_{12}$ and $\mathbf{e}_{13}$ are in the left image, while $\mathbf{e}_{21}$ is in the right image and $\mathbf{e}_{31}$ is in the top image. These epipoles will be transformed to $(1,0,0)^T$ (on the x- axis) or $(0,1,0)^T$ (on the y- axis) after rectification.

Next, we will present one algorithm for rectifying the reference image as described in [21]. Assuming that the image center is at $(u,v,1)^T$ for all the three images, one can use the following transformation $\mathbf{T}$ to shift the origin of the image coordinate system to the image center:

$$\mathbf{T} = \begin{pmatrix} 1 & 0 & -u \\ 0 & 1 & -v \\ 0 & 0 & 1 \end{pmatrix}, \quad \mathbf{R}_1 = \begin{pmatrix} \cos\theta_1 & \sin\theta_1 & 0 \\ -\sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Then the image can be rotated such that the epipole after translation $\mathbf{e}'_{12} = \mathbf{T}\,\mathbf{e}_{12} = (e'_{12}[0], e'_{12}[1], 1)^T$ is further moved onto the x- axis. This rotation transformation takes the form $\mathbf{R}_1$ with $\theta_1 = \arctan(e'_{12}[1]/e'_{12}[0])$.

After the epipole $\mathbf{e}_{12}$ has been transformed to lie on the x- axis, we need to move epipole $\mathbf{e}_{13}$ to the y- axis. This can be obtained by a skew operation:

$$\mathbf{S} = \begin{pmatrix} 1 & s & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $s = -e''_{13}[0]/e''_{13}[1]$ with $(e''_{13}[0], e''_{13}[1], 1)^T = \mathbf{R}_1\mathbf{T}\,\mathbf{e}_{13}$. Now the two epipoles $\mathbf{e}_{12}$ and $\mathbf{e}_{13}$ have been transformed onto the image axes with value k_x on the x- axis for the first epipole and value k_y on the y- axis for the second epipole. The next step will be to shift the epipole positions to infinity. This transformation can be achieved using the following matrix:

$$\mathbf{K} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1/k_x & -1/k_y & 1 \end{pmatrix} = \mathbf{K}_x\mathbf{K}_y$$

with

$$\mathbf{K}_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1/k_x & 0 & 1 \end{pmatrix}, \quad \mathbf{K}_y = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1/k_y & 1 \end{pmatrix}$$

The combined transformation matrix for the reference image is:

$$\mathbf{P}_1 = \mathbf{K}\mathbf{S}\mathbf{R}_1\mathbf{T}.$$

2.3. Shifting Epipoles for Right and Top Images

The transformation matrix for the right image can take the form $\mathbf{P}_2 = \mathbf{K}_2\mathbf{R}_2\mathbf{T}$, generating horizontal epipolar lines. For the top image, transformation matrix $\mathbf{P}_3 = \mathbf{K}_3\mathbf{R}_3\mathbf{T}$ can be used. The $\mathbf{K}_2$ and $\mathbf{K}_3$ matrices for the right and top images are

$$\mathbf{K}_2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1/k_2 & 0 & 1 \end{pmatrix}, \quad \mathbf{K}_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1/k_3 & 1 \end{pmatrix}$$

and $\mathbf{R}_2$ for the right image can be obtained similarly as $\mathbf{R}_1$. $\mathbf{R}_3$ takes the same form as $\mathbf{R}_1$ but with the rotational angle $\theta_3 = \arctan(e'_{31}[0]/e'_{31}[1])$ with $\mathbf{e}'_{31} = \mathbf{T}\;\mathbf{e}_{31}$. The $k_2 = e''_{21}[0]$ with $\mathbf{e}''_{21} = \mathbf{R}_2\mathbf{T}\;\mathbf{e}_{21}$ and $k_3 = e''_{31}[1]$ with $\mathbf{e}''_{31} = \mathbf{R}_3\mathbf{e}'_{31}$. Applying $\mathbf{P}_3$ to the top image generates vertical epipolar lines.

2.4. Aligning Matching Epipolar Lines

After applying $\mathbf{P}_1$, $\mathbf{P}_2$, and $\mathbf{P}_3$ to the left, right and top images respectively, epipolar lines become horizontal and vertical. But the matching epipolar lines are not aligned yet. The alignment of the matching horizontal epipolar lines between the left and right images can be carried out similarly as in the two-view case of [15], but using $\mathbf{P}_{1x} = \mathbf{K}_x\mathbf{S}\mathbf{R}_1\mathbf{T}$ (rather than $\mathbf{P}_1$) and $\mathbf{P}_2$. The alignment transformation is $\mathbf{A}_2\mathbf{T}_v$ for the right image.

We now design a transformation matrix which aligns the matching vertical epipolar lines between the left and top images. Similar to the case for aligning horizontal epipoar lines [15], three regularly spaced points along the horizontal line passing through the center of the left image can be used. The matching epipolar lines can be obtained from the fundamental matrix between the left and top images. We use the following $\mathbf{T}_u$ to align the middle vertical epipolar lines:

$$\mathbf{T}_u = \begin{pmatrix} 1 & 0 & -u_m \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \mathbf{A}_3 = \begin{pmatrix} w_x & 0 & 0 \\ 0 & 1 & 0 \\ k'_x & 0 & 1 \end{pmatrix}$$

where u_m is the location difference for these two middle vertical epipolar lines. The matrix $\mathbf{A}_3$ of the above form can be used to align all the matching vertical epipolar lines. The w_x and k'_x will be obtained using the similar method as for $\mathbf{A}_2$. Here the w_x and k'_x values are obtained by:

$$\begin{cases} w_x = \dfrac{(G_2 - G_1)H_1H_2}{(H_2 - H_1)G_1G_2} \\ k'_x = \dfrac{H_1G_2 - H_2G_1}{(H_2 - H_1)G_1G_2} \end{cases}$$

where the values of H_1, H_2 (in left image), G_1 and G_2 (in top image) are the location values of vertical epipolar lines on the x- axis. The alignment transformation $\mathbf{A}_2\mathbf{T}_v$ corresponds to $\mathbf{P}_{1x}$. $\mathbf{K}_y$ needs to be applied to the right image to correspond to the transformation $\mathbf{P}_1$ for the reference image. This is possible because of the special form of $\mathbf{K}_x$ and $\mathbf{K}_y$ which makes the following equation hold

$$\mathbf{K}_x\mathbf{K}_y = \mathbf{K}_y\mathbf{K}_x$$

We use this special property of the projection matrix $\mathbf{K}$ to rectify the image triplets.

The alignment transformation $\mathbf{A}_3\mathbf{T}_u$ for the top image corresponds to $\mathbf{P}_{1y} = \mathbf{K}_y\mathbf{S}\mathbf{R}_1\mathbf{T}$. Similarly $\mathbf{K}_x$ needs to be applied to the top image to correspond to the transformation $\mathbf{P}_1$ for the reference image. Using the three transformation matrices $\mathbf{P}_1, \mathbf{K}_y\mathbf{A}_2\mathbf{T}_v\mathbf{P}_2$ and $\mathbf{K}_x\mathbf{A}_3\mathbf{T}_u\mathbf{P}_3$, the three original images can be rectified.

2.5. De-skewing Right and Top Images

The rectified right and top images after aligning the matching epipolar lines can be further processed so that two orthogonal vectors in an original image are orthogonal in the rectified image. The two orthogonal vectors in the original image can go through the image center, one horizontally and one vertically. Assuming the two transformed vectors after aligning matching epipolar lines, i.e., after applying $\mathbf{K}_y\mathbf{A}_2\mathbf{T}_v\mathbf{P}_2$ to the original orthogonal vectors, are $m = (u_1, v_1, 0)^T$ and $n = (u_2, v_2, 0)^T$ in the right image, with a de-skewing matrix $\mathbf{S}_2$,

$$\mathbf{S}_2 = \begin{pmatrix} 1 & s_2 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \mathbf{S}_3 = \begin{pmatrix} 1 & 0 & 0 \\ s_3 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

we wish to make the two transformed vectors m and n after applying $\mathbf{S}_2$ orthogonal to each other, i.e., their dot product is 0: $\langle \mathbf{S}_2 m, \mathbf{S}_2 n \rangle = 0$. This gives an equation with variable s_2:

$$v_1 v_2 s_2^2 + (u_1 v_2 + u_2 v_1) s_2 + u_1 u_2 + v_1 v_2 = 0$$

and it can be solved with two solutions. The one with the smallest absolute value is taken as s_2.

For the top image, the de-skewing matrix $\mathbf{S}_3$ can be obtained similarly with $\langle \mathbf{S}_3 m, \mathbf{S}_3 n \rangle = 0$. This gives an equation with variable s_3:

$$u_1 u_2 s_3^2 + (u_1 v_2 + u_2 v_1) s_3 + u_1 u_2 + v_1 v_2 = 0$$

and the solution for s_3 can be obtained the same way as s_2.

2.6. Reducing Image Translation

The rectified images obtained by applying the transformation matrix $\mathbf{P}_1$ for the left image, $\mathbf{S}_2\mathbf{K}_y\mathbf{A}_2\mathbf{T}_v\mathbf{P}_2$ for the right image, and $\mathbf{S}_3\mathbf{K}_x\mathbf{A}_3\mathbf{T}_u\mathbf{P}_3$ for the top image are almost always different from the original images. Our intention is to minimize the image difference before and after the rectification process, or mixamize the visible image regions after rectification. Image translations with (u'_1, v'_1), (u'_2, v'_2) and (u'_3, v'_3) for the left, right and top images respectively can be used for such a purpose.

The vertical shift should have the same value for both the left and right rectified images, i.e., $v'_1 = v'_2$. They are obtained by calculating the average vertical differences of both the four corners in the left image and the four corners in the right image, i.e., totaling of eight corners, before and after applying the rectification transformations.

The value of horizontal shifts of u'_1 and $u'_3 (= u'_1)$ is obtained using the vertical pair of the images. The value of u'_2 is obtained by calculating the average horizontal differences of the four corners from the right image alone, and the value of v'_3 is obtained by calculating the average vertical differences of the four corners from the top image alone. The transformation matrix for the shifts are

$$\mathbf{T}_i = \begin{pmatrix} 1 & 0 & -u'_i \\ 0 & 1 & -v'_i \\ 0 & 0 & 1 \end{pmatrix}$$

with $i = 1, 2, 3$.

2.7. Combined Transformation

The combined transformation to achieve the final image rectification are through the use of $\mathbf{T}_1\mathbf{P}_1$, $\mathbf{T}_2\mathbf{S}_2\mathbf{K}_y\mathbf{A}_2\mathbf{T}_v\mathbf{P}_2$, and $\mathbf{T}_3\mathbf{S}_3\mathbf{K}_x\mathbf{A}_3\mathbf{T}_u\mathbf{P}_3$ for the left, right and top images respectively. If we put them into groups, they become:

$$\begin{array}{llllll} \textit{for left image:} & \mathbf{T}_1 & & & & \mathbf{K}\,\mathbf{S}\,\mathbf{R}_1\mathbf{T} \\ \textit{for right image:} & \mathbf{T}_2 & \mathbf{S}_2 & \mathbf{K}_y & \mathbf{A}_2\mathbf{T}_v & \mathbf{K}_2\mathbf{R}_2\mathbf{T} \\ \textit{for top image:} & \underbrace{\mathbf{T}_3}_{\substack{\uparrow \\ \textcircled{5}}} & \underbrace{\mathbf{S}_3}_{\substack{\uparrow \\ \textcircled{4}}} & \underbrace{\mathbf{K}_x}_{\substack{\uparrow \\ \textcircled{3}}} & \underbrace{\mathbf{A}_3\mathbf{T}_u}_{\substack{\uparrow \\ \textcircled{2}}} & \underbrace{\mathbf{K}_3\mathbf{R}_3\mathbf{T}}_{\substack{\uparrow \\ \textcircled{1}}} \end{array}$$

The transformations in group ① above shift the epipoles in the three images to infinity and therefore all the epipolar lines become horizontal or vertical. Transformations in group ② for the right and top images align the matching horizontal or vertical epipolar lines to the left image. The transformation matrices in group ③ correspond to the $\mathbf{K}$ matrix for the reference image. The transformations in group ④ is the de-skew transformation for the right and top images, and the transformations in group ⑤ shift the three images to maximize visible image regions.

2.8. Algorithm Steps for Three-View Rectification

The steps of our algorithm for the trinocular image rectification are the following:

1. Obtain fundamental matrices as mentioned in Section 2.1.
2. Uncalibrated trinocular image rectification:
   (a) Construct the transformation matrix $\mathbf{P}_1$ for the reference image using the method described in Section 2.2.
   (b) Compute the transformation matrices $\mathbf{P}_2$ and $\mathbf{P}_3$ for the right and top images as described in Section 2.3.
   (c) Compute $\mathbf{A}_2\mathbf{T}_v$ for matching horizontal epipolar lines between the left and right images; and compute $\mathbf{A}_3\mathbf{T}_u$ for matching vertical epipolar lines between the left and top images.
   (d) Obtain the de-skewing matrices $\mathbf{S}_2$ and $\mathbf{S}_3$ for the right and top images.
   (e) Obtain shifts $\mathbf{T}_1, \mathbf{T}_2$ and $\mathbf{T}_3$.
   (f) Apply the three transformation matrices $\mathbf{T}_1\mathbf{P}_1$, $\mathbf{T}_2\mathbf{S}_2\mathbf{K}_y\mathbf{A}_2\mathbf{T}_v\mathbf{P}_2$ and $\mathbf{T}_3\mathbf{S}_3\mathbf{K}_x\mathbf{A}_3\mathbf{T}_u\mathbf{P}_3$ to the left, right and top images respectively to obtain the rectified images.

3. EXPERIMENTAL RESULTS

This section shows some of the trinocular stereo image rectification results obtained using our new method described in previous sections. A variety of real images have been tested. For each triplet of images we have the left-right pair of images and left-top pair of images. The fundamental matrix for each pair of images can be obtained using the methods proposed in [24, 25]. When resampling the input images for rectification, bilinear interpolation can be used.

Figure 1(a,b,c) shows an input image triplet (top image in (a), left/reference image in (b), and right image in (c)) with some epipolar lines overlaid. In the reference image, there are two sets of epipolar lines passing through two epipoles. Figure 1(d,e,f) shows the rectified images with overlaid horizontal and vertical epipolar lines. The matching horizontal epipolar lines are in Figure 1(e,f) while the matching vertical epipolar lines are in Figure 1(d,e). In Figure 1(e), the two sets of epipolar lines are orthogonal to each other and parallel to the image axes.

The rectification process has been applied to a dozen of image triplets, and very convincing results are obtained. Figure 2(a,b,c) shows the rectification result of another example image triplet. The matching epipolar lines become horizontal or vertical.

The running time of our rectification process is about 0.395 s for a 756×504 pixel image on a Linux PC with a 3.00GHz Intel Core2 Duo CPU using the C language. The majority of the CPU time is on the actual image resampling process which takes about 0.384 s. The process for obtaining the rectification matrices only takes about 11.7 ms.

4. ONLINE DEMO

An online web demo for trinocular stereo image rectification using our method is available at the following address. Interested readers can try their own images.

`vision-cdc.csiro.au/rectify3v`

5. CONCLUSIONS

In this paper, a new method for automatically rectifying uncalibrated trinocular stereo images has been presented. The rectification matrices applied to the original trinocular images are obtained just based on the epipolar geometries between image pairs, i.e., only using the fundamental matrices. The matching points that may have been used initially for estimating the fundamental matrix are not used during the rectification process. Therefore, the algorithm does not depend on the matching points in the images. There is no iterative parameter optimization process in our method. That is, our method is in closed-form and just uses the fundamental matrices. Real images have been tested and the results validate our new method.

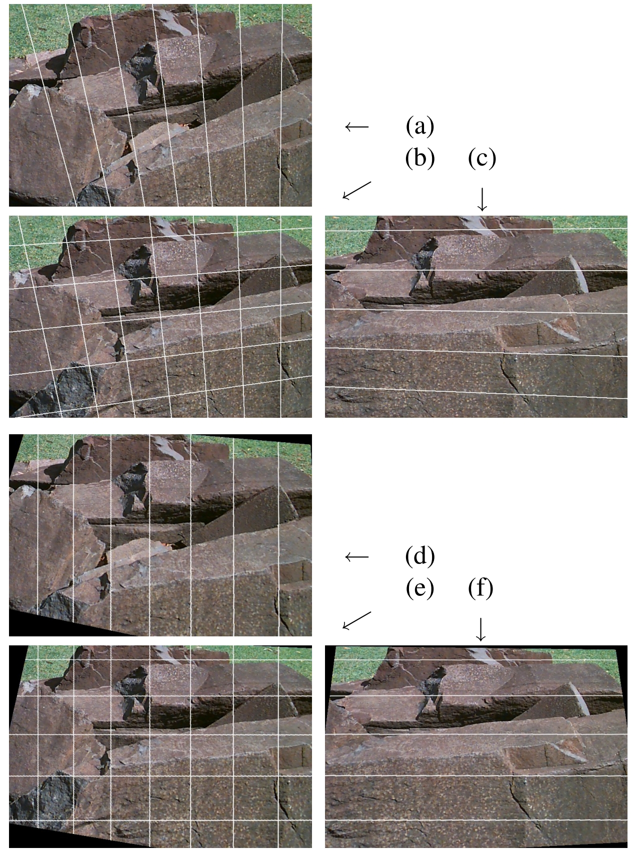

Fig. 1. Trinocular image rectification. (a,b,c) Original top, left, and right images with epipolar lines overlaid. (d,e,f) Rectified images with epipolar lines being horizontal or vertical.

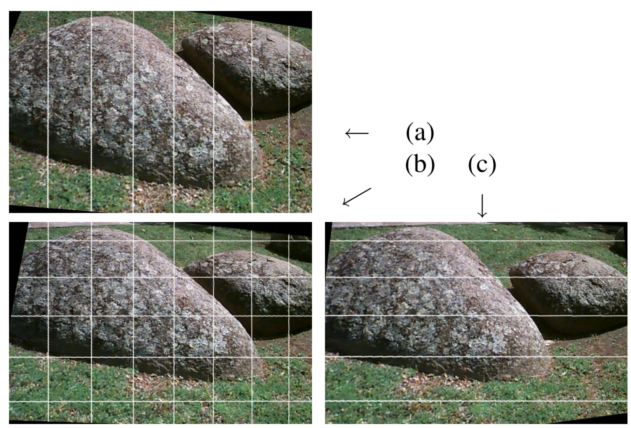

Fig. 2. (a,b,c) Rectified trinocular images for another triplet. Epipolar lines are becoming horizontal (left-right) or vertical (left-top).

Future work should include more quantitative evaluations of different rectification methods.

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