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A new image rectification algorithm ☆

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Abstract

A novel and efficient image rectification method using the fundamental matrix is proposed. In this approach, camera calibration is not required, and image resampling becomes very simple by using the Bresenham algorithm to extract pixels along the corresponding epipolar line. The rectified images are guaranteed to be effective for all possible camera motions, large or small. The loss of pixel information along the epipolar lines is minimized, and the size of rectified image is much smaller. Furthermore, it never splits the image and the connected regions will stay connected, even if the epipole locates inside an image. The effectiveness of our method is verified by an extensive set of real experiments. It shows that much more accurate matches of feature points can be obtained for a pair of images after the proposed rectification.

Keywords: Rectification; Disparity; Epipolar geometry; Binocular stereovision; Uncalibration; Minimal epipolar distortion

1. Introduction

Image rectification is an important step in stereo vision and has been studied by many researchers (Hartley et al., 1992; Faugeras, 1993; Roy et al., 1997; Hartley, 1999; Pollefeys, 1999; Dong and Wang, 2000; Fusiello and Trucco, 2000; Hartley and Zisserman, 2000; Kimura and Saito, 2001). The rectification process consists in extracting epipolar lines, and realigning them horizontally in the new rectified images with the epipolar lines coinciding with an image scan line. As a result, the epipolar lines run parallel to the x-axis and the disparities between the images are in the x-direction only. There are many efficient stereo-matching algorithms using the assumption that conjugate epipolar lines are collinear (or near collinear) in the literature. This assumption enables them to restrict the search for homologous image points to one dimension (Lew et al., 1994; Hoff and Ahuja, 1989). As a result, such an algorithm will be very fast and accurate.

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Traditionally, a rectification scheme usually consists of transforming the image planes so that the corresponding space planes coincide with each other (Faugeras, 1993; Papadimitriou and Dennis, 1996). It is, however, not possible when the epipole is located in the image. Even when it is not the case, the image can still become very big (i.e. if the epipole is close to the image). To tackle this problem, Roy et al. (1997) proposed a cylindrical rectification scheme. However, their method is relatively complex, and some important implementation details are not described. Hartley (1999) considers the problem of obtaining matched points between pairs of images, and develops further the method of applying projective geometry, and calibration-free methods to the stereo problem. His idea is to resample the two images according to the matching projective transformation $\boldsymbol{F}$ and $\boldsymbol{F}'$, taking account of the fact that the matching projective transformation $\boldsymbol{F}$ and $\boldsymbol{F}'$ have multiple results in general. In some cases, it is possible for a projective transform to split the image so that the connected regions are no longer connected. This is of course undesirable. The key idea of the method proposed by Pollefeys (1999) consists in reparameterizating the images with polar coordinates. Due to the fact that the pixel coordinates of an image are Cartesian coordinates, in the case of dense matching, it is necessary to transform the polar coordinates to Cartesian coordinates. This is a time-consuming procedure.

A novel algorithm for rectification based on the fundamental matrix between a pair of images is proposed in this paper. In spite of its simplicity, it performs well under all situations. The pair of images is resampled by using the Bresenham algorithm to extract pixels along the corresponding epipolar line. The perspective distortion and the resample distortion are much reduced by transforming both images to a common reference frame. The size of rectified image is much smaller than that of other methods. Furthermore, it never splits an image, and the connected regions will stay connected after rectification. This method is ideal for use as the first step in dense stereo matching, since stereo frames are rectilinear, and the resampled images are practically as good as the original ones, the 3D reconstruction will be accurate and simple. The proposed method has been verified extensively by many real experiments. The experimental results also show that the proposed algorithm is very fast and the original image pair has more than 90% of correct matches after rectification.

This paper is organized as follows. Section 2 gives an introduction of the epipolar geometry constraints and the epipolar line transformation. In Section 3, a detailed description is made on the resampling the rectified images by using Bresenham's algorithm to extract pixels along an epipolar line. In Section 4, the proposed rectification algorithm is summarized. The experimental results of real image pairs are shown in Section 5 and the conclusions are given in Section 6.

2. Epipolar geometry constraints

Consider two images of a 3D scene acquired by a stereo pair of cameras (or a single camera moving) related by a rotation $\boldsymbol{R}$ and non-zero translation $\boldsymbol{t}$. An image point $\boldsymbol{m}_{\mathrm{i}}$ in the first view corresponds to an image point $\boldsymbol{m}'_{\mathrm{i}}$ in the second if they are images of the same 3D point. The epipolar geometry constraints describe the relations between the two images. Every point in a plane that passes through both centers of projection will be projected in each image on the intersection of this plane with the corresponding image plane. Therefore these two intersection lines are called epipolar correspondence.

Epipolar geometry can easily be robustly recovered from a pair of images. From the epipolar geometry constraints, we have

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

$$\boldsymbol{F}\boldsymbol{e} = \boldsymbol{F}^{\mathrm{T}}\boldsymbol{e}' = 0 \tag{2}$$

where $\boldsymbol{m}$ and $\boldsymbol{m}'$ are the perspective projection points of a 3D point $\boldsymbol{M}$, with their homogenous coordinates being $(x, y, 1)^{\mathrm{T}}$ and $(x', y', 1)^{\mathrm{T}}$ respectively. The fundamental matrix $\boldsymbol{F}$ is a 3×3 matrix, which maps a point $\boldsymbol{m}$ in image I to its corresponding epipolar line $l' \sim \boldsymbol{F}\boldsymbol{m}$ in image II. This matrix has rank two ("$\sim$" means equality up to a non-zero scale factor). The fundamental matrix has only seven degrees of freedom. Thus, in order to estimate fundamental matrix, at least seven pairs matching points $\boldsymbol{m}_i \leftrightarrow \boldsymbol{m}'_i$ between the two images are needed. If we have eight matching points, the improved 8-point algorithm (Hartley, 1995) can be used. If we have more than eight matching points, the non-linear iterative method (Zhang, 1998; Luong and Faugeras, 1998; Chen et al., 1999, 2000) can be used.

3. Rectification

3.1. Determining the common region

Before determining the common epipolar lines, the extreme epipolar lines for a single image should be determined. These are the epipolar lines that touch the outer image corners. The different regions for the position of the epipole are given in Fig. 1.

The extreme epipolar lines always pass through corners of the image. For example, if the epipole is in region 1, an area between eB and eD, if the epipole is in region 3, an area between eA and eC, etc.

The extreme epipolar lines from the second image can be obtained through the same procedure. The common region is then easily determined as shown in Fig. 2.

Suppose the image size is $m \times n$, and then the corners A, B, C and D with their homogenous coordinates are $(0,0,1)^{\mathrm{T}}$, $(0,n,1)^{\mathrm{T}}$, $(m,n,1)^{\mathrm{T}}$ and

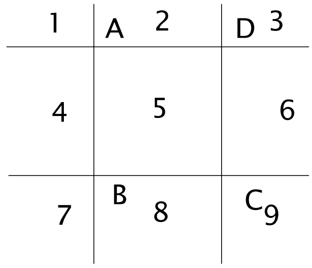

Fig. 1. The extreme epipolar lines can easily be determined according to the location of the epipole in one of the nine regions. The image corners are given by A, B, C, and D.

$(m,0,1)^{\mathrm{T}}$ respectively. The epipolar lines l_3, l_4, l'_1 and l'_2 are given as follows:

$$l'_1 \sim \boldsymbol{F}\mathrm{D}, \quad l'_2 \sim \boldsymbol{F}\mathrm{B}, \quad l_3 \sim \boldsymbol{F}^{\mathrm{T}}\mathrm{D}, \quad l_4 \sim \boldsymbol{F}^{\mathrm{T}}\mathrm{B}, \tag{3}$$

where "$\sim$" means equality up to a non-zero scale factor. If the line l'_1 intersects the right boundary of the image II, and the intersection lies out of image II, then the extreme upper epipolar line of image I is l_3. Otherwise, the extreme upper epipolar line of image I is l_1. The extreme lower epipolar line of image I can be obtained through the same procedure. The common regions EFGHI in image I and E′F′G′H′I′ in image II can be obtained respectively.

3.2. Review of the Bresenham's algorithm

Bresenham's algorithm is an accurate and efficient raster line-generating algorithm (Hearn and

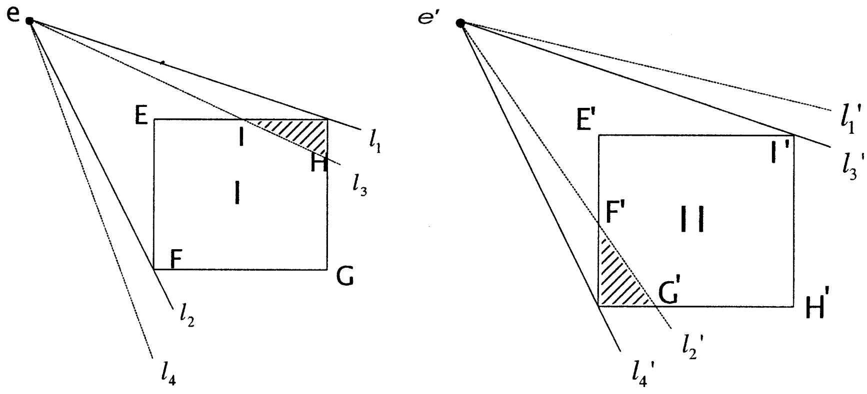

Fig. 2. Determination of the common region. The extreme epipolar lines are used to determine the maximum angle.

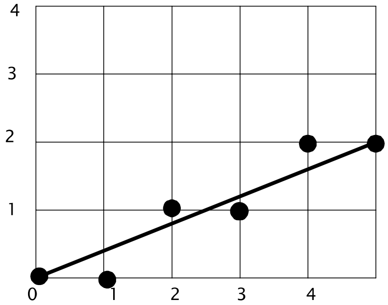

Fig. 3. Bresenham's algorithm.

Baker, 1998). This algorithm converts scan-line by using only incremental integer calculations. Fig. 3 illustrates sections of a display screen where straight-line segment is to be drawn. The vertical axis shows scan-line positions, and the horizontal axis identifies pixel columns. Sampling at unit x intervals in this example, we need to decide which of two possible pixel positions is closer to the line path at each sample step. Starting from the left endpoint $(0, 0)$, we need to determine at the next position whether to plot the position $(1, 0)$ or the one at $(1, 1)$. Bresenham generalized an efficient recursive algorithm. This recursive calculation of decision parameters is performed at each integer x position, starting at the left coordinate endpoint of the line.

Bresenham's line drawn algorithm $(0 \leqslant \Delta x/\Delta y \leqslant 1)$

1. Input the two line endpoints and store the left endpoint in (x_0, y_0).
2. Load (x_0, y_0) into the frame buffer, that is, plot the first point.
3. Calculate constants Δx, $\Delta y(\Delta x = x_{\text{endpoint}} - x_{\text{startpoint}}, \Delta y = y_{\text{endpoint}} - y_{\text{startpoint}})$ and obtain the starting value for the decision parameter as $p_0 = 2\Delta y - \Delta x$.
4. At each x_k along the line, starting at $k = 0$, perform the following test: If $p_k < 0$, the next point to plot is $(x_k + 1, y_k)$ and $p_{k+1} = p_k + 2\Delta y$. Otherwise, the next point to plot is $(x_k + 1, y_k + 1)$ and $p_{k+1} = p_k + 2\Delta y - 2\Delta x$.
5. Repeat step 4 Δx times.

Bresenham's algorithm is generalized to lines with arbitrary slope by considering the symmetry between the various octants and quadrants of the xy plane. For a line with positive slope greater than 1, we interchange the roles of the x and y directions. That is, we step along the y direction in unit steps and calculate successive x values nearest the line path. Also, we could revise the program to plot pixels starting from either endpoint.

3.3. Epipolar line transfer

To avoid losing pixel information, the area of every pixel should be at least preserved when we transform it to the rectified image. The worst-case pixel is always located on the image boundary opposite to the epipole (i.e. the right boundary). In Fig. 4, $\boldsymbol{e}$ is the epipole of image I, l_i is an arbitrary epipolar line. It intersects the left boundary at A and the right boundary at B. The line A′B′ is the epipolar line corresponding to AB, and it is parallel to resample image scan lines. The coordinates of B′ are coinciding with B.

In order to draw the epipolar line A′B′ and avoid pixels loss, every pixel along the line AB corresponding A′B′ can be extracted by using Bresenham's algorithm. Drawing lines AB and A′B′ is accomplished by calculating intermediate positions along the line path between two endpoints. An output device is then directed to fill in these positions between the endpoints. Fig. 5 illustrates a section of a display screen where the straight-line segment is to be drawn. The vertical axis shows scan-line positions, and the horizontal axis identifies pixel columns. So plotted positions may only approximate actual line positions between two specified endpoints.

In Fig. 6, l_{i-1} and l_i are two consecutive epipolar lines. Let the coordinates of $\boldsymbol{e}$ is (e_x, e_y).

The epipole $\boldsymbol{e}$ *lies outside the image*. When the epipole $\boldsymbol{e}$ lies inside the region 1 (Fig. 6(a)), and $(|e_y| + n)/|e_x| > 1$, let extreme upper epipolar line of the common regions intersect the right boundary at C, and the extreme lower epipolar line of the common regions intersect the bottom boundary at D, the start-point is C, and the endpoint is D. Otherwise, the endpoint is E, the intersection point of the extreme lower epipolar line of the common

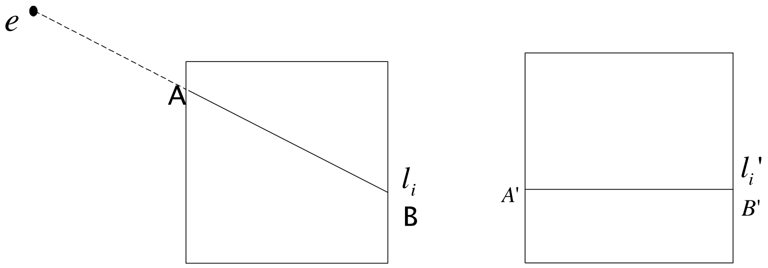

Fig. 4. Epipolar line transfer.

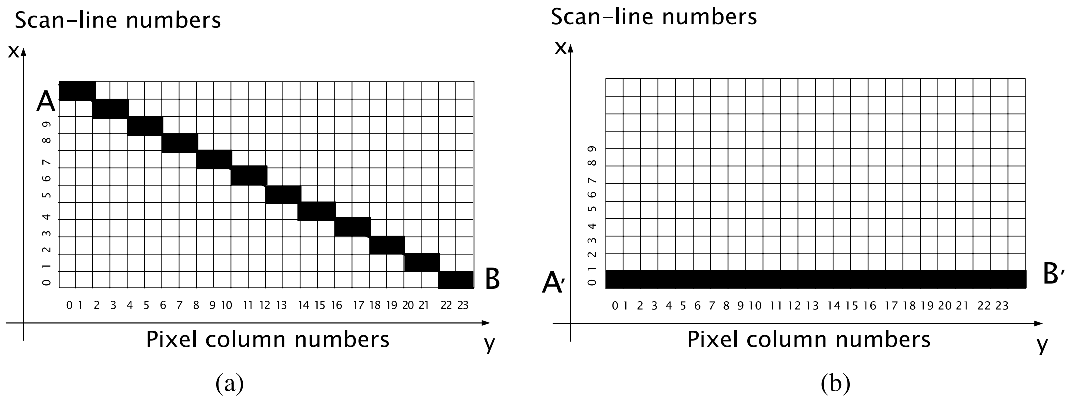

Fig. 5. Resample algorithm: (a) original epipolar line; (b) resample epipolar line.

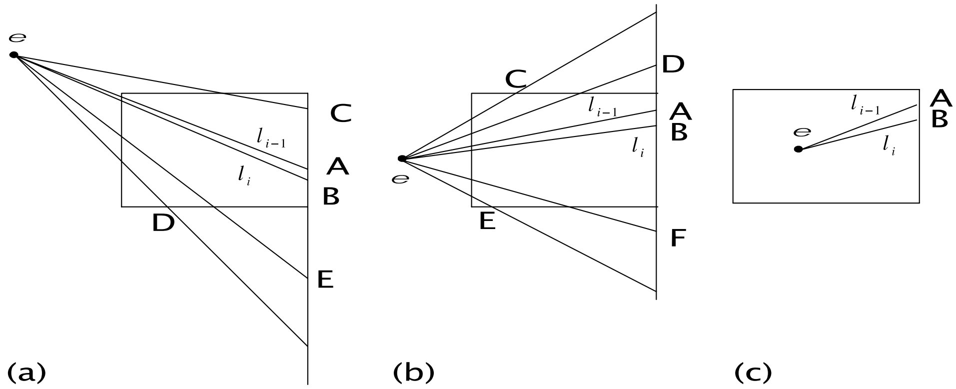

Fig. 6. Determining the minimum distance between two consecutive epipolar lines.

regions and the right boundary. Let l_{i-1} and l_i intersect image boundary at A and B respectively, the distance $|AB|$ should be shorter than one pixel to avoid pixel loss. In this case, the maximal height of rectified image is $m + n$. The same procedure can be carried out in the other regions, such as regions 3, 7, 9.

When the epipole $\boldsymbol{e}$ lies inside the region 4 (Fig. 6(b)), and $|e_y|/|e_x| > 1$, the start-point is C, the intersection point of the extreme upper epipolar line of the common regions and the top boundary. Otherwise the start-point is D, the intersection point of the extreme upper epipolar line and the right boundary. When the epipole $\boldsymbol{e}$ is in the region 4, and if $(n - |e_y|)/|e_x| > 1$, the endpoint is E, the intersection point of the extreme lower epipolar line of the common regions and the bottom boundary. Otherwise the endpoint is F, the intersection point of the extreme lower epipolar line and the right boundary. To avoid pixel loss, the distance $|AB|$ should be shorter than one pixel as well. In this case, the maximal height of rectified image is $2m + n$. The same procedure can be carried out in the other regions, such as regions 2, 6, 8.

The epipole $\boldsymbol{e}$ *lies inside the image.* If the epipole lies inside the image, an arbitrary epipolar line can be chosen as a starting point. In this case boundary effects can be avoided by adding an overlap of the size of the matching window of the stereo algorithm. Let l_{i-1} and l_i intersect four boundaries of image, the intersection points are A and B, the distance |AB| should also be shorter than one pixel. In this case, the height of rectified image is $2(m + n)$ (Fig. 6(c)).

3.4. Resample the rectified image

To resample the rectified image, the first step consists of determining the common regions for both images. Then, starting from one of the extreme epipolar lines, the rectified image is built up line by line. Each row corresponds to a certain angular sector, and the number of pixels along the epipolar line is preserved. So all pixels in the image are preserved, which minimizes the loss of pixel information along the epipolar line. The same procedure can be carried out in the other image. In this case the obtained epipolar line should be transferred back to the first image. The minimum of both displacements is carried out. At the same time, the coordinates of every pixel along the epipolar line are saved in a list for later reference, when the pixel is transferred back to original images.

3.5. Transferring information back

Information about a specific point in the original image can be obtained as follows. Every pixel in the rectified image corresponds to the unique pixel in the original images, so we can look it up pixel by pixel in the list which has been saved by the paragraph above.

4. Algorithm outline

The rectification algorithm will now be summarized. The input is a pair of images containing a common overlapping region, and the output is a pair of images resampled so that the epipolar lines in the two images are horizontal (parallel with the x-axis), and the epipolar lines coincide with scanline so that corresponding points in the two images are as close to each other as possible. Any remaining disparity between matched points will be along the horizontal epipolar line. The algorithm outline can be generalized as follows:

1. Find at least seven matching points $\boldsymbol{m}_{\mathrm{i}} \leftrightarrow \boldsymbol{m}'_{\mathrm{i}}$ between the two images.
2. Estimate the fundamental matrix $\boldsymbol{F}$ robustly and compute the epipoles $\boldsymbol{e}$ and $\boldsymbol{e}'$ in the two images.
3. Determine the common region by using epipolar geometry constraints.
4. Transfer the epipolar line by using formula (3), and extract pixels by using Bresenham's algorithm.
5. Resample the rectified images.

5. Experimental results

A large number of real images are selected to evaluate the performance of the proposed algorithm. Two images of Xi'an Bell Tower (a famous place of interest in China, it is also a typical ancient architecture) taken from widely different relatively oblique viewing angles are shown in Fig. 7. A set of about 229 matched points is extracted automatically by KLT method (Lucas and Kanade, 1981; Shi and Tomasi, 1994) and the fundamental matrix is calculated by using the algorithm proposed in paper Chen et al. (2000). The result is listed in Table 1.

A set of 240 matched points is selected from the two resampled images. Partial matched points are

Fig. 7. Two images of Xi'an Bell Tower and a few of epipolar lines.

Table 1
The fundamental matrix and two epipoles of a pair of images

Fundamental matrix	Left epipole	Right epipole
$\begin{bmatrix} 0.00000002348270 & -0.00005649700000 & 0.02343669000000 \\ 0.00005943780000 & 0.00000083158570 & 0.08142824000000 \\ -0.02427306000000 & -0.08300799000000 & 0.99264330000000 \end{bmatrix}$	(−1375.8, 414.3)	(−1463.2, 409.0)

listed in Table 2. It is shown that the y-coordinates of an arbitrary point in the left image are almost as the same as the y-coordinates of the corresponding point in the right image. It is our expected results that any disparities between the two images are parallel to the x-axis.

We define the disparity for point (x_l, y_l) in the left camera coordinate system as

$$(d_{cx}, d_{cy}) = (x_r - x_l, y_r - y_l) \tag{4}$$

then the disparity along y-direction is $y_r - y_l$, and average disparity along the y-direction is only 0.0036 pixels. The variance is 1.2716e−005. However, before rectification average disparity along the y-direction is 6.6128 pixels. The variance is 63.062. This result illustrates the validity of our method. It is just what we expected.

The original image size is 640×480. The rectified image pairs by both the methods of Pollefeys and ours are side by side shown in Fig. 8, respectively. The size of the rectified image pairs by Pollefeys' method is 681×685, but the size of the rectified image pairs by our method is only 640×683. Obviously, the image size by our method is smaller than that of Pollefeys.

Table 2
A set of about 20 matched points is selected from resampled images

Left image (x, y)	Matched points of right image (x, y)
(303.0130, 172.7900)	(304.5490, 172.7968)
(319.3720, 184.0286)	(321.5060, 184.0364)
(303.5450, 180.4540)	(304.8420, 180.4626)
(307.2380, 235.0332)	(313.7370, 235.0417)
(316.5840, 248.0232)	(323.2100, 248.0342)
(291.6640, 250.1605)	(297.2830, 250.1606)
(274.4420, 253.9815)	(278.8790, 253.9854)
(350.1520, 269.4925)	(355.4480, 269.5023)
(462.8320, 294.4422)	(464.9660, 294.4461)
(362.7740, 279.5148)	(368.7750, 279.5264)
(259.8700, 259.0715)	(264.2160, 259.0800)
(478.9720, 301.1932)	(480.2830, 301.1942)
(310.0430, 272.6914)	(315.7620, 272.6923)
(316.0640, 273.7451)	(321.8870, 273.7452)
(145.4550, 238.2912)	(145.2410, 238.2941)
(327.4710, 278.2581)	(333.3940, 278.2645)
(243.3540, 262.6498)	(247.9200, 262.6555)
(381.1090, 288.6754)	(384.9690, 288.6842)
(466.2080, 305.8267)	(468.3890, 305.8340)
(477.8880, 308.0979)	(480.2530, 308.1043)

Figs. 9 and 10 show the other two pairs of images. The size of images is 720×576 and

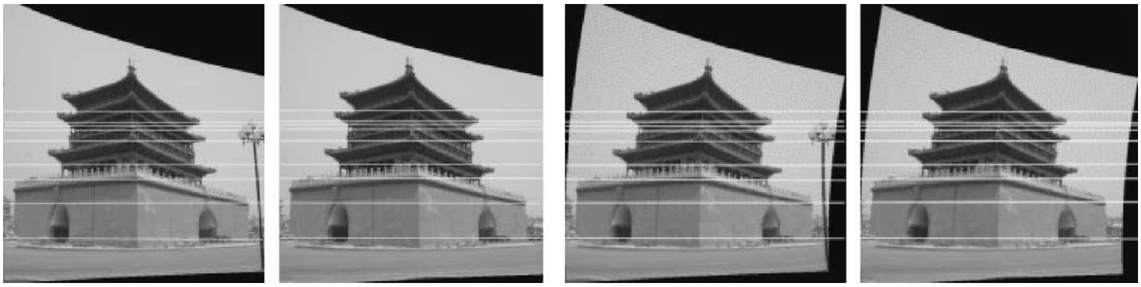

Fig. 8. Rectified image pair of Xi'an Bell Tower for both methods and a few of epipolar lines. The left is the result of new method and the right is the result of Pollefeys' method.

Fig. 9. A pair of images of a palace.

Fig. 10. A pair of the images of library in the Chinese University of Hong Kong.

640×480 respectively. Two sets of matched points are extracted automatically respectively. The fundamental matrix and epipoles are listed in Table 3.

The two pairs images are then resampled according to the methods proposed by Pollefeys and described here, respectively. The results are side by side shown in Figs. 11 and 12. The image sizes by Pollefeys' method are 732×807 and 649×578, respectively. But the image sizes by our method are only 720×732 and 640×579, respectively.

Because of the wide difference in viewpoint, and the 3-D shape of the objects, the two pairs images

Table 3
The fundamental matrix and epipoles of the other two pairs of images

Image pairs	Fundamental matrix	Left epipole	Right epipole
Palace	$\begin{bmatrix} -1.1136e-008 & -1.0169e-005 & 9.3857e-003 \\ 1.3726e-005 & -1.1093e-006 & 4.5815e-002 \\ -1.3037e-002 & -4.6989e-002 & 9.9771e-001 \end{bmatrix}$	(−3262.98, 926.55)	(−4723.99, 945.98)
Library	$\begin{bmatrix} 4.7817e-007 & 3.6093e-005 & -9.1671e-003 \\ -3.7266e-005 & -7.2382e-007 & 1.3094e-001 \\ 7.5064e-003 & -1.3170e-001 & 9.8253e-001 \end{bmatrix}$	(3509.6, 207.5)	(3654.0, 248.3)

Fig. 11. Rectified image pair of the pair of palace for both methods. The left is the result of new method and the right is the result of Pollefeys' method.

Fig. 12. A pair of resampled images of library in the Chinese University of Hong Kong. The left is the results of new method and the right is the results of Pollefeys' method.

look quite different even after resampling. However, it is the case that any point in the first image will now match a point in the second image with the same y-coordinate. Therefore, in order to find further point matches between the images, only a one-dimensional search is required.

6. Conclusions

A novel fast and accurate algorithm for the rectification of a pair of stereo images is proposed in this paper. The images can be taken from widely different viewpoints and camera calibration is not required. This makes the computation of the scene geometry extremely simple. Further, it preserves the connectivity of the images under all situations and the rectified images are guaranteed to be effective for all possible camera motions. It also minimizes the resampling distortion, the loss of pixel information along epipolar line and the size of rectified images. Due to the simplicity of the epipolar transformation, the resampling of the images can be done very quickly. The excellent performance of the proposed algorithm has been verified by a set of extensive real experiments.

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