A Planar Metrology Method Based on Image Sequence

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Abstract—**This paper presents a novel planar metrology method based on image sequence. Compared with the planar metrology method based on single image, the proposed method can enlarge the measuring range effectively. The main reference planar template and the auxiliary reference planar template are used to achieve the transformation between the three-dimensional coordinate systems of different images. The auxiliary reference planar template of the former image is the main reference planar template of the latter image, and their positions remain invariant in the process of the metrology. The main reference planar template are used to obtain the 3D measuring information and the auxiliary reference planar template are used to transform the coordinates of feature points to the same three-dimensional coordinate system. Extensive experimental results show that the proposed method can meet the need of the metrology of the large scene.**

Keywords- camera calibration, homography matrix, image sequence, planar metrology

I. INTRODUCTION

As the single view based metrology method doesn't need image matching and camera calibration, it has been widely used in the traffic accident scene measurement system, the building measurement system, and the crime scene measurement system etc. Criminisi proposed a planar metrology method based on single uncalibrated image for distance measurement on a world plane [1-3]. It assumes that four or more control points in the planar scene are known, and the homography matrix between the scene plane and the image plane was calculated from these control points. Finally the distances in the planar scene are estimated according to the homography matrix. Wang et al. further developed this approach and used a line-based homography estimation method to measure planar distances [4]. Their experimental results showed that the line-based estimation method had better performance in accuracy and robustness than the point-based estimation method. As the line-based homography matrix estimation by the Direct Linear Transformation (DLT) method may have some gross estimation under some camera configurations, Zeng et al. proposed a new normalized line-based homography estimation method to solve this problem [5]. It consists of a new normalized transformation before formulating the linear equations, and the robustness and accuracy of the estimated homography is substantially enhanced. It also retains the traditional DLT method's conceptual simplicity and computational efficiency.

In practical applications, we often need to measure a wide range of scene, and the measured objects may be occluded with each other. For example, in the measurement of traffic accident scene, the distance between two collided cars is often more than ten meters. If we only use a traffic accident scene image to perform the measurement, the accuracy of measurement will be influenced because of the vide view field. In addition, it is difficult to make all of the objects in the traffic accident scene to be included in one image. To solve these problems in practical applications, this paper presents a novel planar metrology method based on image sequence and two reference planar templates are used to extend the measurement range. In the following sections, we will describe the method in detail.

II. PRELIMINARIES

A. Plane-to-Plane Homography

In this paper, the following denotation is used: A 2D point is denoted by $m = (u,v)^T$ and a 3D point is denoted by $M = (X,Y,Z)^T$. Their homogeneous coordinates are in the form of $\tilde{m} = (u,v,1)^T$ and $\tilde{M} = (X,Y,Z,1)^T$. The camera model employed here is the central projection and the relationship between a 3D point $\tilde{P}$ and its corresponding image point $\tilde{m}$ is

$$s\tilde{m} = P\tilde{M} = (p_1, p_2, p_3, p_4)\tilde{M} \qquad (1)$$

where s is an arbitrary scale factor, P is the camera matrix [2]. Without loss of generality, a 3D space plane can be assumed as the plane of $Z = 0$, and then from Eq. (1) we have

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = P\begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix} = \underbrace{(p_1, p_2, p_3)}_{H}\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \qquad (2)$$

By denoting $H = (p_1, p_2, p_3)$ and $\tilde{M}_\pi = (X,Y,1)^T$, Eq. (2) is reduced to

$$s\tilde{m} = H\tilde{M}_\pi \qquad (3)$$

Hence, the mapping between a plane point and its image is a 2D projective transformation, which is called plane to plane homography [6-8]. Usually, H is a non-singular 3×3 homogeneous matrix with 8 degrees of freedom because it can only be defined meaningfully up to a scale factor. The homography can be uniquely determined from four general coplanar space points (no three points are collinear) and their corresponding image points. Let L be a line on the space plane and l be its corresponding image line. From the duality principle about points and lines, we have

$$sL = H^T l \tag{4}$$

According to Eq. (4), each image-to-world line correspondence can give rise to two independent linear constraints on the homography H. Thus, given four or more coplanar line correspondences in general position (no three lines are concurrent), the homography can be determined [9-10]. In this paper, we use the normalized homography estimation method proposed in [5].

B. Single View Based Planar Metrology Method

As long as the homography is obtained, an image point can be back-projected to the world plane via H^{-1}, so the distances on the world plane can be measured. Let M_1 and M_2 be the two 3D planar points that are to be measured. $\tilde{M}_{\pi 1}$ and $\tilde{M}_{\pi 2}$ are their corresponding coordinates in the object coordinate system, whose XOY plane is the reference plane π. Their corresponding image points are denoted by $\tilde{m}_1$ and $\tilde{m}_2$. From Eq. (4), we can obtain

$$\begin{cases} s_1 \tilde{M}_{\pi 1} = H^{-1}\tilde{m}_1 \\ s_2 \tilde{M}_{\pi 2} = H^{-1}\tilde{m}_2 \end{cases} \tag{5}$$

We can obtain $\tilde{M}_{\pi 1}$ and $\tilde{M}_{\pi 2}$ by solving Eq. (5), and then the distance between the 3D point M_1 and M_2 is

$$D = \left\| \tilde{M}_{\pi 1} - \tilde{M}_{\pi 2} \right\| \tag{6}$$

III. PLANAR METROLOGY METHOD BASED ON IMAGE SEQUENCE

In order to expand the measurement range to meet the needs of practical application, this paper proposes a novel metrology method based on image sequences. During the process of measurement, two reference planar templates are laid on the ground: the main reference planar template and the auxiliary reference planar template. Here the main reference planar template is used to obtain 3D information and the auxiliary reference planar template is used to transform the coordinates of the 3D measures points into the same 3D coordinate system. According to the two reference planar templates, we can perform accurate measurement for large scene.

As shown in Figure 1, two "回"-type reference planar templates are laid on the ground, and the right one is the main reference planar template and the left one is the auxiliary reference planar template. In the aspect of template placement, we require the auxiliary reference planar template of the previous image is the main reference planar template

of the next image, and the space position of the two planar templates remain fixed. That is to say, we only move the main reference planar template in the process of obtaining image sequence, and it is taken as the auxiliary reference planar template of the next image. Through the transformation of the roles of the two planar templates, the effective measurement range is expanded. Here we must illustrate that the sizes of the two planar templates are known. The two planar templates can be placed according to the practical need, and don't need strictly according to the placement method described in this paper. But one of the two templates must remain fixed for two consecutive images. In this paper, in order to determine the relationship between the image lines of different images, three corners are marked with red, blue and green circles in each "回"-type reference planar template.
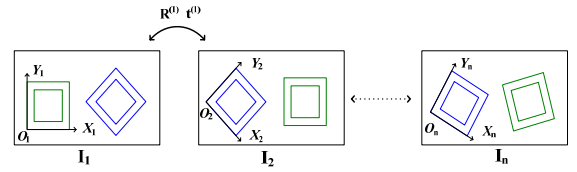

Figure 1.   The distribution of the two planar templates

For the i-th ($i = 1, 2, \cdots, n$) image, let the main reference planar template lie on the plane $X_i O Y_i$ of the 3D space coordinate system $O_i - X_i Y_i Z_i$. The line of the main reference planar templates is denoted by $L_j^{(i)}$ ($j = 1, 2, \cdots, 8$), and its corresponding image line is denoted by $l_j^{(i)}$. The line of the auxiliary reference planar template is denoted by $Lf_j^{(i)}$, and its corresponding image line is denoted by $lf_j^{(i)}$. Here the coordinates of $L_j^{(i)}$ are known and the coordinates of $l_j^{(i)}$ can be obtained by edge detecting and line fitting. Then the homography matrix H_i between the main reference planar template and its corresponding image can be computed using the normalized line-based estimation method []. From Section 2.2 we can conclude that the distance between any two points on the ground in the range of the i-th image's view field can be obtained according to the homography matrix H_i. The coordinates of $Lf_j^{(i)}$ in the 3D coordinate system $O_i - X_i Y_i Z_i$ can be computed by

$$s_f^{(i)} Lf_j^{(i)} = H_1^{-T} lf_j^{(i)} \tag{7}$$

As the position of the auxiliary reference planar template of the previous image and the position of the main reference planar template of the next image remain invariant, this constraint can be used to estimate the transformation between the 3D space coordinate systems of two adjacent images. For the image point of the i-th image, its corresponding 3D space point in the coordinate system $O_i - X_i Y_i Z_i$ is denoted by $M^{(i)} = (X^{(i)}, Y^{(i)}, 0)^T$. For the image line of the i-th image, its corresponding 3D space line in the coordinate system $O_i - X_i Y_i Z_i$ is denoted by

$L^{(i)} = (a^{(i)}, b^{(i)}, c^{(i)})^T$. Let $\tilde{M}^{(i)} = (X^{(i)}, Y^{(i)}, 1)^T$, and the transformation matrix A between the coordinate system $O_i - X_i Y_i Z_i$ and $O_{i+1} - X_{i+1} Y_{i+1} Z_{i+1}$ includes the rotation matrix $R^{(i)} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$ and the translation vector $t = \begin{bmatrix} t_1 & t_2 \end{bmatrix}^T$. Then the relationship between the 3D space coordinate systems corresponding to the i-th image and the i+1-th image can be written as

$$\tilde{M}^{(i)} = \begin{bmatrix} R^{(i)} & t^{(i)} \\ 0 & 1 \end{bmatrix} \tilde{M}^{(i+1)} = A\tilde{M}^{(i+1)} \tag{8}$$

Let the 3D space point $M^{(i)}$ lie on the line $L^{(i)}$ and the 3D space point $M^{(i+1)}$ lie on the line $L^{(i+1)}$, and they have the constraints $\tilde{M}^{(i)T} L^{(i)} = 0$ and $\tilde{M}^{(i+1)T} L^{(i+1)} = 0$. Then the Eq. (8) can be written as

$$L^{(i+1)} = A^T L^{(i)} = \begin{bmatrix} R^{(i)T} & 0 \\ t^{(i)T} & 1 \end{bmatrix} L^{(i)} \tag{9}$$

Let $L_j^{(i)} \leftrightarrow L_j^{(i+1)} (1 \le j \le n)$ be a set of line correspondence, and $L_j^{(i)} = (a_j^{(i)}, b_j^{(i)}, c_j^{(i)})^T$, $L_j^{(i+1)} = (a_j^{(i+1)}, b_j^{(i+1)}, c_j^{(i+1)})^T$. Then we have

$$\begin{bmatrix} a_j^{(i)} & b_j^{(i)} \\ b_j^{(i)} & -a_j^{(i)} \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} = \begin{bmatrix} a_j^{(i+1)} \\ b_j^{(i+1)} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} a_j^{(i)} & b_j^{(i)} \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = c_j^{(i+1)} - c_j^{(i)} \tag{11}$$

As the transformation matrix A has three unknown parameters θ , t_1 and t_2 , given two or more line correspondences, the matrix A can be determined. When the measurement data exists errors, the algorithm described above may not meet the intrinsic constraint $(\cos\theta)^2 + (\sin\theta)^2 = 1$. So in the practical applications, we use this constraint to optimize the results. If the transformation relationship between the spatial coordinate system of the two adjacent images has been estimated, we can put them in a unified 3D coordinate system and can perform the measurement in the range of the view field. Using the similar principle, the image sequence based planar measurement can be performed.

IV. EXPERIMENTAL RESULTS

As the correctness of the method proposed in this paper can be strictly proved in mathematics, we only give the experimental results of real images. All images are taken by a Nikon Coolpix 5700 digital camera with resolution of 2560×1920. During the test, the main reference planar template and the auxiliary reference planar template are laid on the ground. At first, for each image, use Canny edge detector to detect the edge points of the two templates and use a least-squares technique to fit the detected edge points into lines. Then we use the normalized line-based method to estimate homography matrixes, and the space coordinates of

the lines of the auxiliary reference planar template can be estimated. Finally the transformations between different images are estimated. After completing the steps above, the distances between any two points on the ground in the range of view field can be computed from image sequence. In order to validate the practicability and accuracy of the proposed method, we obtain a lot of images to verify. Figure 2 and Figure 2 give two set of image sequence, and Table 1 and Table 2 are their measurement results. For a single image, the measurement accuracy is about 98%; for two images, the measurement precision is about 96%; for three images, the measurement precision is about 95%. Therefore, the measurement precision of the proposed method decreases with the increasing number of images. But the measurement results still have certain precision. In many practical applications, people need flexible and simple measurement method, and the requirements on the measurement accuracy is not very high, such as traffic accident scene measurement system etc. So the method proposed in this paper can be well used in the measurement of large scale scene.

V. CONCLUSIONS

In this paper, an image sequence based planar metrology method is proposed. In practical applications, we often need to obtain large scale scene distance information. For example, one image couldn't include all feature points in the traffic accident scene. By using the main reference planar template and the auxiliary reference planar template, the method proposed in this paper can solve the accurate planar measurement of large scale scene. Extensive real image tests validate the proposed method and show that the proposed method can be successfully used in image sequence based planar metrology.
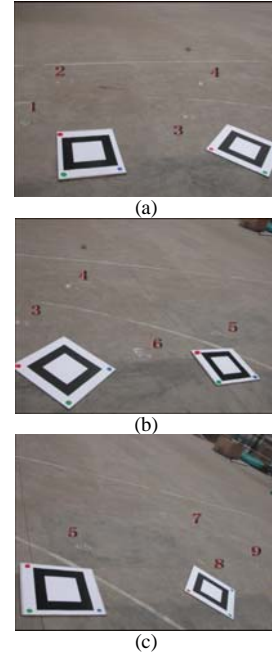

(a)

(b)

(c)

Figure 2. A set of image sequence

TABLE I. THE MEASUREMENT RESULTS OF THE IMAGE SEQUENCE SHOWN IN FIGURE 2

	Line Segments	True Distance (cm)	Estimated Value (cm)	Absolute Error (cm)	Relative Error (%)
One image	1-2	113	113.79	0.78	0.69
	1-3	197	198.28	1.28	0.65
	2-3	194.5	194.26	0.24	0.12
	2-4	241.5	241.48	0.022	0.0094
	3-5	264.5	269.58	5.08	1.92
	4-5	210.5	211.58	1.08	0.51
	5-9	351.5	345.68	5.82	1.66
Two images	1-4	291.5	284.49	7.01	2.40
	2-4	241.5	236.78	4.72	1.95
	1-6	342	336.97	5.03	1.47
	2-6	344	335.88	8.12	2.36
	4-5	210.5	211.04	0.54	0.26
	5-9	351.5	340.17	11.33	3.22
	6-7	389	375.34	13.66	3.51
	6-8	334	330.25	3.75	1.12
	6-9	480	461.29	18.71	3.90
Three images	1-5	461	443.61	17.39	3.77
	1-8	606	608.34	2.34	0.39
	2-5	441	422.11	18.89	4.28
	1-7	706	732.22	26.22	3.71
	1-8	606	608.34	2.34	0.39

TABLE II. THE MEASUREMENT RESULTS OF THE IMAGE SEQUENCE SHOWN IN FIGURE 3

	Line Segments	True Distance (cm)	Estimated Value (cm)	Absolute Error (cm)	Relative Error (%)
One image	1-2	112	112.02	0.02	0.02
	1-3	257.5	259.58	2.08	0.81
	2-3	276.5	275.26	1.24	0.45
	4-5	101.5	99.54	1.96	1.93
	4-6	185.5	182.83	2.67	1.44
	5-10	310	313.36	3.36	1.08
	6-10	407.5	410.53	3.03	0.74
Two images	1-4	580.7	591.88	11.18	1.92
	1-5	527.5	532.38	4.88	0.92
	2-4	568	576.58	8.58	1.51
	2-5	532.5	531.40	1.10	0.21
	3-4	330	342.69	13.69	4.15
	3-5	269.5	278.15	8.65	3.21
	4-5	101.5	99.54	1.96	1.93
Three Images	1-4	580.7	561.43	19.27	3.32
	1-5	527.5	522.59	4.91	0.93
	2-4	568	546.33	21.67	3.81
	2-5	532.5	521.05	11.45	2.15
	3-5	269.5	279.15	9.65	3.58

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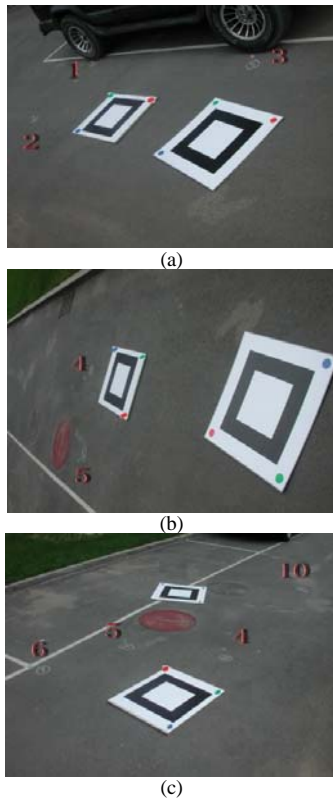
(a)

(b)

(c)

Figure 3. A set of image sequence