BASED ON STEREO SEQUENCE IMAGE 3-D MOTION PARAMETERS DETERMINATION

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ABSTRACT:

Deriving accurate 3-D motion information of a scene is an essential and important task in computer vision, and is also one of the most difficult problems. In this paper, using photogrammetry method and computer vision technique the author investigates the determination of 3-D motion parameters from binocular stereo image sequences method and steps. Discussing the in-situ calibration for binocular stereo computer vision systems, combining correlation coefficients and relaxation method for performing motion and binocular stereo matching of images based on point feature, 3-D feature points in the motion object correspondences before and after motion, using “Skew-Symmetric Matrix Decomposition (SSMD)” algorithms which exploits the fewest variables and without losing the linearity in computation to reduce computing complexity and improve accuracy about motion parameters R and T acquirement etc. Finally, the motion parameters of real data based on 3-D correspondences feature estimation method are given.

1. PREFACE

It is an important question in computer vision to restore the motion information of objects from the sequence image. The three-dimensional space coordinates of the feature points of moving object is obtained from the binocular stereo sequence image. Then, according to the above three dimensional positional information(revolve matrix R and translation vector T), the moving parameters are figured out. Compared to the single sequence image movement analysis method, this computation is simple and also can obtain the absolute translation quantity. But in this method the spatial three dimensional coordinates gain, movement object feature point position extraction, effective match between feature point stereo and movement(sequence), and 3-D feature points in the motion object correspondences before and after motion constitute to the key to solve this question. In order to guarantee different time movement object feature point correspondence, the method presented in this paper at first establish binocular stereo vision system, and obtains the translation relationship between image space and object space coordinates; then carries on sequence and stereo match of binocular stereo sequence image of movement object random feature points. The calibration result is used to obtaining the object space coordinates of feature point, and from this to estimate the parameter of object movement (R, T).

2.BINOCULAR STEREO VISION SYSTEM CALIBRATION

The calibration about camera is an essential procedure in the binocular sequence image three-dimensional determination. The precision and the reliability of camera calibration directly influence 3D measure precision of Stereovision system. In order ot fit for such case that the off-the-shelf CCD camera’s interior parameters are unstable during the moving object tracking process, The author describes the methods of real-time in-suit calibration of CCD camera in the process of movement analyses based on feature correspondence by use of the known feature lines (points) which have geometric relation in object side. This calibration model is direct linear transformation (DLT) with distortion correction.

$$I + v_i + \delta_i + \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} = 0$$

$$J + v_j + \delta_j + \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} = 0 \qquad (1)$$

Where ($L_1, L_2, \cdots, L_{11}$)are 11 unknown DLT parameters, （X, Y, Z） is the space coordinates control point in object space. (I, J) is the pixel coordinates, （δ_i, δ_j） is the pixel distortion value, （v_i, v_j） is the correction values of (I, J) when redundancy exists. The quantites of the elements about exterior orientation and the photoelectricity transforms distortion basic term Nx, Ny coefficient may be obtained from $L_1, L_2, \cdots, L_{11}$.

After L_i is obtained, the space coordinates（U,V,W）of moving object random feature point can be obtained by matching result in both left and right images took from stereo vision system.Supposes the coefficients L_i of two images be （$L_1, L_2, \cdots, L_{11}$） and （$L'_1, L'_2, \cdots, L'_{11}$） respectively，the mathematical models for calculating object space feature point （U,V,W） is:

$$\begin{bmatrix} L_1 + xL_9 & L_2 + xL_{10} & L_3 + xL_{11} \\ L_5 + yL_9 & L_6 + yL_{10} & L_7 + yL_{11} \\ L'_1 + x'L_9 & L'_2 + x'L_{10} & L'_3 + x'L'_{11} \\ L'_5 + y'L_9 & L'_2 + y'L_{10} & L'_7 + y'L'_{11} \end{bmatrix} \begin{bmatrix} U \\ V \\ W \end{bmatrix} + \begin{bmatrix} L_4 + x \\ L_8 + y \\ L'_4 + x' \\ L'_8 + y' \end{bmatrix} = 0 \qquad (2)$$

3.IMAGE MATCH AND SPATIAL FEATURE POINTS CORRESPONDING

3.1 Object feature point extraction

Acquiring the feature points from the picture is the first step of matching. The present study applied the Harris operator that is commonly used in the computer vision community. Harris operator has the following features: it is simple, stable, and insensitive to the noise and illumination, it can quantitively extract feature points, and the distribution of obtained feature point is reasonable. The expression of Harris operator is as below:

$$M = G(\tilde{s}) \otimes \begin{bmatrix} g_x & g_x g_y \\ g_x g_y & g_y \end{bmatrix} \qquad (3)$$

$$I = Det(M) - kTrace^2(M), k = 0.04$$

where g_x and g_y indicate the x and y directional derivatives respectively; $G(\tilde{s})$ is Gauss template, $\otimes$ is convolution operation; I is interest value of each point; Det is matrix determinant; k is constant.

3.2 Initial matching

The goal of initial matching is to determine a candidate match concourse T. Correlation score was used here. For each feature point $m_1 \in$ image1, $m_2 \in$ image2, Supposes their image coordinates are (u_1, v_1) , (u_2, v_2) respectively, if the difference between coordinates m_1 and m_2 is less that a certain threshold, the grayscale correlation score of $(2n+1)\times(2n+1)$ window centered in m_1 and m_2 was calculated individually.

$$Score(m_1, m_2) = \frac{\sum_{i=-n}^{n}\sum_{j=-m}^{m}\left[I_1(u_1+i, v_1+j) - \bar{I}_1(u_1, v_1)\right]*\left[I_2(u_2+i, v_2+j) - \bar{I}_2(u_2, v_2)\right]}{(2n+1)(2m+1)\sqrt{\sigma^2(I_1)\times\sigma^2(I_2)}}$$

where (4)

$$\bar{I}_k(u, v) = \sum_{i=-n}^{n}\sum_{j=-m}^{m} I_k(u+i, v+j)/\left[(2n+1)(2m+1)\right]$$

is the average at point (u, v) of I_k (k =1,2),and $\sigma(I_k)$ is the standard deviation of the image, I_k in the neighbourhood $(2n+1)\times(2m+1)$ of (u, v) which is given by

$$\sigma(I_k) = \sqrt{\frac{\sum_{i=-n}^{n}\sum_{j=-m}^{m} I_k^2(u, v)}{(2n+1)(2m+1)} - I_k^2(u, v)} \quad (k = 1,2)$$

The score ranges from –1,for two correlation windows, which are not similar at all, to 1,for two correlation windows, which are identical.

A constraint on the correlation score is then applied in order to select the most consistent matches: For a given couple of points to be considered as a candidate match, the correlation score must be higher then a given threshold. If the above constraint is fulfilled, we say that the pair of points considered is self consistent and forms a *candidate match.* For each point in the first image, we thus have a set of candidate matches from the second image (the set is possibly nil); and in the same time we have also a set of candidate matches from the first image for each point in the second image.

Assigns a pair matched point, if it is thought as the candidate matched point, the correlation score must be bigger than some threshold value. (threshold value is 0.8 in this paper). The size of search window is usually determined by priori knowledge (the size of corrlated window is 11×11 in experiment). Therefore, the candidate match relations between a certain feature point in image 1 and some feature points in image 2 is established. This point was then joined to the candidate match concourse T.

3.3 The relaxation law that is based on matching support

The law of relaxation is to allow the candidate match pair in T to dismiss oneself and to automatically match each other through iterative so as to make the “continuity" and "uniqueness" to obtain biggest satisfaction. The continuity refers to the massive other corret match pair usually existing in the neighborhood of correct match pair; Uniqueness refers to the identical feature point existing in only one matched pair. Or it can be expreesed as the phenomenon that if candidate matching is right, there must be many candidate matching around it, while if candidate matching is wrong, there are less candidate matching around it. Matching support is defined as the degree that the neighbor candidate supports the candidate matching. It means that the strongest the matching support is, the more possible that the candidate matching is true.

The detailed calculation is as below:

Supposes there are two set of feature points P ={ P_1 , P_2 ,…, P_m } and Q ={ Q_1 , Q_2 ,…, Q_n }.For each paired point (P_i , Q_j), relative excursion between two set of feature points is defined. Given $\delta_{ij}(h,k)$ is the distance between P_h and Q_k when P_i and Q_j matches (only shift), If $|\delta_{ij}(h,k)|$ is zero, it means that Q_k corresponding Q_j equals to P_h corresponding P_i , therefore, points pair (P_h , Q_k) should give (P_i , Q_j) strongest support. Along with $|\delta_{ij}(h,k)|$ increasing its support decreases. As a result, given the support of (P_h , Q_k) on (P_i , Q_j) is:

$$\phi(|\delta_{ij}(h,k)|) = \frac{1}{1+|\delta_{ij}(h,k)|^2} \qquad (5)$$

It is reasonable require when (P_i , Q_j)is a good match, P_h match with Q_j only, that is (P_h , Q_k) is related with P_h and be paired to(P_i , Q_j)with maximize support. a measure of support for a match is defined below:

$$\max_{k\neq j}\phi(|\delta_{ij}(h,k)|) \qquad (6)$$

$\delta_{ij}(h,k)$ and $\phi(|\delta_{ij}(h,k)|)$ are defined as:

$$\delta_{ij}(h,k) = \frac{|d(P_i, P_h) - d(Q_j, Q_{kl})|}{dist(P_i, P_h; Q_j, Q_{kl})} (l = 0,1...) \qquad (7)$$

where: $d(P_i, P_h)$ = $\| P_i - P_j \|$, the Euclidean distance between P_i and P_j .

$d(Q_j, Q_{kl})$ = $\| Q_j - Q_{kl} \|$, the Euclidean distance between Q_j and Q_{kl} . $dist(P_i, P_h; Q_j, Q_{kl})$ is the average distance of the two pairing, that is

$dist(P_i, P_h; Q_j, Q_{kl}) = [d(P_i, P_h) + d(Q_j, Q_{kl})]/2$

$$\phi(|\delta_{ij}(h,k)|) = \begin{cases} e^{-\delta_{ij}(h,k)/\varepsilon_r} & \text{If } (Q_j, P) \text{ is a candidate match and } |\delta_{ij}(h,k)| < \varepsilon_r \\ 0 & \text{Otherwise} \end{cases}$$

Where ε_r is the threshold of relative distance difference, its empiric value is applied in calculation and 0.3 is applied in paper. Since the candidate matching points Q_k of P_h are more than one, the numbers of $\phi(|\delta_{ij}(h,k)|)$ values are more than one; only the maximum $\max_{k \neq j} \phi(|\delta_{ij}(h,k)|)$ is applied as support of point P_h and its unknown match point pair (P_i, Q_j) .In actual calculation, the points in the neighbour domain of P_i are more than one, if $N(P_i)$ is used to express the point set（excluding P_i ）in the neighbour domain of point P_i , calculates the support of point pair (P_i, Q_j) in $N(P_i)$ one by one, then the average after accumulative serves as generally initial support：

$$S^0(P_i, Q_j) = \frac{1}{m} \sum_{h \neq i} \max_{k \neq j} \phi(|\delta_{ij}(h,k)|) \qquad (8)$$

Where m is the number of points in $N(P_i)$.

When calculating $S^0(P_i, Q_j)$， treat each point pair (P_h, Q_k) initially and equally because there is no priori knowledge at beginning. But after the r time iterant (r > 0)， the support of (P_h, Q_k) on (P_i, Q_j) relies not only on the difference of location between P_h and Q_k ， but also on their $S^{r-1}(P_i, Q_j)$ value, namely allowing feedback of local support. These two factors can be combined together as a different way; the minimum value is selected, therefore:

$$S^r(P_i, Q_j) = \frac{1}{m} \times \sum_{h \neq i} \max_{k \neq j} \min[S^{r-1}(P_i, Q_j), \phi(|\delta_{ij}(h,k)|)] \qquad (9)$$

the iterative until expect for P_i ,the measure of support for less then known threshold value.

3.4 Sequence, stereo double matching restraint

Stereo correspondence and sequence correspondence simultaneously exist in the three-dimensional feature correspondence movement analysis. The method and goal of these two matches are identical from the aspects of image processing. During the process of object three-dimensional feature point's correspondence, both stereo-sequence match and sequence-stereo match can be applied. However, the different matching order will has different matching effect to the final moving object three-dimensional feature point correspondence. In actual operation, the adjacent images took by one camera are similar, because the time interval between two adjacent images is very short. Thus, the sequence image match from same camera is easy, but because its base line between viewpoints is relatively short, three-dimensional reconstruction is difficult. Therefore, the estimated depth is not precise in the situation when noise exists (it is even impossible when baseline is fairly short). With this correspondence, there is usually a certain baseline between different cameras, the three-dimensional reconstruction precision is fairly high among stereovision because the distance between viewpoints is large, but stereo matching is difficult, especially when huge disparity and image distortion exist. The double match restraint namely first extracts random feature points on moving objects from different-time but same-sequence images, determining the corresponding relationship of feature points among the same sequence images, establish the sequence match of binocular image sequences. If the image sequence sample density is appropriate, the reliability of the feature match in sequence image can be guaranteed. Then according to match corresponding point coordinates which obtained from the sequence match result matching with corresponding images of same-time different sequence (left and right images stereo match). Therefore, the difficulty of random stereo match can be decreased to a great level through this double match restraint. As a result, the whole correspondence of moving object random three-dimensional feature points can be obtained preferably.

Double match restraint process is shown as Figure1. Where the left and right image stereo vision system at time t_i are I_i and $I_i^{'}$ respectively, the corresponding feature points on image I_i and $I_i^{'}$ are m_i and $m_i^{'}$, the three-dimensional feature points on moving object corresponding to m_i and $m_i^{'}$ is M_i , $R_{i,i+1}, t_{i,i+1}$ is rotational matrix and translation vector of moving objects between time t_i to time t_{i+1} , R_{LR}, t_{LR} are rotational matrix and translation vector between left and right stereo vision camera, the match between feature points m_i *and* $m_i^{'}$ is stereo match (correspondence)；the match between feature point m_i *and* $m_i^{'}$ or m_i *and* $m_{i+1}^{'}$ is sequential (moving) match (correspondence) ； the correspondence between feature points M_i *and* M_{i+1} is correspondence of moving objects random three-dimensional feature points. $i = 3$ in Figure 1.

In practical realization, when carrying on the preceding stage match, the feature points are extracted from two images (front and rear) simutaneously, and original matching table is created between the features of two images, the possible candidate match points of a feature is found in the other image. But when carrying on the latter match, corresponding feature point is searched on the other image for matching according to the preceding match result (coordinates) in order to enhance the computation speed and the match precision. Before the movement sequence match, the image difference can be used to examine the dynamic moving object, and limit the matched object on moving object (adandoning the static background of moving object).

Through the sequence-match and stereo-match, after obtaining the pixel coordinates of corresponding binocular sequence image feature points of moving object at different time, and using the transformation relation of image and object coordinates obtained from calibration, the object coordinates of corresponding feature points can be obtained from formula (2). Using these points sequences in the three-dimensional space, the object parameters of movement are estimated.

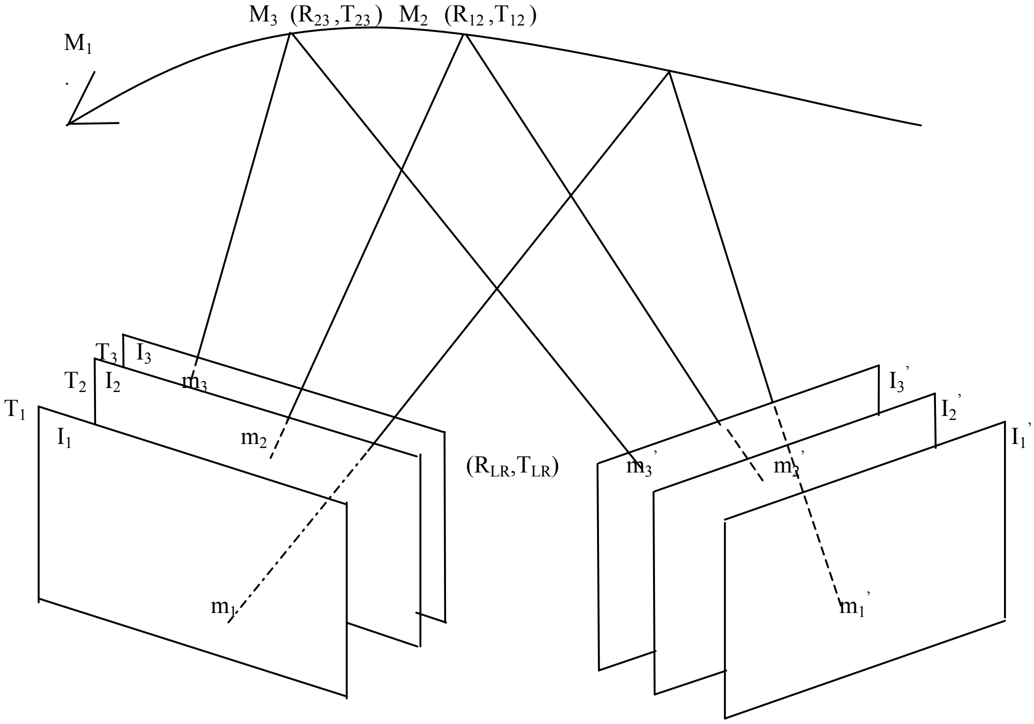

Figure 1 Sequence, stereo double matching restraint

4.THREE-DIMENSIONAL MOTION PARAMETER DETERMINATION

4.1The basic methods of three-dimensional moving parameter estimation in solid sequential images

According to dynamics and the space analytic geometry theory, rigid body movement in the three-dimensional space can be decomposed into rotation and translation. Supposes that the three dimensional coordinates of random feature points P_i at time t on moving rigid body is $(x_i, y_i, z_i)^T$,after time Δt it moves to feature $P_i^{'}$ whose three-dimensional coordinate is $(x_i^{'}, y_i^{'}, z_i^{'})^T (i = 1,2,\cdots,n)$, and the corresponding relation of P_i and $P_i^{'}$ is as the following rigid body moving equation:

$$P_i^{'} = RP_i + T \quad (i = 1,2,\cdots n,) \qquad (10)$$

Where R is a 3×3 rotational matrix, T is translation vector named $T = (\Delta x, \Delta y, \Delta z)^T$ .Thus the rotational matrix R and translation vector T of the above equation can be determined from sequential images. According to the equation (10), suppose there are three feature corresponding points at time t and time t+ Δt on the object, then has:

$$R\begin{bmatrix} P_1 - P_2 \\ P_2 - P_3 \end{bmatrix} = \begin{bmatrix} P_1^{`} - P_2^{`} \\ P_2^{`} - P_3^{`} \end{bmatrix} \qquad (11)$$

The equation (11) is a linear equation about the R, the condition that has the unique solution is that the rank of coefficient matrix is less than 2, in a nother word P_1-P_2 and P_2-P_3 must be not co-line .It means that the three-dimensional moving parameter can be determined uniquely so long as more than three uncoline three-dimensional feature points on the object are obtained. In order to guarantee the precision and the computation speed, the actual computation adopts the method of center of gravity to the three dimensional feature point coordinates. Supposes the gravity center of the three dimensional feature points set $\{P_i\}$ and $\{P_i^{`}\}$ is:

$$\overline{P} = \frac{1}{n}\sum_{i=1}^{n} P_i \qquad \overline{P^{`}} = \frac{1}{n}\sum_{i=1}^{n} P^{`}_i \qquad (12)$$

Thus: $$\overline{P^{`}} = R\overline{P} + T \qquad (i = 1,2,\cdots,n) \qquad (13)$$

So: $$\left[P_i^{`} - \overline{P^{`}}\right]^T R = \left[P_i - \overline{P}\right]^T$$

After Obtaining rotational matrix R，translational vector can be determined as follow：

$$T = \overline{P^{`}} - R\overline{P} \qquad (14)$$

4.2 The solution of rotational matrix R

As revolved above matrix R is a 3x3 orthogonal matrix, 9 components of R are calculated directly, but the algorithm is complex, the solution is not orthogonal, the reliability is poor. Because there are only 3 independent variables in the rotational matrix, by selecting these 3 independent variable for computation, no doubt it will reduce computation quantity, and enhance the reliability of algorithm. By applying this linear algorithm based on skew-symmetry matrix decomposition to determine three-dimensional rotational matrix parameters, not only computation quantity is reduced, but also linear computation is realized.

As Cayley theorem, a three-dimensional orthogonal matrix R,if satisfy I+R is full rank， it is can be decomposed skew-symmetry matrix S and unit matrix I uniquely, that is :

$$R = (I + S_{[N]})(I - S_{[N]})^{-1} \qquad (15)$$

There into：

$$N=\begin{bmatrix}a\\b\\c\end{bmatrix}\qquad S_{[N]}=\begin{bmatrix}0&-c&b\\c&0&-a\\-b&a&0\end{bmatrix}\qquad I=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$$

$$R=\frac{1}{1+a^2+b^2+c^2}\begin{bmatrix}1+a^2-b^2-c^2 & 2ab-2c & 2ac+2b\\ 2ab+2c & 1-a^2+b^2-c^2 & 2bc-2a\\ 2ac-2b & 2bc+2a & 1-a^2-b^2+c^2\end{bmatrix} \quad (16)$$

according to(13)there is relation formula below：

$$A_{m\times3}R=B_{m\times3} \quad (17)$$

There into： $A_{m\times3}=\left[P_i^{`}-\overline{P^{`}}\right]^T$ $B_{m\times3}=\left[P_i-\overline{P}\right]^T$

Replace(15)into(17)

$$A_{m\times3}\,(I+S_{[N]})=B_{m\times3}\,(I-S_{[N]}) \quad (18)$$

solution equation(18)obtain independent variable (a,b,c), thereby obtain the rotational matrix R .replace R into(14)translation T can be obtained.

5. EXPERIMENTAL RESULTS

In present study, we use a binocular stereo computer vision system, to acquire binocular stereo image sequences pair in turn constant duration (the true quantity of motion about every spaced interval of time is $\Delta x=25/\sqrt{2}mm, \Delta y=-25/\sqrt{2}mm$) about the toy car, which is undergoing an approximate even velocity rectilineal moving in one XY plane in the view scope of a video camera. The three-dimensional moving parameters of the moving object sequence images are calculated. The detail procedures are as below:

①the binocular stereo sequence images pair of moving object in different time is obtinaed using binocular stereovision computer system.

②Using the line (point) features with known geometry relations established in scene, the stereo vision system is calibrated in order to obtain the direct linear transformation coefficient L_i according to the 2 Binocular Stereo vision system calibration model.

③Sequence, stereo matching is done with the law of relaxation and relative matching in order to obtain the image coordinates of moving object corresponeding feature point image coordinates

④ The three-dimensional coordinates of moving object corresponded feature points are calculted according the coefficient L_i.

⑤The parameters R and T of object relative movement are calculated using Skew-Symmetric Matrix Decomposition (SSMD).

The results of rotational matrix and translation vector in 10 time intervals are shown in Table 1. The error between calculated values and true values in x and y directions in 10 time intervals are shown in Table 2. The mean errors of moving point are shown in Table 3. In Table 3, the mean error is the error between three-dimensional coordinate P_i' $(x_i', y_i', z_i')^T$ of corresponded feature point in the time of $t+\Delta t$ which is reconstructed from procedure ④ and the three-dimensional coordinate $\hat{P}_i'(\hat{x}_i', \hat{y}_i', \hat{z}_i')^T$ of corresponding feature point that is calculated from a random feature point $P_i\,(x_i, y_i, z_i)^T$ in a moving object in time t that has moved for Δt according to the R and T vector obtained from the above procedures and using movement equation (10). Here $(i=1,2,\cdots,n)$ and n=16.

Table 1 The results of rotational matrix and translation vector Unit：d • cm

	φ	ω	κ	DX	DY	DZ
1	0.06	−0.56	−0.41	−1.79	1.78	−0.06
2	−0.90	−0.81	0.31	−2.34	1.27	0.12
3	−1.09	−1.48	0.63	−2.10	1.55	0.34
4	0.01	−0.01	1.25	−1.38	1.83	0.22
5	−2.11	1.26	0.76	−1.92	1.86	0.35
6	−0.10	−0.18	1.60	−1.16	1.81	0.28
7	−1.23	0.06	1.50	−1.86	1.54	0.24
8	1.41	1.37	−1.71	−1.77	1.93	−0.12
9	−0.30	−0.33	0.90	−1.68	1.58	0.01
10	1.24	0.59	−0.64	−1.91	1.57	−0.34

Table 2 The mean errors of moving point Unit：cm

	1	2	3	4	5	6	7	8	9	10
$d_{\Delta x}$	−0.02	−0.58	−0.33	0.38	−0.15	0.60	−0.09	−0.01	0.08	−0.14
$d_{\Delta y}$	0.01	−0.48	−0.21	0.06	0.09	0.04	−0.22	0.17	−0.18	−0.18

Table3 The mean errors of moving point Unit： cm

	1	2	3	4	5	6	7	8	9	10
m_x	0.57	0.50	0.24	0.30	0.63	0.39	0.49	0.23	0.13	0.31
m_y	0.28	0.23	0.15	0.27	0.55	0.39	0.36	0.30	0.14	0.20
m_z	0.31	0.19	0.12	0.21	0.28	0.18	0.21	0.13	0.11	0.13

As shown in Table 2, the mean translation errors are 2.4 mm and 1.7mm, in the directions of X and Y, respectively. Due to the limitation of experimental conditions, there is no way to precisely measure the true values of rotating angle and translation value（ΔZ）in direction Z. As alternative, the error value was obtained indirectly from the mean shifting errors in the direction X and Y. on the other hand, the rotating angle and ΔZ are approximately zero because the object undergoes an approximate rectilineal moving in plane XY. This phenomenon is verified approximately by the experimental results of φ 、 ω 、 κ . Concluded from each step of the experiment, there are following aspects that take responsibilit of the error source between calculated values and true values in the process of estimating the entire movement parameters:

① The measuring precise of object space coordinates and corresponding image coordinates. The coefficient L_i obtained from calculation has errors if the error exists in either object coordinates or corresponding image point coordinates because DLT reflects the translation relationship between object coordinate and corresponding image point coordinates.

②The accuracy of stereo and sequence (moving) matching is the crisis of the experiment. The error matching is inevitable in the process of matching. The strict correspondence of random feature points in object before and after is required in three-dimensional movement parameter that is based on point feature. In the present study, photogrammetry is combined effectively with computer vision. As a result, the methods and procedures is obtained to determine the parameters of object movement from the binocular stereo sequence images pair of moving object. Therefore, the solution of correspondence of three-dimensional feature point of moving object is obtained effectively. The future direction is to predict and estimate the moving object based on the current existing achievements in order to achieve the goal tracking determination.

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