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Estimation on Three-dimensional Motion Parameters in Binocular Vision of Robot Tracking and Control System

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Abstract: Motion is an important part of visual research. There are lots of motion vision problems in industrial process control, vehicle navigation, flying target tracking and traffic monitoring. Combing three-dimensional motion of computer vision to position and track spatial position of moving objects for the achieved sequential image is a great challenge for computer vision, which is worthy of deep research. The paper analyzes the determination of motion parameter of objects from two-dimensional feature and three-dimensional feature. And three-dimensional motion and structure information of motion objects is achieved by using binocular vision to timely track motion state and image sequential process of objects. And the motion information of objects is sent to the robot, and the robot uses the achieved data to track objects, which realizes tracking.

Keywords: Camera calibration, SIFT feature matching, Camshift, Three-dimensional motion analysis.

1. INTRODUCTION

Motion is an important part of vision research, the reason for which is that even simple animals have complicated observation, tracking and the function of using motion information. For example, mosquitoes can track moving objects and discover the relative motion between objects and background. Under the situation that the object is the same with the background texture, it can capture the target information [1]. If there is no relative motion, it is difficult to differentiate the background and object. There are lots of motion vision problems in industrial process control, vehicle navigation, flying target tracking, analysis of satellite cloud picture and traffic monitoring. With the promotion of computer performance and CCD technique, and the accumulation of people processing static images, analyzing moving images by computers has become a research hotspot [2].

Moving image analysis needs to solve the problems including motion segmentation, target movement and structure estimation, target tracking and data compression of sequential images. Early moving image analysis is based on two-dimensional moving image analysis [3]. But the application area of intelligent robot and autonomous land vehicle requires the function of three-dimensional vision, which forms image analysis based on three-dimensional motion. The methods researching the problem include optical flow method and characteristic method. The disadvantage of optic flow method is that there is great noise and error, and the additional constraint condition is not perfect, which makes it difficult to recover three-dimensional motion and structure from optic flow with noises [2]. However, characteristic method completely depends on correspondence problem [4]. But the method is difficult to be implemented, which makes many researches based on three-dimensional motion estimation implement under the condition that characteristic correspondence problems have been solved. For moving object analysis, the researches about achieving structural parameters of objects and dynamic image sequential analysis of objects involve characteristic correspondence problem, which means that motion is inseparable from correspondence problem [5].

Using image sequential process to achieve three-dimensional motion and structure information of moving objects is one of the core of dynamic target tracking [6]. In three-dimensional motion structural estimation, the research on tracking and positioning of moving objects in three-dimensional space is seldom. The aim of the paper is to combine three-dimensional motion of computer vision to position, measure and track the space and position of moving objects for the achieved sequential images, which is great challenge for computer vision [7].

2. DESCRIPTION OF RIGID MOTION

Motion of objects only change the position and direction, and can't change the size and shape, so any motion of objects is rigid transformation. If point θ can be seen by two cameras in different positions, the coordination of two cameras is $\mathbf{p}_1 = (x_1, y_1, z_1)$ and $\mathbf{p}_2 = (x_2, y_2, z_2)$. Obviously, the movement of two cameras is rigid motion. Therefore, the coordination $\mathbf{p}_1$ of point p in the first field is be transformed into the coordination $\mathbf{p}_2$ of the second field by rotation and translation transformation.

$$\mathbf{p}_2 = \mathbf{R}\mathbf{p}_1 + \mathbf{t} \tag{1}$$

Matrix R is a orthogonal squares, which is used for rotation transformation.

$$\mathbf{R} = \begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix} \quad (2)$$

R and T are important parameters of describing three-dimensional space motion, and are major solution parameters of three-dimensional motion analysis. Formula (1) can't be applied in practice. In some occasions, the objects have different motion forms at different time intervals, and the motion of the objects should be divided into time intervals to be processes. As shown in Fig. (**2**), from time t1 to time t2, the motion can't be described by the same R and T, and it should be segmented for description [5]. From time t1 to time t2, R1 and T1 is used for description. From t2 to time t3, R2 and T2 is used for description. And from time t3 to time t4, R3 and T3 are used for description [8].

3. EXPRESSION OF ROTATION TRANSFORMATION

The set composed by rotation matrix is expressed as S(3)(The determinant value is a three-dimensional orthogonal matrix), which is called rotation group. The rotation group has important feature of topology (refer to the analysis on topology structure in literature) [9]. A rotation matrix has 9 elements which are independent. And there are 6 constraint equations (3), so the freedom degree of rotation group is 3. We hope to find three variables to represent the transformation space. There have been researchers proving that it is impossible to use 3 parameters to express rotation group without singular point, and at least 5 parameters are required to represent rotation group. There are the following expression methods in which there are singular points, but it is applied because of simpleness. Under the condition, it should be ensured that the computation process can't be ineffective near singular points [10].

$$\begin{aligned} & r_{11}^{\ 2} + r_{12}^{\ 2} + r_{13}^{\ 2} = 1 \\ & r_{21}^{\ 2} + r_{22}^{\ 2} + r_{33}^{\ 2} = 1 \\ & r_{31}^{\ 2} + r_{32}^{\ 2} + r_{33}^{\ 2} = 1 \\ & r_{11}r_{21} + r_{12}r_{22} + r_{13}r_{33} = 0 \\ & r_{21}r_{31} + r_{22}r_{32} + r_{33}r_{33} = 0 \\ & r_{33}r_{11} + r_{32}r_{12} + r_{33}r_{13} = 0 \end{aligned} \quad (3)$$

The common rotation matrix expressions include Eulerian Angles representation, rotation axis representation and quaternion representation. Quaternion representation is introduced as follows:

3.1. Representation

In the filed of robot and vision, Quaternion is widely applied. Quaternion is the element in four-dimensional space, and a non-swapable multiplication is defined. A quaternion is a four vector R= (n_1, n_2, n_3, q), and it can represent rotation of coordinates. In order to know how quaternion represents rotation, we firstly imagine that there is a unit circle in two-dimensional place $x-y$, and any place of unit circle only corresponds to a rotation angle.

And the unit ball in three-dimensional space is considered,

$$x^2 + y^2 + z^2 = 1 \quad (4)$$

Any point of the unit ball only corresponds to the angle θ and ϕ rotating around x and y, and it can't represent the third angle φ rotating around z. If another freedom degree is added, it can express three rotation angles. The unit ball in four-dimensional space is defined as follows.

$$x^2 + y^2 + z^2 + \omega^2 = 1$$

Three rotation angles in three-dimensional space can be represented by the points in four-dimensional unit ball, and the rotation formula represented by unit quaternion is as follows.

$$n_1^{\ 2} + n_2^{\ 2} + n_3^{\ 2} + q^2 = 1$$

Each unit quaternion and (antipole)- $\bar{q}$ (-n1, -n2- n3- q) represents the rotation in three-dimensional space. And unit quaternion is used to express rotation matrix in rigid transformation.

$$R = \begin{bmatrix} q^2 + n_1^{\ 2} - n_2^{\ 2} - n_3^{\ 2} & 2(n_1n_2 - qn_3) & 2(n_1n_3 - qn_2) \\ 2(n_1n_2 + qn_3) & q^2 - n_1^{\ 2} + n_2^{\ 2} - n_3^{\ 2} & 2(n_2n_3 - qn_1) \\ 2(n_1n_3 - qn_2) & 2(n_2n_3 + qn_1) & q^2 - n_1^{\ 2} - n_2^{\ 2} + n_3^{\ 2} \end{bmatrix} \quad (5)$$

After computing unit quaternion, the above formula can be used to compute the rotation matrix.

Unit quaternion has close relationship with the above rotation angle and rotation axis. Rotation can be represented by using rotator a and rotation axis direction, which means that quaternion consists of a scalar relating to rotation tensor and a rotation axis vector.

If the unit vector of rotation axis is $\omega_x, \omega_y, \omega_z$, and i, j and k represents coordinate axis, the unit vector of rotation axis can be expressed as $\omega_x i + \omega_y j + \omega_z k$.

Unit quaternion rotating around the axis for angle α is

$$\begin{aligned} \vec{q} &= \cos\frac{a}{2} + \sin\frac{a}{2}(\varpi_x i + \varpi_y j + \varpi_z k) \\ &= q + n_x i + n_y j + n_z k \end{aligned} \quad (6)$$

The first item of the above formula is the scalar of quaternion, and the other vectors are vectors. The quaternion r of space point P = (x, y, z)' only has vector part. And the vector is the vector representation of space point P.

3.2. Feature

Theorem 1: the following four-order square matrix Q consisting of unit quaternion $\bar{q}$=(N', q)' is an orthogonal matrix.

$$Q=\begin{bmatrix} qI-S_{[N]} & N \\ N^t & -q \end{bmatrix}=\begin{bmatrix} q & -n_3 & n_2 & n_1 \\ n_3 & q & -n_1 & n_2 \\ -n_2 & n_1 & q & n_3 \\ n_1 & n_2 & n_3 & -q \end{bmatrix} \quad (7)$$

I is 3×3 unit matrix, and $S_{[N]}$ is the anti-symmetry matrix corresponding to vector N, $N=(n_1,n_2,n_3)^t$.

$$S_{[N]}=\begin{bmatrix} 0 & -n_3 & n_2 \\ n_3 & 0 & -n_1 \\ -n_2 & n_1 & 0 \end{bmatrix} \quad (8)$$

Theorem 2: any rotation matrix R only has two unit quaternion's $(N^t,q)^t$ and $(-N^t,-q)^t$, which makes the following decomposition possible.

$$\begin{bmatrix} R & O_{3\times1} \\ O_{1\times3} & 1 \end{bmatrix}=Q^2 \quad (9)$$

Theorem 3: R composed by unit quaternion $\bar{q}=(N^t,q)^t$ $=(n_1,n_2,n_3,q)^t$ is

$$R=\begin{bmatrix} q^2+n_1^2-n_2^2-n_3^2 & 2(n_1n_2-qn_3) & 2(n_1n_3-qn_2) \\ 2(n_1n_2+qn_3) & q^2-n_1^2+n_2^2-n_3^2 & 2(n_2n_3-qn_1) \\ 2(n_1n_3-qn_2) & 2(n_2n_3+qn_1) & q^2-n_1^2-n_2^2+n_3^2 \end{bmatrix} \quad (10)$$

3.3. Decomposition Algorithm of Unit Quaternions of Rotation Matrix

From the feature of unit quaternions, we can know that rotation matrix R corresponds to unit quaternion (N, q), so the computation of rotation matrix R can be simplified to be the computation of unit quaternion (N, q). Horn and Faugeras proposed rotation matrix estimation algorithm based on unit quaternion's. The common feature of them is to convert the problem into unit feature vector corresponding to quadratic minimum eigenvalue (unit quaternion's). Firstly, R and T is solved, which makes the residual sum of squares of formula (1) minimal, and the objective function is

$$\min J=\sum_{j=1}^{n}\left\|P_j'-(RP_j+T)\right\|^2 \quad (11)$$

If $$P_c=\frac{1}{n}\sum_{j=1}^{n}p_j \qquad P'_c=\frac{1}{n}\sum_{j=1}^{n}p'_j$$
$$\bar{p}_j=p_j-P_c \qquad \bar{p}'_j=p'_j-P'_c \quad (12)$$

Formula (12) can be converted into

$$\min J=\sum_{j=1}^{n}\left\|\bar{P}_j'-R\bar{P}_j\right\|^2 \quad (13)$$

After achieving R, T can be achieved by using the following formula,

$$T=\bar{P}_j'-R\bar{P}_j \quad (14)$$

Formula (13) is written as the following form,

$$\min J=\sum_{j=1}^{n}\left\|AR-B\right\|^2 \quad (15)$$

Using the least squares criterion is to seek for R making objective function minimal.

$$\min J=tr\{(AR-B)'(AR-B)\} \quad (16)$$

$tr\{\bullet\}$ Represents trace of matrix.

According to the derivation operation rule of matrix trace,

$$\frac{\partial f}{\partial R}=\frac{\partial f}{\partial R}tr\{R^tA^tAR-R^tA^tB-B^tAR+B^tB\}$$
$$=2((A^tAR-A^tB) \quad (17)$$

and the solution of the least square is:

$$\frac{\partial f}{\partial R}=0 \quad (18)$$

And formula (18) is equivalent to

$$\begin{bmatrix} A^tA & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} R & 0 \\ 0 & 1 \end{bmatrix}=\begin{bmatrix} A^tB & 0 \\ 0 & 1 \end{bmatrix} \quad (19)$$

According to theorem 1 and theorem 2, formula (19) can be changed into

$$\begin{bmatrix} A^tA & 0 \\ 0 & 1 \end{bmatrix}QQ=\begin{bmatrix} A^tB & 0 \\ 0 & 1 \end{bmatrix}$$
$$\begin{bmatrix} A^tA & 0 \\ 0 & 1 \end{bmatrix}Q=\begin{bmatrix} A^tB & 0 \\ 0 & 1 \end{bmatrix}Q \quad (20)$$

and

$$\begin{bmatrix} A^tA & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} qI+S_{[N]} & N \\ N^t & -q \end{bmatrix}=\begin{bmatrix} A^tB & 0 \\ 0 & 1 \end{bmatrix}$$
$$\begin{bmatrix} qI-S_{[N]} & N \\ N^t & -q \end{bmatrix} \quad (21)$$

$$\begin{bmatrix} A^tA(qI+S_{[N]}) & A^tAN \\ N^t & -q \end{bmatrix}=\begin{bmatrix} A^tB(qI-S_{[N]}) & A^tBN \\ N^t & -q \end{bmatrix}$$

Theorem 4: the general form of linear model of rotation matrix is

$$A_{m\times3}R = B_{m\times3} \tag{22}$$

R is the rotation matrix to be determined, and A and B is the determined coefficient matrix, and m(≥2) is the number of lines of matrix. And the least square solution of quaternion orthogonal decomposition form of formula (22) is the following equation set.

$$\begin{cases}(A+B)A^tS_{[N]}+(A-B)A^tq=0\\(A-B)A^tN=0\end{cases} \tag{23}$$

4. MOTION ESTIMATION OF OBJECTIVES

The paper selects three-dimensional moving objects as analysis objects. According to correspondence model of feature points, the filtering method is used to estimate three-dimensional translation of moving objects with uniform motion.

In the process of camera tracking and positioning objects, the motion velocity and acceleration value of objects is a function of time f(t).

It can be expressed by a curve. The polynomial approximation can be used to describe the function f(t). During the continuous period, when linear function, square function or proper combination of them is used to approximate to the above function f(t), the linear outer filtering and square filtering can be achieved. The linear outer filtering is introduced as follows.

The measurement value of the original function f(x) at N time is f(t)(t = 1, 2, …, N). If f(x) is approximated by the linear function Y=A+tB,

$$Y=\begin{bmatrix}1 & t\end{bmatrix}\begin{bmatrix}A\\B\end{bmatrix} \tag{24}$$

The error of measurement value and approximation value is

$$\Delta\delta_i = f(t_i)-A-tB \tag{25}$$

And the mean square error estimated by point N is

$$E(\Delta\delta^2{}_i)=\sum_{i=1}^{n}(f(t_i)-A-Bt_i)^2 \tag{26}$$

In order to achieve approximation, the minimal point of the above function of two variables is solved. And by using the least square operation, we can get

$$\begin{bmatrix}A\\B\end{bmatrix}=\begin{bmatrix}\dfrac{\sum_{i=1}^{n}t_i^2\sum_{i=1}^{n}f(t_i)-\sum_{i=1}^{n}t_i\sum_{i=1}^{n}f(t_i)t_i}{D}\\[2ex]\dfrac{\sum_{i=1}^{n}t_i\sum_{i=1}^{n}f(t_i)-N\sum_{i=1}^{n}f(t_i)t_i}{D}\end{bmatrix} \tag{27}$$

and $D=N\sum_{i=1}^{n}t_i^2-(\sum_{i=1}^{n}t_i)^2$ (28)

The value which is solved in formula (27) is substituted into formula (24), which can get the general solution of the best linear approximation of f(t) in the minimal square.

If first three-frame value is used to predict the characteristic value of the next frame, which means to use the known feature value of k-2, k-1 and k frame to solve the feature value of k＋1, we can get

We know:

$$\begin{aligned}&t_1=1 && f(t_1)=f(k-2)\\&t_2=2 && f(t_2)=f(k-1)\\&t_3=3 && f(t_3)=f(k)\end{aligned} \tag{29}$$

Solving: $t_3=4 \qquad f(t_4)=f(k+1)$ (30)

$$f(k+1)=A+Bt_{k+1}=A+4B \tag{31}$$

The above t_i and $f(t_i)$ is substituted into formula (4), and we can get the value of A and B, and then it is substituted into (5), we can get

$$f(k+1)=A+Bt_{k+1}=A+4B=\frac{1}{3}[4f(k)+f(k-1)-2f(k-2)] \tag{32}$$

If there is need to predict characteristic values after frames, under the condition that memory point N is determined, the number of the first memory frames should be N, and

$$\begin{aligned}&t_{N-1}=N-1 && f(t_{N-1})=f(k-2)\\&t_N=N && f(t_{N-2})=f(k-1)\\&t_{N+1}=N+1 && f(t_{N+1})=f(k)\\&t_{N+2}=N+1 && f(t_{N+2})=f(k+1)\\&\cdots\quad\cdots && \\&t_1=1 && f(t_1)=f(k-1-N)\end{aligned} \tag{33}$$

By the same computation, the above data can be solved.

5. EXPERIMENTAL RESULTS

5.1. Experiment of Monocular and Binocular Vision Motion Analysis

(1) Experiment objects

Binocular three-dimensional vision system is established for the research. And the three-dimensional images of toy car with uniform linear motion in four positions are achieved as the experiment image. The linear distance interval of moving objects is 5cm (the interval of direction x and y is $5/\sqrt{2}$). The method introduced in three-dimensional analysis on

Table 1. Computation results of QOD angle and translation vector.

	ϕ	ω	k	DX	DY	DZ
1	2.200	1.211	0.712	-3.317	3.307	-0.681
2	1.226	-1.702	3.810	-3.302	2.425	-0.050
3	0.639	-1.621	2.734	-3.324	2.731	0.062
4	-0.516	-0.349	-0.468	-3.342	3.460	0.121

Unit: degree. cm.

Table 2. Translation error value of double sequence in direction X and Y.

	1	2	3	4
ΔDX	0.219	0.234	0.212	0.014
ΔDY	0.229	1.111	0.864	0.07

monocular vision and binocular vision is used to estimate motion parameters of the same moving object, which can bet the difference, disadvantages and advantages of them.

(2) Experiment results and analysis

The premise of the experiment is that after experiment 5.5 completes sequential and three-dimensional constraint matching of moving object, unit QOD is used to determine rotation matrix of motion equation, and determine three-dimensional motion parameters of objects. Tables (**1** and **2**) are three-dimensional motion analysis results of using QOD algorithm to compute binocular vision, and Tables (**3** and **4**) are the three-dimensional motion analysis results of using camshif method to computer monocular vision. As monocular vision is difficult to achieve the depth of objectives, we only consider the condition, Z=0, which means that it is in XY plane.

The achieved motion information based on single-lens image motion analysis has an unascertainable scale factor. And camshift uses color to achieve the position of objectives. When the color of objects is selected as templates, the light makes the color not good, which makes the experiment have error.

5.2. Estimation and Prediction on State of Moving Objects

(1) Experiment objectives

The linear distance interval of moving object is 2.5cm (the interval in direction x and y is $5/\sqrt{2}$).

By checking binocular three-dimensional vision system, moving and three-dimensional matching of any feature point of moving object image, three-dimensional feature point of moving objects is achieved. And filtering method is used to get the present best estimation value of object state, and the prediction estimation value of the state of objects in the future.

(2) Experiment results and analysis

Table (**5**) introduces the computation value and filtering value of moving object at time 3, 4, 5, 6, 7 and 8, and the prediction estimation results on the next time of moving objects.

From the experiment analysis, we can see that no matter solving the present best estimation value of objects or comparing the calculation value of prediction value and motion parameters in direction X, Y and Z, the error of using linear filtering method to estimate the objects with average motion is minimal.

CONCLUSION

The paper introduces the estimation on three-dimensional motion parameters and motion analysis on monocular vision and binocular vision. In monocular vision motion analysis, Camshift algorithm (the improvement of mean shift) is used to overcome the disadvantage of Mean shift that it is not suitable for timely tracking. Binocular vision motion analysis introduces that unit quaternion is used to solve three-dimensional motion parameter R and T of objects. It not only improves the stability of algorithm, but also ensures linearity of the original algorithm. In order to track and position the objectives, the motion state of moving objects needs to be predicted and estimated. By standardizing the binocular three-dimensional vision system, and the sequential and three-dimensional matching process of any feature point of moving object images, under the situation of achieving the corresponding three-dimensional feature points of moving objects, it is used as feature value of different frames of sequential images. Linear function method is used to estimate objects with uniform motion. The robot is adjusted according to estimation value and initial state, which realizes tracking moving objects. The experiment proves that no matter solving the present best estimation value of objects or comparing

Table 3. Computation results of three-dimensional translation vector under monocular vision (movement amount under plane XY).

	DX	DY
1	-2.283	2.280
2	-2.254	2.224
3	-2.285	2.259
4	-3.346	3.331

unit: cm.

Table 4. Translation error value of monocular vision in direction X and Y.

	1	2	3	4
ΔDX	0.703	1.282	1.251	0.19
ΔDY	1.256	1.312	1.277	0.205

Table 5. Linear filtering estimation results.

Memory Points	Position Vector	Computation Value	Filtering Estimation Value	Estimation Computation Value
3	X	-4.151	-4.114	-6.216
	Y	3.056	3.006	4.459
	Z	0.061	0.060	0.094
4	X	-6.172	-6.160	-8.214
	Y	4.712	4.473	6.130
	Z	0.654	0.635	0.852
5	X	-475	-442	-9.031
	Y	6.663	6.667	8.330
	Z	1.125	1.122	1.153
6	X	-8.895	-9.451	-11.12
	Y	9.965	9.254	11.11
	Z	2.247	2.009	2.251
7	X	-10.01	-10.06	-12.24
	Y	11.73	11.12	13.31
	Z	3.336	3.003	3.353
8	X	-12.06	-12.66	-14.44
	Y	13.34	12.29	14.47
	Z	4.414	3.392	4.484

unit: cm.

the calculation value of prediction value and motion parameters in direction X, Y and Z, the error of using linear filtering method to estimate the objects with average motion is minimal.

The paper analyzes the accuracy of position of objects under the condition of monocular and binocular vision. The experiment proves that under the situation of monocular vision, only two-dimensional motion can be estimated because that deep image of object can't be achieved, but binocular vision can meet the requirements of convenience and accuracy.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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