ICARCV '92

SECOND INTERNATIONAL CONFERENCE ON AUTOMATION, ROBOTICS AND COMPUTER VISION

16-18 September 1992

PROCEEDINGS

(VOLUME 1 OF 3)

ORGANISED BY

School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore

The Institution of Engineers, Singapore

Motion from a Image Sequence using a Prior Relation of a Pair of Line Segments

M.Terauchi, K.Ito[1]*, T.Joko*[2]*, T.Tsuji and M.Nagamachi*

Faculty of Engineering, Hiroshima University
1-4-1 Kagamiyama, Higashi-Hiroshima, 724 Japan

[1] Dept. of Information Processing, Toyohashi Institute of Technology
1-1 Hibarigaoka, Tempaku-cho, Toyohashi, 441 Japan

[2] Atsugi Development Center, Minolta Camera Co., Ltd.
231-1 Kamiochiai, Atsugi, 243 Japan

Abstract

We propose a new conventional method to reconstruct motion from a sequence of monocular images by using a prior geometrical relation between a pair of straight line segments. In general, the problem in motion estimation from monocular viewed images is ill-posed, therefore additional information is required to recover depth. In this paper we utilize line correspondence between sequential images and a given information on the geometrical relationship between two line segments in the scene. The relation between the coordinates of points can be described only by a rotation term, if it is formulated by relative representation. Then if there exists a pair of line segments, whose relation is given, the matrix can be solved by using linear equations. After that the translation vector is computed. Finally some experimental results for simulated data sets are given.

1 Introduction

The reconstruction of 3D motion or structure from a monocular image is ill-posed problem, because the information on depth would be reduced through the projection onto the image. It follows that it is necessary for the reconstruction to introduce some constraints about characteristics of motion or the structure of the objects. In the problem of *Motion from Image Sequence*, there often assumed that the motion is sufficiently smooth [1], [2], [3].

Ullman studied motion estimation based on points correspondence between sequential images by using the assumption of rigidity of the objects. He showed it is possible to obtain motion and structure of an object from points correspondence of 4 points on 3 frames of the sequential images under the parallel projection, and 5 points on 3 frames under the perspective projection [4]. Tsai and Huang derived linear equations by using decomposition of the singular point of the matrix which contains medial parameters obtained from motion information [5]. The equation consists of 8 variables and is linear, and it enables us to obtain solutions from 8 points correspondence on 2 frames under the perspective projection. They realized to get linear solution, while it had been analysed using nonlinear equations. It is, however impossible to solve the linear equations, if all the 8 points lie on 2 planes where one of two planes intersects the origin of 3D coordinates (at least 5 of 8 points satisfy the condition), or on the surface of the cone which intersects the origin (at least 6 of 8 points satisfy the condition).

On the other hand we proposed a method combining optical flow and correspondence of line segments, in which we derived linear equations by using an assumption of existence of two pair of parallel line segments [6], [7]. However it was limited to motion with small displacement between points on two different frames, because the velocity components were approximated using differential equations. And then we proposed a linear algorithm to estimate motion of a rigid object utilizing the relative expression of coordinates by assuming the existence of a pair of parallel line segments [8]. The method did not adopt any approximation so that it yielded error-free results for all types of motion. It is also possible to examine if a chosen pair of line segments is parallel or not, estimating the motion parameters. The method can be applied to a number of industrial applications, because it needs only a pair of parallel line segments, i.e. 4 points correspondence on 2 frames. However the method requires existence of a pair of *parallel* line segments.

In this paper, we give an extension of the above method to admit other geometrical relation than parallelism. This method can use theoretically almost the all relations between two line segments. It is, however, necessary to give it in advance of motion estimation.

2 Motion Formulation

In this paper we focus on the motion reconstruction from two sequentialized images onto which one rigid object in the scene is projected by the perspective projection. In this section we formulate the motion of one end-point of a line segment and the relative motion of another end-point. Motion of a line segment on the image is shown in Fig.1. We define (x, y) as one end-point of a line segment and (r, s) as the relative position of another one, and the positions after motion are defined as (x', y') and (r', s') respectively as well as ones before motion.

2.1 Motion of Terminal Points

We show the geometrical relationship between the motion of point P in the scene and the image plane in Fig.2. The origin of the world coordinate system $OXYZ$ is set at the lens center of camera, and the Z axis of the coordinate system is placed along the optical axis. Then the 3D motion of point P can be generally represented by the rotational component Φ and the translational component Γ as follows,

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \Phi \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \Gamma \qquad (1)$$

where Φ and Γ are represented as follows,

$$\Phi = \begin{bmatrix} \phi_1 & \phi_2 & \phi_3 \\ \phi_4 & \phi_5 & \phi_6 \\ \phi_7 & \phi_8 & \phi_9 \end{bmatrix}, \ \Gamma = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}, \qquad (2)$$

where the rotation matrix Φ can be described as follows,

$$\Phi = \begin{bmatrix} \sigma_1^2 + (1-\sigma_1^2)\cos\theta & \sigma_1\sigma_2(1-\cos\theta) - \sigma_3\sin\theta & \sigma_1\sigma_3(1-\cos\theta) + \sigma_2\sin\theta \\ \sigma_1\sigma_2(1-\cos\theta) + \sigma_3\sin\theta & \sigma_2^2 + (1-\sigma_2^2)\cos\theta & \sigma_2\sigma_3(1-\cos\theta) - \sigma_1\sin\theta \\ \sigma_1\sigma_3(1-\cos\theta) - \sigma_2\sin\theta & \sigma_2\sigma_3(1-\cos\theta) + \sigma_1\sin\theta & \sigma_3^2 + (1-\sigma_3^2)\cos\theta \end{bmatrix} \tag{3}$$

where θ and $(\sigma_1, \sigma_2, \sigma_3\ )$ denote the rotation angle and the rotation axis respectively. Then the unit cosine vector can be written as

$$\sigma_1{}^2 + \sigma_2{}^2 + \sigma_3{}^2 = 1. \tag{4}$$

The relation between ϕ_i ($i = 1$ to 9) and their parameters $\theta, \sigma_1, \sigma_2, \sigma_3$ yields a nonlinear function. It is, however, possible to solve a pair of solution sets of $\theta, \sigma_1, \sigma_2, \sigma_3$ [5]. The two solutions are dual and the difference of them is based on whether the parameters are described in cw or ccw. Hence as the difference can not be discriminated physically, they can be assumed as the same. Here the relations between two points in the 3D world $P(X, Y, Z)$ and $P'(X', Y', Z')$, and their projection onto image plane $p(x, y)$ and $p'(x', y')$ are given as follows,

$$x = \frac{X}{Z},\ y = \frac{Y}{Z},\ x' = \frac{X'}{Z'},\ y' = \frac{Y'}{Z'}. \tag{5}$$

2.2 Relative Expression of Motion

Here we introduce a new Cartesian coordinate system $\hat{O}\hat{X}\hat{Y}\hat{Z}$ whose origin $\hat{O}$ is set at the end-point of line segment P as shown in Fig.3. Then another end-point can be represented as $M(m_1, m_2, m_3)$ in this coordinate system. The corresponding point after motion can be represented as $M'(m_1', m_2', m_3')$, where M and M' are the vectors along the line-segments. The relations between the vectors M, M' and their projection onto the image plane (r, s), (r', s') are given as follows,

$$r = \frac{m_1 - m_3 x}{Z + m_3},\quad s = \frac{m_2 - m_3 y}{Z + m_3}, \tag{6}$$

$$r' = \frac{m_1' - m_3' x'}{Z' + m_3'},\quad s' = \frac{m_2' - m_3' y'}{Z' + m_3'}. \tag{7}$$

Next, the motion between M and M' is represented only by the rotation matrix Φ as follows,

$$M' = \Phi M \tag{8}$$

Here we introduce parameters t and t' defined as follows,

$$t = \frac{m_3}{Z + m_3},\ t' = \frac{m_3'}{Z' + m_3'}, \tag{9}$$

we obtain the following equations,

$$M = (Z + m_3)N,\quad N = \begin{bmatrix} r + tx \\ s + ty \\ t \end{bmatrix}, \tag{10}$$

$$M' = (Z' + m_3')N',\quad N' = \begin{bmatrix} r' + t'x' \\ s' + t'y' \\ t' \end{bmatrix}. \tag{11}$$

For each line segment before and after motion we define unit vectors along the line segments as I and I' respectively,

$$I = \frac{N}{|N|},\ I' = \frac{N'}{|N'|}. \tag{12}$$

Substituting Eq.(12) into Eq.(10) and Eq.(11), we get the following equations,

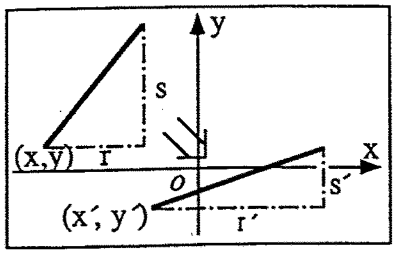

Fig.1 Relative expression of motion on an image.

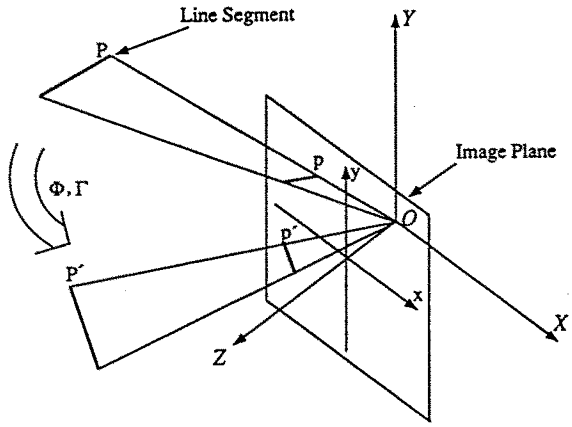

Fig.2 Geometry of the perspective projection.

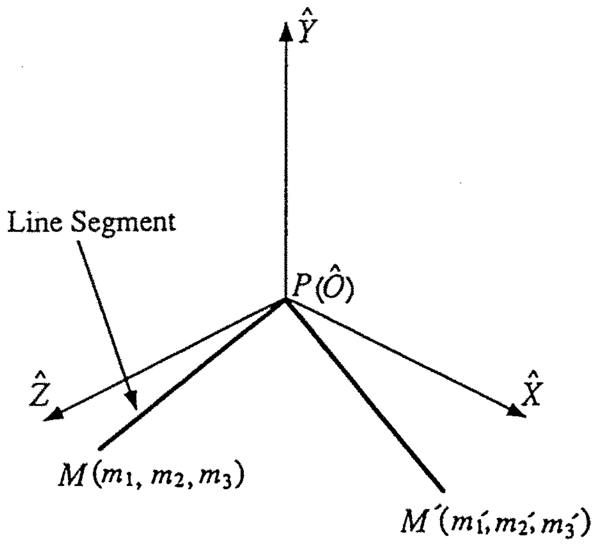

Fig.3 Coordinate system based on the object point.

$$M = (Z + m_3)|N| I, \quad (13)$$
$$M' = (Z' + m_3')|N'| I'. \quad (14)$$

M and M' has the same length, because they are relatively represented and denote the same line segment. As the Z components of the coordinates of the end-points $Z + m_3$ and $Z' + m_3'$ are positive, we can define the following value K from Eq.(13) and Eq.(14),

$$K = \frac{Z' + m_3'}{Z + m_3} = \frac{|N|}{|N'|}. \quad (15)$$

Here it is possible to compute the value K, if t and t' defined in Eq.(9) could be obtained.

After Eq.(8) representing the rotation in the 3D space can be described by using the coordinates on the image as follows,

$$KN' = \Phi N. \quad (16)$$

In this equation the unknown parameters are Φ, t and t'.

2.3 Constraint of Planarity

The relative representation of motion of two line segments is shown in Fig.4. Here we define the relative vectors from one end-point to another one of the line segments as M_1 and M_2, and those after motion as M_1' and M_2'. Then relationship between vector products of M_1 and M_2, and of M_1' and M_2' are given by using just the rotation matrix Φ as follows,

$$M_1' \times M_2' = \Phi(M_1 \times M_2). \quad (17)$$

From Eq.(10), Eq.(11) and Eq.(15) we get,

$$K_1 K_2 N_1' \times N_2' = \Phi(N_1 \times N_2). \quad (18)$$

In this equation the unknown parameters are Φ, t_1, t_1', t_2 and t_2'.

3 Motion Estimation

3.1 Motion Parameters

When the correspondence between two line segments in the 3D space is found from an image, the parameters in Eq.(16) can be obtained, and so forth the parameters in Eq.(18) from the vector products of the line segments. In order to cover those relationships we introduce matrices H and H' defined below,

$$H = [N_1, N_2, N_1 \times N_2], \quad (19)$$
$$H' = \left[K_1 N_1', K_2 N_2', K_1 K_2 \left(N_1' \times N_2'\right)\right]. \quad (20)$$

From Eq.(16) and Eq.(18) we get,

$$H' = \Phi H, \quad (21)$$

where Φ is a unitary matrix, then we obtain the following equation,

$$H'^{\mathrm{T}} H' = H^{\mathrm{T}} \Phi^{\mathrm{T}} \Phi H = H^{\mathrm{T}} H. \quad (22)$$

The above can be rewritten as the equations of components as follows,

$$\left|K_1 N_1'\right|^2 = |N_1|^2, \quad (23)$$
$$\left|K_2 N_2'\right|^2 = |N_2|^2, \quad (24)$$
$$K_1 K_2 N_1'^{\mathrm{T}} N_2' = N_1^{\mathrm{T}} N_2. \quad (25)$$

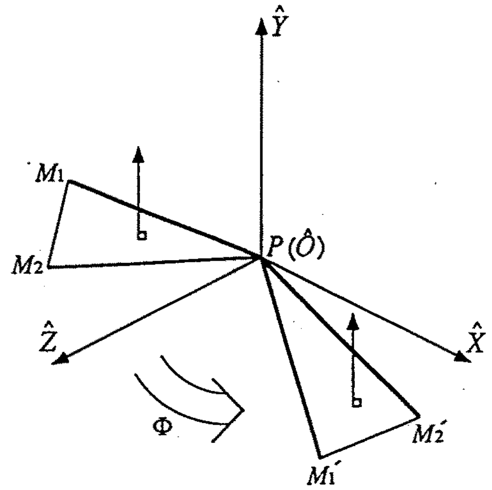

Fig.4 Constraint planes and vector products.

3.2 Linearization by using a given Relation

Eq.(21) states that if the relative lengths t and t' could be computed, it is possible to obtain the rotation matrix Φ by using the relations of two line segments. Therefore we assume that the geometrical relation of a pair of line segments on an object surface is given. This assumption is obviously the constraint for obtaining a unique solution for the parameters t and t'. In general, the relation between two line segments l_1 and l_2 is given by using a rotational matrix $\mathbf{A}$ as follows, neglecting their translational displacement,

$$\begin{bmatrix} r_1 + t_1 x_1 \\ s_1 + t_1 y_1 \\ t_1 \end{bmatrix} = \mathbf{A} \begin{bmatrix} r_2 + t_2 x_2 \\ s_2 + t_2 y_2 \\ t_2 \end{bmatrix}. \quad (26)$$

where,

$$\mathbf{A} = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix}. \quad (27)$$

If the given relation is parallelism, the above equation can be rewritten as,

$$\begin{bmatrix} r_1 + t_1 x_1 \\ s_1 + t_1 y_1 \\ t_1 \end{bmatrix} = \alpha \begin{bmatrix} r_2 + t_2 x_2 \\ s_2 + t_2 y_2 \\ t_2 \end{bmatrix}, \quad (28)$$

where, α is constant value. Here, we can eliminate α in Eq.(28), and can solve in terms of t and t'. Then we get,

$$t_1 = \frac{r_2 s_1 - r_1 s_2}{s_2 x_1 - s_2 x_2 + r_2 y_2 - r_1 y_1}, \quad (29)$$
$$t_2 = \frac{r_2 s_1 - r_1 s_2}{s_1 x_1 - s_1 x_2 + r_1 y_2 - r_1 y_1}. \quad (30)$$

Thus we can get the relative lengths t and t' by using the given relation between line segments.

3.3 Motion Estimation by using Parallelism

As mentioned above, the parameters t and t' can be obtained by using a given geometrical relationship between two line segmaents, here parallelism. It is, however, impossible to compute motion parameters, i.e. the rotation matrix, by using just the relationship between parallel two line segments, because the equations derived from them do not become independent. Therefore, we also introduce virtual lines which are the line segments obtained by connecting each end-point of two line segments not as to make diagonals. The virtual lines are shown in Fig.5a. Next we show how to obtain the relative motion in terms of K defined in Eq.(15) by following processes.

STEP.1 In Fig.5a the line segments l_1 and l_2 denote the real line, and l_3 and l_4 the virtual line. At first the parameters t_1, t_1', t_2 and t_2' can be obtained from parallelism of line segments l_1 and l_2.

STEP.2 From the parameters t_1, t_1', t_2 and t_2', we can get the vectors N_1, N_1', N_2 and N_2' which are functions of t_1, t_1', t_2 and t_2'. Substituting these results into Eq.(15) we have the ratios of vector lengths K_1 and K_2, which are for the real line segments.

From next step we now get the parameter K for the virtual line segments by using the computed parameters K_1 and K_2, which are for the real line segments.

STEP.3 Eq.(10) and Eq.(11) which define the parameter t can be rewritten as follows,

$$Z + m_3 = \frac{Z}{1-t}. \tag{31}$$

We define the absolute coordinates along Z axis of each base-point (the origin of local coordinates system) of the line segments as Z_1, Z_2, Z_3 and Z_4, and the relative ones of the end-points as m_1, m_2, m_3 and m_4 paying attention to depth (Z axis) component of all points. Then the absolute coordinates of each point is shown in Fig.5b. As four line segments share their base/end-points each other, we have following relationships,

$$\begin{aligned} Z_1 &= Z_3 + \mu_3, & (32)\\ Z_1 + \mu_1 &= Z_4 + \mu_4, & (33)\\ Z_2 + \mu_2 &= Z_4, & (34)\\ Z_2 &= Z_3. & (35) \end{aligned}$$

Here we define the ratios of vector lengths for the virtual line segment l_3 as K_3, shown as below,

$$K_3 = \frac{Z_3' + \mu_3'}{Z_3 + \mu_3}. \tag{36}$$

Substituting Eq.(32) into Eq.(36) we get,

$$K_3 = \frac{Z_1'}{Z_1}. \tag{37}$$

Substituting Eq.(31) into Eq.(37) we obtain following equation,

$$\begin{aligned} K_3 &= \frac{Z_1'}{Z_1} = \frac{1-t_1'}{1-t_1}\cdot\frac{Z' + \mu_1'}{Z + \mu_1} \\ &= \frac{1-t_1'}{1-t_1}\cdot K_1. \end{aligned} \tag{38}$$

Thus the parameter K_3 can be obtained from K_1. In the same way, the ratios of vector lengths K_4 for the virtual line segment l_4 is solved as follows,

$$K_4 = \frac{Z_4' + \mu_4'}{Z_4 + \mu_4}. \tag{39}$$

Substituting Eq.(33) into Eq.(39) we get,

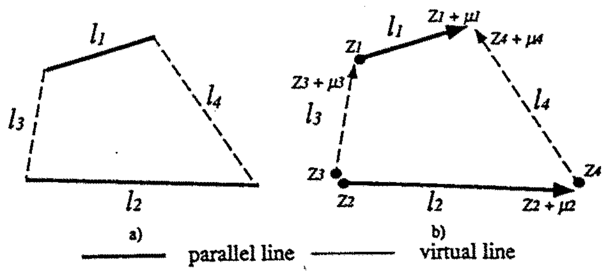

Fig.5 Definition of the virtual lines.

$$K_4 = \frac{Z_1' + \mu_1'}{Z_1 + \mu_1} = K_1. \tag{40}$$

Then, the parameter K for the virtual line segment can be acquired by using K for the real line segments. It is self-evident that we can solve them even for replacing the end-point and the base-point of the line segment. Finally we can get components of a vector which represents a direction of a virtual line segment, in this case l_3 or l_4, according to the next step (STEP.4).

STEP.4 Eq.(24) and Eq.(25) hold for the virtual line segments as well as for the real line segments. These are written as follows,

$$\begin{aligned} \left|K_3 N_3'\right|^2 &= |N_3|^2, & (41)\\ K_1 K_3 N_1'^{\mathrm{T}} N_3' &= N_1^{\mathrm{T}} N_3. & (42) \end{aligned}$$

where N_1 and K_1 are given from Eq.(10), Eq.(11) and Eq.(1) etc. As the equation: $K_3 = \alpha K_1$, derived from Eq.(38), Eq.(41) and Eq.(42) have unknown parameters N_3 and N_3'. The unknowns N_3 and N_3' can be expressed by t_3 and t_3' using Eq.(10) and Eq.(11), so Eq.(24) is regarded as a second order equation with respect to t and t', and Eq.(25) as a first order equation. Then we get two solutions for the above simultaneous equations. Furthermore we can select the unique solution using coefficients of variation, if the image data contains less error or noises.

On the other hand if we introduce the assumption that there exist two pairs of parallel line segments, we can independently solve each t and t' from the parallelism and Eq.(29), (30). Therefore the solutions are robust against added error or noise. The results of this will be also discussed in the next section.

4 Experiments and Results

4.1 Estimation of Motion Parameters

The estimation of the motion parameters are performed for one or two pairs of parallel line segments on the same plane (See Table 1). The set of terminal points of four line segments as the input data is one of the examples which Huang's method could not solve [5]. The experiment is performed as follows.

At first, the terminal points of the line segments are given as (X_{ij}, Y_{ij}, Z_{ij}), $i = 1,\cdots,4, j = 1,2$. Next, the rotational and translational components are given, and then we get the coordinates of the terminal points after the motion as $(X_{ij}', Y_{ij}', Z_{ij}')$, $i = 1,\cdots,4, j = 1,2$. All the points are projected onto the image plane by using Eq.(5) and are added random noises according to their values. Then values $r_i = x_{i0} - x_{i1}$ and $s_i = y_{i0} - y_{i1}$ are computed. The reason why we added the random noise is that we must take into account the error of quantization and miss-correspondence of the line segments between images.

In error free case, the estimated motion parameters are listed in the second column of Table 1, and coincide with the true values. This implies that this method is capable even when there exist more than six points on the same plane, on the other hand it is not by Huang's method [5]. In addition, our method can get the solution with the same accuracy, even if the translational components along X or Y axis get zero or if the rotational component is too small.

The next results are for a pair of line segments with 0.1% random noise (See line segment 1,2 of Table 1 below). In this case we have two solutions from Eq.(24). However we can select one plausible solution according to the coefficient of variation. In the Table1 the coefficient of the first solution (shown in third column) is much smaller than that of the second one (shown in fourth column). Hence we can select the first one as plausible solution. This means that the coefficients can be used to select a plausible solution, even when the added random noise gets large.

Table 1 Experimental results

$\Delta X=5.0$, $\Delta Y=6.0$, $\Delta Z=1.0$

	True	Estimation: Two (Noise Free)	Estimation: One Pair (0.1 Noise: Solution	Estimation: One Pair (0.1 Noise: Solution
σ_1	0.5	0.5	0.5010	-0.03401
σ_2	0.4	0.4	0.3984	-0.5631
σ_3	0.7681	0.7681	0.7683	-0.8257
θ	0.3	0.3	0.2976	0.3408
$\Delta X/\Delta Z$ (mean)	5.0	5.0	4.865	2.309
$\Delta Y/\Delta Z$ (mean)	6.0	6.0	5.824	3.181
$\Delta X/\Delta Z$ (CV)		0	0.02438	1.295
$\Delta Y/\Delta Z$ (CV)		0	0.02391	1.325

CV: Coorfficient of Variance

		Coordinates of Terminal			(True (before Motion)		
		X	Y	Z	X	Y	Z
Line	1	5	7	10	8	13	19
Line	2	-3	12	10	1	20	22
Line	3	45	-18	10	54	-3	13
Line	4	21	-3	10	36	-8	15

Table 2 Experimental results (with random noise).

$\Delta X=3.0$, $\Delta Y=2.0$, $\Delta Z=1.0$

Noise(%	Tru	0.0	0.1	0.5	1.0	2.0
σ_1	0.6	0.6	0.5957	0.5862	0.5528	0.5973
σ_2	0.7	0.7	0.7016	0.7119	0.7276	0.6715
σ_3	0.3873	0.3873	0.3910	0.3867	0.4062	0.4386
θ	0.5	0.5	0.5006	0.5045	0.5117	0.4838
$\Delta X/\Delta Z$ (mean)	3.0	3.0	3.0536	2.728	2.203	6.738
$\Delta Y/\Delta Z$ (mean)	2.0	2.0	2.0338	1.966	1.048	2.358
$\Delta X/\Delta Z$ (CV)		0.0	0.04429	0.4581	0.2755	1.938
$\Delta Y/\Delta Z$ (CV)		0.0	0.06310	0.4602	0.5925	2.170

CV: Coorfficient of Variance

		Coordinates of Terminal			(True (before Motion)		
		X	Y	Z	X	Y	Z
Line	1	-82.212	28.290	52.020	-49.875	6.3568	30.670
Line	2	30.872	8.4991	2.0142	-14.972	39.594	32.282
Line	3	24.658	-32.590	35.892	21.048	1.3519	19.601
Line	4	-48.502	-40.860	13.556	-46.089	-63.540	24.441

4.2 Relation between Added Noise and Error

In order to examine the effects of the quantization error to the solution, we have experiments for the terminal points of line segments with 0.1%, 0.5%, 1% and 2% errors. The results for two pairs of parallel line segments are shown in Table 2. From the results our method is sufficiently robust for about 0.1% noise addition. Especially the rotational components are much accurate, even when random noise is added.

5 Conclusion

In this paper we proposed a new linear algorithm to estimate 3D motion parameters of a rigid object from two sequential images by using parallelism of a pair of line segments. We formulate the motion in 3D space by means of the relative coordinate systems paying attention to the line segments on the surface of the object. Then the motion can be described only by the rotational components, and hence we get the nine nonlinear equations. We derived that if there exist a pair of parallel line segments, the nonlinear equations can be resolved into the linear ones. We also give a method to extract pairs of parallel line segments. The present method seems especially effective for a parallelpiped object, because there must exist parallel line segments on the surface of the object. When the motion trajectory is smooth, it is not difficult to catch up with the parallel line segments. In addition, as the method achieves the linear solutions, the algorithm is very simple and runs very fast.

Acknowledgment

The work presented in this paper is partly supported by Kumahira Security Foundation.

References

[1] D.Marr, "A Computational Investigation into the Human Representation and Processing of Visual Information," W.H.Freeman, New York (1982).

[2] T.Kitahashi et al, "On Image Understanding," J.of Artificial Intelligence, Vol.4, No.1, pp.2-51 (1989).

[3] J.K.Aggarwal and N.Nandhakumar, "On the Computation of Motion from Sequence of Images -A Review," Proc. of IEEE, Vol.76, No.8, pp.917-935 (1988).

[4] S.Ullman, "The Interpretation of Visual Motion," MIT Press, Boston (1979).

[5] R.Y.Tsai and T.S.Huang, "Uniqueness and Estimation of Three-Dimensional Motion Parameters of Rigid Object with Curved Surface," IEEE Trans. of PAMI, Vol.PAMI-6, No.1, pp.13-27 (1984).

[6] M.Terauchi et al, "A Linear Algorithm for Motion Estimation using Features of Optical Flows and Line Segments," Proc of ICARCV'90, pp.856-860 (1990).

[7] T.Joko et al, "A Linear Algorithm for Motion of Rigid Objects Using Features of Parallel Lines and Optical Flow," Trans. of IEICE, Vol.J73-D-II, No.9, pp.1485-1492 (1990).

[8] M.Terauchi et al, "Motion Estimation of a Block-shaped Rigid Object for Robot Vision," Proc.of IEEE/RSJ International Workshop on Intelligent Robots and Systems, pp.842-847 (1991).