DETERMINATION OF ROBOT LOCATION USING GENERALIZED CYLINDRICAL OBJECT SHAPES

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ABSTRACT

In this paper, a new approach to the determination of robot location using the generalized cylindrical object is proposed. From a monocular image of the object, image processing and numerical analysis techniques are applied to extract the projection characteristics of the generalized cylindrical portion of the object, from which the position and the rotation parameters of a camera-mounted robot can be determined. Owing to the full linearity of the derivation, this approach can achieve high speed requirement. In addition, no prerequisite restriction is imposed on the image-grabbing process. Experimental results show that the location determination time is about 1.2 sec in a 33 MHz IBM compatible PC/AT computer system and the location error is less than 5% on average.

1 Introduction

For a robot to navigate automatically in various environments, it is important to determine its position with respect to some known objects in order to catch the objects or avoid collision. Several remarkable approaches have been proposed to solve the problem alternatively by use of the "standard mark"[1-3] to simplify the problem and to reduce computation time. The major concept is to use special marks that include a wealth of geometric information under perspective projection such that robot location parameters can be easily computed from monocular images of the mark. In general, the methods using special marks can be categorized into two classes according to the condition that whether the camera optical axis goes through the center of the mark. When the camera optical axis is constrained to go through the center of the mark, the camera location can be simply represented by position parameters since the orientation is implicitly determined by the condition. In the other class, both the position and the orientation parameters are necessary.

Curved objects are also encountered frequently in various environments. Haralick and Chu [6] solved camera parameters using the image of a parameterized curve such a conic or a polygon. The solution procedure involves an iterating search to optimize the orientation parameters. The translation parameters are solved by an algebraic method based on the solutions of the orientation angles. Chen and Tsai [7] proposed a method for determining robot location by using surface patches of curve objects under the constraint that the focal length and the shape of the curved object are known in advance, and the equations of the curve can be described by a polynomial in two variables. However, since the focal length f (the actual distance between the camera lens center and the image plane) varies with the distance of the object to the camera, it is apparently unpractical to assume f to be known as a fixed value. Additionally, their method consumes much execution time by using iteration procedures.

In this paper, a new approach to robot location determination by using the generalized cylindrical object is proposed. Assumptions under the proposed approach include 1) the desired object has a cylindrical portion, 2) the height of the cylindrical portion of the object is known. Many objects found in indoor and outdoor environments satisfy the above constraints, such as cubes, cylinders, cans, furniture, machine parts, buildings, and so on. An example is shown in Fig. 1. Each generalized cylindrical object used in this approach is composed of four space features; two planar curves (the curves C_1 and C_2 in Fig. 1, for example), and two normal lines perpendicular to the top and bottom planes containing the curves C_1 and C_2 (L_a and L_b in Fig. 1, for example).

In this approach, a monocular image of a generalized cylindrical object with known height is taken whenever the robot is to be located. The corresponding image features are then extracted and the side lines of the cylindrical shape are fitted in the least square error sensed by a line equation. Next, two point-pairs are found from the upper and lower curves of the cylindrical shape by using the point-pair estimation strategy and robot location parameters can then be determined uniquely by 3-D vector analysis and simple algebraic computation. In the next section, the determination formulas of the robot location of the proposed approach are described. Image processing techniques required to obtain the desired features are presented in section 3. Experimental results and discussions are included in section 4, followed by conclusions in section 5.

2 Location Determination Method

Fig. 2 illustrates the imaging geometry of the system to be dealt with in this paper. In the figure, O-XYZ is the object coordinate system with the origin at the center of the curve formed by the lower edge of the generalized cylindrical object. The Z-axis coincides with the object axis and the X-Y plane is chosen to be located on the bottom surface of the object (see Fig. 2). O'-X'Y'Z' is the camera coordinate system with the origin at the camera lens center and the Y'-axis coinciding with the optical axis. Let the X'-axis and Z'-axis be parallel to the u-axis and v-axis, respectively. So, an image point located at (u, v) has the coordinates (u, f, v) in the camera coordinate system, where f is the focal length of the camera. Without loss the generality, for any point P_n in the 3-D space with the object coordinates (x, y, z), the camera coordinates (x',y',z') and the image coordinate (u,v) of its corresponding point P_n' in the image plane, the following equations have to be satisfied.

$$(x,y,z)^t = R\cdot(x',y',z')^t + (0,Y_c,Z_c)^t, \quad (1)$$

$$(x',y',z') = \lambda\,(u,f,v);$$

and

$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}, \text{(i. e., the rotation matrix).}$$

where λ is a ratio factor, $(0,Y_c,Z_c)$ is the coordinates of the camera lens center (robot location) in the object coordinate system.

To obtain an unique solution to the 3D location problem, it is well known that at least four points are needed. Therefore, in our approach, two point-pairs are extracted from the image of the cylindrical object by point-pair estimation strategy [8]. The so-called point-pairs is formed by two points, one at the upper curve and the other at the lower curve of the generalized cylindrical object, with their line segment parallel to the object axis. Let $[P_1,P_2]$ and $[P_3,P_4]$ denote two point-pairs. Since both the upper and the lower curves of the generalized cylindrical object are perpendicular to the object axis, the four line segments formed by the two point-pairs (i.e., $\overline{P_1P_2}$, $\overline{P_3P_4}$, $\overline{P_1P_3}$, and $\overline{P_2P_4}$) constitute a rectangle with P_1, P_2, P_3 and P_4 as its four vertices, and the length of $\overline{P_1P_2}$ (or $\overline{P_3P_4}$) is equal to the vertical height of the generalized cylindrical object (i.e., h).

Assume that the image coordinates of P_i' are (u_i,v_i), i=1..4, respectively. Thus P_i, i=1..4, have the camera coordinates $\lambda_i(u_i,f,v_i)$, i=1..4, respectively. Again, assume that P_i, i=1..4, have the object coordinates (x_1,y_1,h), (x_1,y_1,o), (x_2,y_2,h) and (x_2,y_2,o), respectively, where x_1, y_1, x_2 and y_2 are constants depending on the positions of P_1 and P_3. Since $\overrightarrow{P_1P_2} = \overrightarrow{P_3P_4}$, we have

$$\lambda_2(u_2,f,v_2)-\lambda_1(u_1,f,v_1) = \lambda_4(u_4,f,v_4)-\lambda_3(u_3,f,v_3). \quad (2)$$

From Eq. (2), we get

$$-u_1\lambda_1+u_2\lambda_2+u_3\lambda_3=u_4\lambda_4, \quad (3a)$$

$$-\lambda_1+\lambda_2+\lambda_3=\lambda_4, \quad (3b)$$

$$-v_1\lambda_1+v_2\lambda_2+v_3\lambda_3=v_4\lambda_4. \quad (3c)$$

From Eqs. (3a)-(3c), we can derive the relation between λ_1, λ_2, λ_3, and λ_4 as

$$\lambda_i=K_i\lambda_4, \quad i=1..3 \quad (4)$$

where K_i, i=1..3, are constants. From Eq. (4), λ_1, λ_2 and λ_3 can be solved once λ_4 is solved.

Before solving λ_4, we have to solve the focal length f. Since $\overrightarrow{P_1P_3}\cdot\overrightarrow{P_1P_2} = 0$, we have

$$[\lambda_3(u_3,f,v_3)-\lambda_1(u_1,f,v_1)]\cdot[\lambda_2(u_2,f,v_2)-\lambda_1(u_1,f,v_1)] = 0 \quad (5)$$

Substituting Eq. (4) into Eq.(5), we can derive

$$f = \left[-\frac{(K_3u_3-K_1u_1)(K_2u_2-K_1u_1)+(K_3v_3-K_1v_1)(K_2v_2-K_1v_1)}{(K_3-K_1)(K_2-K_1)}\right]^{1/2}$$

From the above equation, we learn that the focal length can be calculated with the image coordinate of two point-pairs chosen by point-pair estimation strategy, whenever a new image is grabbed.

Since $\overline{P_3P_4} = h$, we have

$$\| \lambda_3(u_3,f,v_3) - \lambda_4(u_4,f,v_4)\| = h, \qquad (6)$$

where $\| \cdot \|$ denotes the Euclidean norm of a vector. Substituting Eq. (4) into Eq. (6), we get

$$\lambda_4 = \frac{h}{[(K_3u_3 - u_4)^2 + (K_3f - f)^2 + (K_3v_3 - v_4)^2]^{1/2}}$$

After deriving λ_4, the other three ratio factors λ_1, λ_2 and λ_3 can be solved from Eq. (4).

Let L_i, i=1..4 denote the distances between the camera lens center O' and P_i , i= 1..4, respectively. That is

$$L_i = \overline{O'P_i} = \|\lambda_i(u_i,f,v_i)\| \qquad (7)$$

Therefore, L_1, L_2 , L_3 and L_4 can be calculated from the above equations. The object coordinates of O' are $(0,Y_c,Z_c)$, and L_1 and L_2 are also given by

$$L_1 = \|(0,Y_c,Z_c) - (x_1,y_1,h)\| \qquad (8a)$$
$$L_2 = \|(0,Y_c,Z_c) - (x_1,y_1,0)\| \qquad (8b)$$

Squaring Eqs.(8a) and (8b), and subtracting one from the other, we can get

$$Z_c = \frac{L_2^2 - L_1^2 + h^2}{2h}$$

Substituting the camera coordinates and the object coordinates of P_1, P_2, P_3 and P_4 into Eq.(1), we have

$$\begin{bmatrix} R_{31} \\ R_{32} \\ R_{33} \end{bmatrix} = \begin{bmatrix} \lambda_1 u_1 & \lambda_1 f & \lambda_1 v_1 \\ \lambda_2 u_2 & \lambda_2 f & \lambda_2 v_2 \\ \lambda_3 u_3 & \lambda_3 f & \lambda_3 v_3 \end{bmatrix}^{-1} \cdot \begin{bmatrix} h - Z_c \\ -Z_c \\ h - Z_c \end{bmatrix}$$

To derive the coordinate (X_o', Y_o', Z_o') of the origin O in O'-X'Y'Z' coordinate system, an arbitrary point (except P_2' and P_4') on the lower curve, say, P_5' with the image coordinates (u_5,v_5), is required as shown in Fig. 3. The camera coordinates and object coordinates of P_5 are $\lambda_5(u_5,f,v_5)$ and $(x_5,y_5,0)$, respectively, where λ_5 is the ratio factor defined by $\overline{O'P_5} = \overline{O'P_5'}$, and x_5 and y_5 depend on the location of P_5'. Here, λ_5 is an unknown to be solved. According to Eq. (1), we have

$$\lambda_5u_5R_{31} + \lambda_5fR_{32} + \lambda_5v_5R_{33} + Z_c = 0$$

and

$$\lambda_5 = -\frac{Z_c}{u_5R_{31} + fR_{32} + v_5R_{33}}$$

Since $\overrightarrow{P_2O} \times \overrightarrow{P_2P_4} // \overrightarrow{P_2P_1}$, where × represent the outer product of two vectors, we have

$$\begin{vmatrix} i & j & k \\ X_0 - \lambda_2u_2 & Y_0 - \lambda_2 f & Z_0 - \lambda_2 v_2 \\ \lambda_4u_4 - \lambda_2u_2 & \lambda_4 f - \lambda_2 f & \lambda_4v_4 - \lambda_2v_2 \end{vmatrix}$$

$$= \zeta(\lambda_1u_1 - \lambda_2u_2, \lambda_1f - \lambda_2f, \lambda_1v_1 - \lambda_2v_2) \qquad (9)$$

where ζ is a scaling constant. Besides, the determinant of the matrix formed by the three coplanar vectors $\overrightarrow{P_5O}$, $\overrightarrow{P_5P_2}$ and $\overrightarrow{P_5P_4}$ is equal to zero, we have

$$\begin{vmatrix} X_0' - \lambda_5 u_5 & Y_0' - \lambda_5 f & Z_0' - \lambda_5 v_5 \\ \lambda_2 u_2 - \lambda_5 u_5 & \lambda_2 f - \lambda_5 f & \lambda_2 v_2 - \lambda_5 v_5 \\ \lambda_4 u_4 - \lambda_5 u_5 & \lambda_4 f - \lambda_5 f & \lambda_4 v_4 - \lambda_5 v_5 \end{vmatrix} = 0 \qquad (10)$$

From Eqs. (9) and (10), we can obtain (X_o', Y_o', Z_o'). Next, Y_c can be derived as below

$$Y_c^2 = \|OO'\|^2 - Z_c^2$$

where

$$\|OO'\|^2 = X_o'^2 + Y_o'^2 + Z_o'^2$$

From the above derivation, we have obtained the robot location $(0, Y_c, Z_c)$ relative to the generalized cylindrical object.

3 Image Processing Techniques

The required features for robot location determination are the equations of lines L_a and L_b and the points on the upper and the lower curves, as shown in Fig. 1. Five cylindrical objects have been made for testing, including a triangular cylinder, a rectangular cylinder, an elliptic cylinder, a circular cylinder and a hexangular cylinder. To extract the required features (i.e.,two point-pairs), the image processing techniques are described as follows.

Step 1. Perform the image preprocessing. Usually geometric distortion exists in the image taken, therefore, it is necessary to correct each image by applying the geometric correction method[9]. Sobel edge operator is used to detect edge points in the corrected image and the fast parallel thinning algorithm proposed by Zhang and Suen [10] is used to thin the edge points found by the Sobel operator.

Step 2. Locate L_a and L_b in the thinned image. The Hough transform [11] is applied for line detection.

Step 3. Use least-square-error line fitting [12] to improve the accuracy of L_a and L_b.

Step 4. Detect the upper and the lower curves (i,e., the projections of the upper and the lower edges of the generalized cylindrical portion) in the thinned image.

Step 5. Adopt a two-stage detection procedure [8] to find two exact point-pairs.

The above image procedures is performed under the assumption that there is only one cylindrical object in the image. If there are multiple cylindrical objects in the image and some one is partially occluded by another, the above procedures should be replaced by more complicated methods [8]. The details of the those method are omitted here.

Once the required features are extracted, the robot location relative to the object can be calculated from the formulas derived in Section 2.

4 Experimental Results

Image were processed by a Series 150/151 modular image processor connected to an IBM compatible PC/AT and programs were written in C language. In the experiments, each tested object was placed at several different locations and two pictures were taken for each object at each location. The real robot location $(0, Y_c, Z_c)$ was manually measured as the reference for checking location results. The two point-pairs were chosen for constructing the rectangle-shaped standard mark. Table 1 shows the experimental result of robot location for each object at each location. In the table, the unit is cm and the last column show the error percentage for each object compared with the real reference position and according to the results, all the average error percentages can be seen to be less than 5%, which shows that the approach is feasible for practical applications.

5 Conclusion

A feasible approach to the problem of determining the robot location relative to a generalized cylindrical object by a single image is proposed in this paper. The principle idea of the approach is to use a rectangle-shaped standard mark for performing monocular image analysis. The standard mark is constructed by two point-pairs found by the two-stages point-pair estimation. The derivation involved in the proposed approach consists of mere 3-D vector analysis and simple algebraic computation. Owing to the linear derivation, this approach can achieve high speed requirement. Moreover, since the camera focal length can be derived, there is no need to perform the calibration of the camera focal length. This is especially useful in the sensor systems where autofocusing cameras are used. In addition, no prerequisite is imposed on the image-grabbing process. Experimental results show that the location determination time is about 1.2 sec in a 33 MHz IBM compatible PC/AT computer system and the location error is less than 5% on average.

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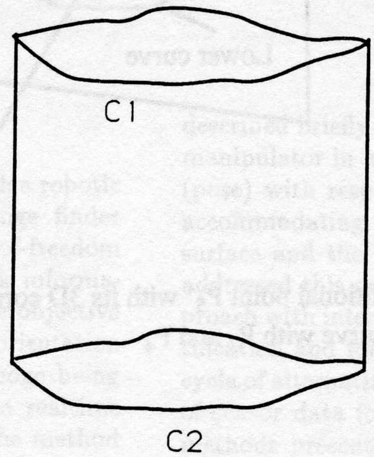

Fig. 1: A generalized cylindrical object with the height known as h

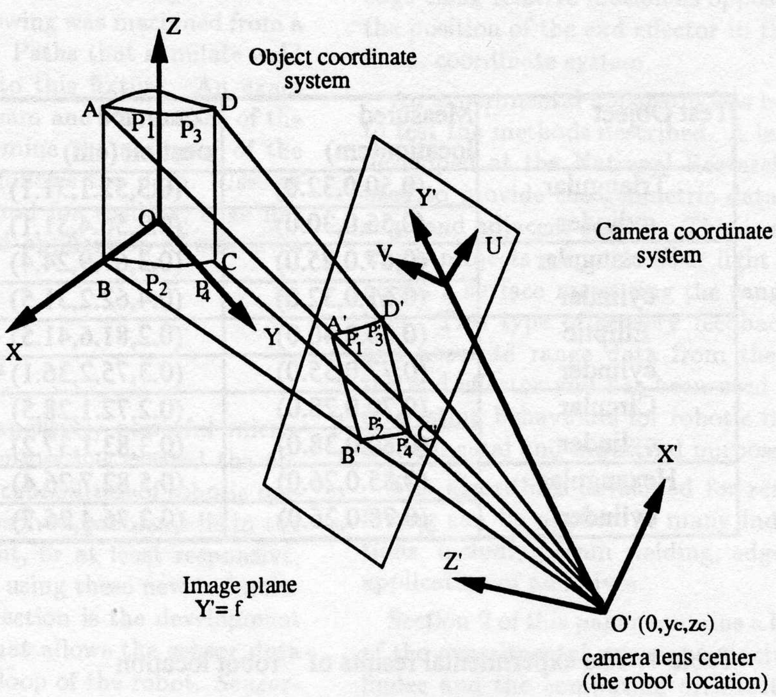

Fig. 2: The camera viewing model of a generalized cylindrical object

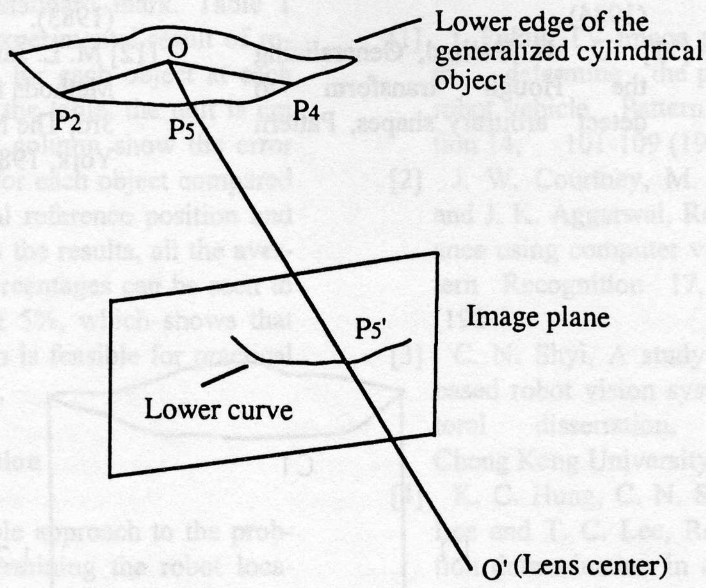

Fig. 3: An additional point P_5' with its 3D corresponding point P_5 located on the same curve with P_2 and P_4

Test Object	Measured location(cm)	Computed location (cm)	Error percentage (%)
Triangular	(0,50.0,32.0)	(0.3,52.1,31.1)	(3.0,4.2,2.8)
cylinder	(0,55.0,30.0)	(0.2,56.4,31.1)	(2.0,2.5,3.6)
Rectangular	(0,67.0,25.0)	(0.3,67.9,24.4)	(3.0,1.3,2.4)
cylinder	(0,61.0,32.0)	(0.4,62.2,31.5)	(4.0,1.9,1.5)
Elliptic	(0,80.0,40.0)	(0.2,81.6,41.5)	(2.0,2.0,3.7)
cylinder	(0,77.0,35.0)	(0.3,75.2,36.1)	(3.0,2.3,3.1)
Circular	(0,70.0,28.0)	(0.2,72.1,28.5)	(2.0,3.0,1.8)
cylinder	(0,80.0,38.0)	(0.3,83.1,37.2)	(3.0,3.8,2.1)
Hexangular	(0,85.0,26.0)	(0.5,82.7,26.4)	(5.0,2.7,1.5)
cylinder	(0,78.0,26.0)	(0.3,76.4,26.7)	(3.0,2.0,2.6)

Table 1: The experimental results of robot location