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Control of a Mobile Robot Supporting a Task Robot on the Top

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Abstracts

This paper addresses the control problem of a mobile robot supporting a task robot with needs to be positioned precisely. The main difficulty residing in the precise control of a mobile robot supporting a task robot is providing an accurate and stable base for the task robot. That is, the end-plate of the mobile robot which is the base of the task robot can not be positioned accurately without external position sensors. This difficulty is resolved in this paper through the vision information obtained from the camera attached at the end of a task robot. First of all, the camera parameters were measured by using the images of a fixed object captured by the camera. The measured parameters include the rotation, the position, the scale factor, and the focal length of the camera. These parameters could be measured by using the features of each vertex point for a hexagonal object and by using the pin-hole model of a camera. Using the measured pose (position and orientation) of the camera and the given kinematics of the task robot, we calculate a pose of the end-plate of the moblie robot, which is used for the precise control of the mobile robot. Experimental results for the pose estimations are shown.

Keywords Mobile, Task, Vision, Camera, Parameters.

1. Introduction

Recently, in the factory automation, not only productivity but also flexibility are required to produce small quantity of several items in the same production line to overcome the versatile tastes of customers. A mobile robot carrying a task robot is a good alternative to conveyor lines for this purpose. So far, we are interested in using the mobile robot for a simple carrier of an object. Many of papers on mobile robots focused on how to avoid collisions of the mobile robots. Now, we need to control the mobile robot very accurately, since the end-plate of the mobile robot will be used as a base for the task robot which should be controlled precisely[1]. There are two major difficulties in the control of the mobile robot. One difficulty lies in the dynamic modeling of the mobile as other complex structures. The other difficulty lies in the uncertainties of the boundary in between the wheels of the mobile robot and the ground. The frictions in between the wheels and the ground are nonlinear and time-varying, which we can not either estimate or model at all. In addition to this, there exits slippage in between the wheels and the ground, which causes high positioning error to the mobile robot. This error caused by the motion of the mobile robot will make inaccurate positioning of the base of the task robot which needs high positioning accuracy to perform given tasks. Recently, there are several researches on the accurate control of the mobile robot with the recognition of the environment using the laser, ultrasonic, and vision sensors to perform various tasks intelligently[8-10].

In this paper, we proposed a method of measuring the position/orientation of the base of the task robot (it is actually the end-plate of the mobile robot.) using the images caught by the camera attached at the end of the task robot for an object located at a known position so that the task robot can perform various tasks efficiently and precisely. Generally, there are two methods measuring the pose of the camera: pin-hole model[2-5] and two plane model[6,7]. The pin-hole model is simple to implement since it does not require any information on camera parameters. However, it is difficult to apply for the coordinates transformation from the camera coordinates to robot coordinates. In this paper, we adopt Yuncai Lui's method[3] which is efficient for the calculation and which requires minimum number of corresponding points to estimate camera pose. Camera model is derived from the pin-hole model, which makes the camera system as a linear system such that camera parameters can be analyzed easily. Using the feature points whose locations are given *a priori*, we calculate the pose of the camera. After the pose of the camera is obtained, we can obtain the homogeneous transformation of the base of the task robot relating to the reference frame using the known kinematics of the task robot. The homogeneous transformation between the robot and the camera is obtained through the forward kinematics of the task robot, which is generally accurate within the accuracy of the task robot itself. Note that the small task robot has very light and precise structure to perform given tasks fast and accurately.

This paper is composed of 5 sections including this section: In section 2, the structure of the robot and vision system and the homogeneous transformation will be explained. In section 3, the camera model to measure the pose of the camera with the camera parameters will be described, and the method of estimating the position/orientation of the camera and the camera parameters will be explained. In section 4, the experimental results of obtaining the position/orientation of the camera and the camera parameters are shown. Finally, conclusion of the paper will be given in section 5.

2. Robot/Vision System

2.1 The structure of the Overall system

The structure of the mobile robot which carries a task robot on the top of it's body[1], is described in this subsection. The task robot has 5 links and a gripper, and the mobile robot has 3 d.o.f to carry an object to any point in the three dimensional space. Fig.1 shows the coordinates assignment for this overall system. The reference frame, {R}, is assigned to at a known point and the base frame, {B}, is assigned to at the top of the mobile robot, i.e., at the base of the task robot. And the positioning vector from the reference point to the base of the task robot is denoted as rP_0 in terms of the reference frame.

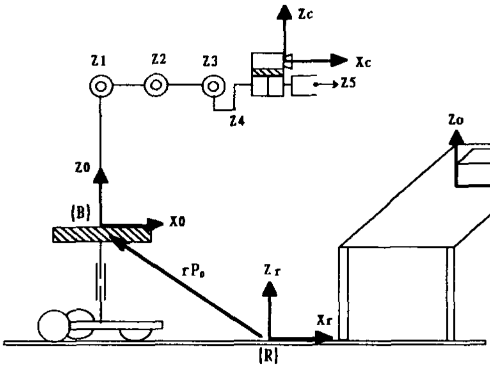

Fig. 1. Link Coordinates of Mobile Robot Supporting a Task Robot

When the joint values of the task robot are given the gripper pose, $X = [P_x, P_y, P_z, \alpha, \beta, \gamma]$, can be obtained in terms of the base frame, {B}, through the forward kinematics of the task robot, and it can be represented as a homogeneous transformation matrix as follows:

$$X = \begin{bmatrix} r_{11} & r_{12} & r_{13} & Px \\ r_{21} & r_{22} & r_{23} & Py \\ r_{31} & r_{32} & r_{33} & Pz \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

where the rotation matrix has three unknown of α, β and γ, and those variables can be defined as[13]

$$\alpha = A\tan 2(r_{23}, r_{13}), \qquad \beta = A\tan 2\left(\sqrt{r_{31}^2 + r_{32}^2}, r_{33}\right),$$

$$\gamma = A\tan 2(r_{32}, -r_{31}).$$

2.2 Homogeneous Transformation

Fig.2 shows the coordinates transformation relationship among the frames of the mobile robot supporting a task robot.

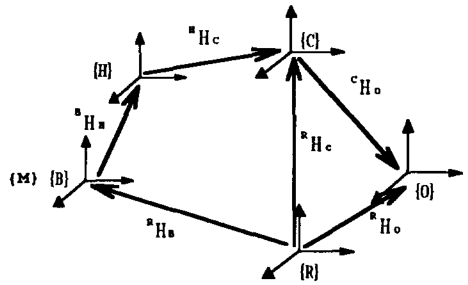

Fig. 2. Coordinates Transformation of Robot/Vision System

In Fig.3 {R} is the reference frame for the whole system, {O} is a coordinates system for the fixed object located at a known position, {C} is the camera frame, {H} is the hand frame where the camera is attached, {B} is the base frame of the task robot, and {M} is a frame assigned at the center of the top plate of the mobile robot. As we see in the figure, the frame {B} and {M} are assigned at the same point. Note that we assumed that the camera is attached at the end of the task robot.

In this paper, we are going to measure the relative position/orientation of the mobile robot with respect to the reference frame through the visual information processing of the known object. The task can be decomposed into two steps. The first step is measuring the relative pose of the camera(${}^RH_C$) using the images of the fixed object. The second step is obtaining the homogeneous transformation of the mobile robot in terms of the reference frame, ${}^RH_B$, using the measured homogeneous transformation for the camera pose, ${}^RH_C$, the homogeneous transformation, ${}^BH_H$ which can be obtained through the forward kinematics of the task robot, and ${}^HH_C$ which represents the position/orientation of the camera frame in terms of the hand frame. This process can be represented by the following equations.

$${}^RH_B = {}^RH_C \cdot {}^BH_C^{-1} \qquad (2)$$

$${}^RH_C = {}^BH_H \cdot {}^HH_C. \qquad (3)$$

The structure of the task robot is assumed to be light and small. Therefore, the homogenous transformation matrix, ${}^BH_C$, can be obtained accurately through the forward kinematics. In the following section, the process of obtaining ${}^RH_C$ will be described in detail.

As it is shown in Fig. 2, if ${}^RH_C$ is obtained from the images of the fixed object, the relative camera pose w.r.t the fixed object can be determined. This can be represented as following equation:

$$^{C}H_{O} = {^{R}H_{C}^{-1}} \cdot {^{R}H_{O}}. \quad (4)$$

3. Estimation of the Camera Pose

The estimation of the camera pose(position and orientation) can be done with the estimation of camera parameters, i.e., the focal length and the scale factor using the correspondence in between the coordinates of feature points of a fixed object in terms of the reference frame and the image coordinates of the feature point in terms of the computer memory frame.

3.1 Perspective Model of a Camera

A perspective model of a camera represents the relationship in between the two dimensional object location on the image plane and the actual object location in the three dimensional space[12].

Fig. 3 represents geometrical perspective model of a camera. Here, the coordinates $(O_r\, X_r\, Y_r\, Z_r)$ is a reference frame in the 3-D space, the coordinates $(O_c\, X_c\, Y_c\, Z_c)$ is a camera frame whose origin is assigned at the center of the lens of the camera and the Z_c axis is coincident with the optical axis of the camera.

A point in the space can be represented as a vector, $P_r=(x_r, y_r, x_r)$ in terms of the reference frame, and it can be also represented as $P_c=(x_c, y_c, x_c)$ in terms of the camera frame. The coordinates $(O_i\ X_i\ Y_i)$ represents the image frame of the camera, which is assigned in front of the camera. The X_i - Y_i plane is parallel to the X_c - Y_c plane and is orthogonal to the optical axis, Z_c. The effective focal length of the camera, f, represents the distance between the image plane and the origin of the camera frame.

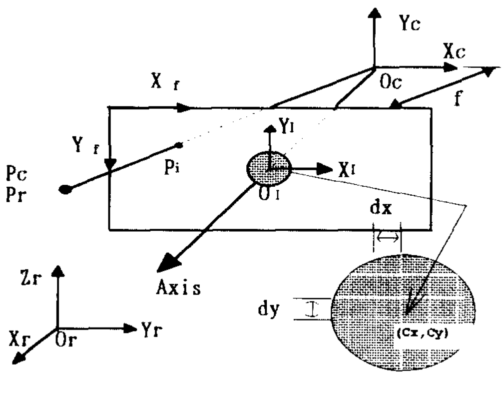

Fig. 3. Perspective Model of Camera

A point, $P_i= (X_i\ ,\ Y_i)$, on the image plane representing to a feature point of the fixed object, P_r, corresponds to the vector, P_c, w.r.t the camera frame. The coordinates (X_f, Y_f) represents the coordinates in the computer memory frame, which can be obtained through the image processing of the image of the fixed object. The parameters, *dx* and *dy*, represent the distance between pixels along the x axis and y axis respectively, and their value can be obtained by using the number of pixels and area of image of the camera. These parameters will be used in transforming the image coordinates to the frame memory coordinates.

The coordinate, $(C_x\ ,C_y)$ represents the center position of the image in the computer memory frame. R.Y Tsai[11] showed that the value of (C_x ,C_y) can be changed within 10 pixels without affecting the measurement accuracy of the three dimensional object. In this paper, we assumed that the center of the image frame is located at the center of the computer memory frame such that matching the two centers are not incorporated in the process of estimating camera parameters. Using the camera perspective modeling, basic equations and parameters to be estimated for the measurement of the camera pose can be obtained with the additional transformation from the reference frame to the computer memory frame.

3.2 Camera Parameters

As it is described in the previous section, by the coordinates transformation between the robot and camera frames, the positioning vector, P_c, represented in terms of the camera frame can be represented as P_r in terms of the reference frame.

$$P_r = RP_c + T \quad (5)$$

where R and T represents a rotation matrix and a translation vector from the reference frame to the camera frame, respectively, and they are defined as follows:

$$R = \begin{bmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{bmatrix}, \quad T = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix}. \quad (6)$$

A positioning vector for a feature point on the three dimensional object in terms of the camera frame, $P_c=(x_c, y_c, z_c)$ is mapped to a point $P_i = (X_i\ , Y_i)$ on the two dimensional image frame using the camera perspective model[2], and it can be described as follows:

$$X_i = f\frac{x_c}{z_c} \quad (7)$$

$$Y_i = f\frac{y_c}{z_c} \quad (8)$$

Where, f represents the effective focal distance. The image coordinates are obtained by the linear pin-hole model, and the distortion effects of the lense are not considered in this formula.

Since the scale values along x axis and y axis have different values in the image frame, a point on the image frame, (X_i, Y_i) corresponds to a location in the computer frame memory, (X_f, Y_f) according to the following relations:

$$X_i = S_x^{-1}\,\overline{X}_i \qquad (9)$$
$$Y_i = S_y^{-1}\,\overline{X}_i \qquad (10)$$

where $\overline{X}_i \triangleq d_x\left(X_f - C_x\right)$, $\overline{Y}_i \triangleq d_y\left(Y_f - C_y\right)$, and S_x and S_y represents the camera scale factor along the x axis and y axis, respectively.

Plugging in the location value (X_f, Y_f) which is obtained through the computer image processing into the equations (9) and (10), we can represent the position of the feature point on the image frame. Generally, the number of y directional scanning lines and the number of rows of computer memory are the same such that the y axis scale factor, S_y=1. Therefore, we are going to use S instead of S_x from now on.

3.3 Parameter Estimation

The camera parameters to be estimated can be classified into two categories: internal parameters and external parameters. The specification related parameters of the camera and lens, for example, the focal distance, f, and image scale factor S, are internal parameters; the rotation matrix, R, and the translational vector, T representing the pose of the moving camera are external parameters. Among these parameters, we first obtain the internal parameters and the rotation matrix using the correspondence of the straight lines, and then we will obtain the translational vector using the correspondence of the feature points[3].

Let us denote a straight line, J which is the locus of the a vector P representing a point $V=(x,y,z)$ which is initiated from P_0 representing a point $U=(x_0,y_0,z_0)$ and moving along the directional vector $n_r = [i\ j\ k]^T$. The line is represented as follows (refer to Fig. 4):

$$J : P = n_r t + P_0 \qquad (11)$$

where n_r represents the directional vector of the straight line, t represents constant, and P_0 and P is a positioning vector for the point U and V in terms of the reference frame, respectively.

A two dimensional line L in the image frame corresponding to this three dimensional line also can be represented as follows:

$$L : AX_i + BY_i + C = 0 \qquad (12)$$

where A,B, and C are determined by the constraint, $A^2+B^2+C^2=1$, if we have two equations like eq. (12) corresponding to the two feature points. Substituting eq. (7) and eq. (8) into eq. (9), we obtain the following equation of a projecting plane which is represented in terms of the camera frame:

$$M{:}\,Ax_c + By_c + f^{-1}Cz_c = 0\,. \qquad (13)$$

The above equation represents a plane which includes both of the straight line J in the three dimensional space and the line L in the two dimensional image plane.

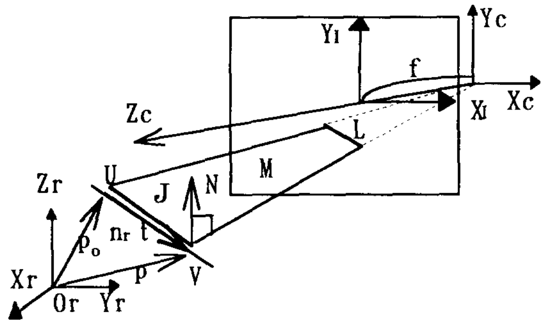

Fig. 4. Projecting plane of a 3-D line and a 2-D line.

The vector N is the normal of the projecting plane M, and it is represented as

$$N = \begin{bmatrix} A & B & f^{-1} & C \end{bmatrix}. \qquad (14)$$

Note that this normal vector N is always orthogonal to the three dimensional line J. The directional vector for the 3-D line J can be denoted as n_c and represented in terms of the camera frame as

$$n_c = R^T n_r\,. \qquad (15)$$

In eq. (15), R represents the rotational matrix from the reference frame to the camera frame, and it is defined as eq. (6). Since the 3-D line J is located on the projecting plane, M, and the directional vector of J is orthogonal to the normal vector of the projecting plane, we have

$$n_c \cdot N = 0\,. \qquad (16)$$

The eq. (16) represents the main idea for obtaining the camera parameters. Substituting eq. (15) into eq. (16), and using the fact that inner product of two orthogonal vectors can be represented as product of two vectors, we have

$$n_r^T RN = 0\,. \qquad (17)$$

Eq. (17) with the correspondence of two lines (a 3-D line J and a 2-D line on the image plane) is used to obtained the camera parameters from linear equations. Since a line is determined by two points, the directional vector, n_r, and normal vector, N, in eq. (17) can be obtained from the correspondence of two feature points. For this purpose, first we obtain the correspondence between the two point in 3-D space, U and V, and the two point in the image plane, $P_i(X_i, Y_i)$ and $P_j(X_j, Y_j)$, respectively. Plugging P_i and P_j

coordinates into eq. (12), and solving the two equations for the line coefficients, A, B and C, we have

$$A = (Y_j - Y_i) \quad (18\text{-a})$$
$$B = (X_j - X_i) \quad (18\text{-b})$$
$$C = (X_j Y_i - X_i Y_j). \quad (18\text{-c})$$

Now, the the normal vector, N, can be represented with the obtained line coefficients as follows:

$$N = \begin{bmatrix} A & B & f^{-1} & C \end{bmatrix}^T. \quad (19)$$

Since the directional vector, n_r, of the 3-D line is parallel to the line passing through the two points, P_i and P_j, it can be denoted as

$$N = (P_i - P_j) / \| P_i - P_j \|. \quad (20)$$

As it is shown in eq. (9) and (10), the point coordinates (X_i, Y_i) on the image plane include scale factor S in the variable. Defining $\underline{X_i} = S X_i$ to separate S from X_i, and substituting this equation into (18), we can represent the normal vector as

$$N = \begin{bmatrix} A & S^{-1}B & S^{-1}f^{-1}C \end{bmatrix}^T \quad (21)$$

where S represents the S_x defined in eq. (9).

Now, let us describe the process of obtaining camera parameters using eq. (17). To obtain the internal parameters (focal distance and scale factor)of the camera and the rotation matrix (R), we substitute eq. (20) and (21) into eq. (17).

$$\begin{bmatrix} i & j & k \end{bmatrix} \begin{bmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{bmatrix} \begin{bmatrix} A \\ S^{-1}B \\ S^{-1}f^{-1}C \end{bmatrix} = 0. \quad (22)$$

Note that the parameters A, B, and C are obtained by eq. (18) and the directional vector $n_r = [i\ j\ k]^T$ is obtained by eq. (20). The eq. (20) can be changed to eq. (21) by decomposing known variables and unknown variables as follows:

$$\begin{bmatrix} iA & iB & iC & jA & jC & kA & kB & kc \end{bmatrix} \begin{bmatrix} S \cdot r_1 \cdot r_5^{-1} \\ r_2 \cdot r_5^{-1} \\ f^{-1} \cdot r_3 \cdot r_5^{-1} \\ S \cdot r_4 \cdot r_5^{-1} \\ f^{-1} \cdot r_6 \cdot r_5^{-1} \\ S \cdot r_7 \cdot r_5^{-1} \\ r_8 \cdot r_5^{-1} \\ f^{-1} \cdot r_9 \cdot r_5^{-1} \end{bmatrix} = -jB. \quad (23)$$

The variables in the second vector of the eq.(23) are independent from the coordinates of the two points and only depend upon the camera specifications and the rotation matrix. And, there are 11 variables of $r_1 \sim r_9$, f and S. However, the rotation matrix has only three independent variables on account of internal constraints, for example, $r_1^2 + r_4^2 + r_7^2 = 1$. Therefore, if we obtain 8 equations of (23) corresponding to 8 lines keeping the same camera parameters, respectively, we can form a matrix equation by superposing the 8 equations on. The matrix equation is

$$M_{8 \times 8} X_{8 \times 1} = T_{8 \times 1} \quad (24)$$

where $X_{8 \times 1}$ is the same vector as the second vector in eq. (23). The unknown camera parameters can be obtained by multiplying the inverse of M at both sides of the eq. (24). When the correspondence of the five feature points are obtained, ten line equations of (23) can be obtained. By superposing all of the 10 equations on a matrix equation, we have an overdetermined system of the form of (24) which can be solved by least squares method[2]. In practice, there may be several dependent rows in the vector, $M_{10 \times 1}$. Therefore, instead of multiplying pseudo inverse of $M_{10 \times 8}$ directly, the matrix is decomposed by the singular value decomposition as $M_{10 \times 8} = UDV^T$. Now we can obtain the matrix $X_{8 \times 1}$ as follows:

$$X = (V \cdot D^{-1}) \cdot (U^T \cdot b) \quad (25)$$

where $D \in \mathrm{R}^{8 \times 8}$ is a diagonal matrix with positive elements, $U \in \mathrm{R}^{10 \times 8}$ and $V \in \mathrm{R}^{8 \times 8}$ are orthogonal matrices.

Now, the correspondence of the feature points are used to calculate the translational vector T of the camera frame. By changing eq. (5) as eq. (26), and substituting this equation into eq. (7) and (8), we have the coordinates of the feature point on the image frame as follows:

$$P_c = R^{-1}P_r - R^{-1}T = P_r' - T' \quad (26)$$

$$X_i = f\frac{x_r' - T_x'}{z_r' - T_z'} \quad (27)$$

$$Y_i = f\frac{y_r' - T_y'}{z_r' - T_z'} \quad (28)$$

where $P_r' = (x_r', y_r', z_r')^T$ and T' represents a positioning vector and a translation vector in terms of the camera frame respectively, which are initially represented in terms of the reference frame.

To obtain the translation vector T from the eq. (27) and (28), the following linearized equation is derived:

$$\begin{bmatrix} f & 0 & -X_i \\ 0 & f & -Y_i \end{bmatrix} \begin{bmatrix} T'_x \\ T'_y \\ T'_z \end{bmatrix} = \begin{bmatrix} f \cdot x'_r - X_i \cdot z'_r \\ f \cdot y'_r - Y_i \cdot z'_r \end{bmatrix} \quad (29)$$

There are two linear equations in the matrix eq.(29), which are obtain by using the correspondence of a feature point. Therefore, if we have two feature points, four linear equations are obtained for the three unknowns, $T'_x, T'_y,$, and T'_z. Finally, using the calculated R, T'_x, T'_y, and T'_z, we obtain the values of T'_x, T'_y, and T'_z. The homogeneous transformation from the reference frame to the camera frame, ${}^R H_C$, can be obtained from eq.(23) and eq.(29). Substituting the obtained ${}^R H_C$ into eq.(2), we can calculate ${}^R H_B$ which represents the position/orientation of the end-plate of the mobile robot.

4. Experiments

In this section, assembly operations of hexagonal bolts and nuts are considered for the experimental environment. Therefore, the camera may catch the hexagonal objects for the pose estimation of the camera. A CCD camera, SFA-410ED, which has pixels of 768 × 494 and the image area of 6.54mm × 4.89mm, is selected for our experiments. The values of d_x and d_y are calculated directly, and they are 0.0085mm and 0.0098mm, respectively. The focal length of the lens for this camera is 16 mm. We placed a bolt on a plane and the vertices of the bolt head are used for the feature points, and they have the coordinates of (0, 4, 0.42), (-4, 3, 0.42), (-5, -2, 0.32), (-1, -4, 0.4), (3, -3, 0.4), and (4, 2, 0.25) w.r.t the reference frame. To estimate the camera parameters, the orientation and position of the camera frame is initially matched to the reference frame. And then, the camera frame is translated by [0, -18, 33.6] cm and rotated 150° along the x-axis, and the image of the bolt-head is caught on the image frame of the camera. Table 1 shows a sample data for the measurement of the focal distance, f, scale factor, S, Z-Y-Z Euler angles and the translational vector, T.

f (mm)	S	Translation Vector T		Euler Angle	
17.542	0.9969	T_x	-0.1567	X	149.5
		T_y	-17.9703	Y	3.4
		T_z	-33.6506	Z	0.0

Table 1. Estimation of camera parameters

Table 2. shows the measured data of the focal distance, f, and the scale factor, S, obtained at the different position/ orientation of the camera. The data, f and S, shown in table 2 are the average value of 10 sets of data. And the error represents the relative % error of each datum from the average value. Through the experiments, we recognized that the data which have less relative error are more reliable than others.

Table 3. shows the estimated values of the camera pose (position and orientation), comparing with the real values. The rotation angle is the value of angle along the x-axis only.

Number	f(mm)	Error(%)	S	Error(%)
1	17.542	0.22	0.9989	0.65
2	17.227	1.57	0.9931	1.22
3	17.450	0.29	1.0061	0.07
4	17.302	1.14	1.0002	0.52
5	17.989	2.78	1.0290	2.35
Average	17.502	1.20	1.0054	0.96

Table 2. Measured values and relative % error of camera parameters

The error represents the % magnitude error of the estimated translation vector compared to the real vector. As it is shown in table 3, the % error is small enough to compensate the real positioning error of a mobile robot. Therefore, this scheme is applicable for the adjustment of a mobile robot and also for the estimation of the position/orientation of the base of a task robot.

Angle (°)	Real Value(cm) (x, y, z)	Estimated Value(cm) (x, y, z)	Error (%)
155	0, -17.4, 40.5	0.02, -17.35, 40.51	0.02
150	0,-18.0, 33.6	0.15, -17.97, 33.65	0.07
145	0, -17.0, 33.0	0.12, -16.98, 32.26	1.79
144	0, -20.6, 30.4	0.23, -20.54, 30.65	0.47
140	0, -19.3, 24.2	0.34, -19.12, 22.84	3.76

Table 3. Measured values and % error of camera

Fig. 5. represents the relative error of the estimated rotation and translation of the camera subjected to the simulated noises.

This experiment was done to check the effects of noises coming from the external illumination and vision processing. The simulated noises which are uniformly distributed random noises with zero average and unity standard deviation, are added to the location of the feature points (vertices of the hexagonal objects) on the computer frame memory.

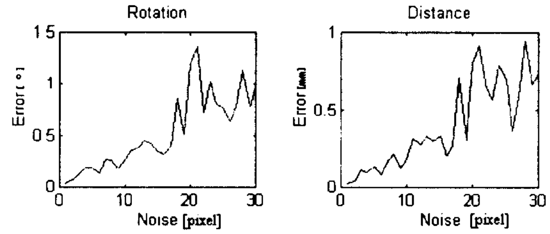

Fig. 5. Relative errors of camera pose with additional noises

The unit magnitude of the noises was 1/4 pixel. As it is shown in the figure, the estimation of the camera pose is highly dependent on the magnitude of the noises, as we can expect.

5. Conclusion

In this paper, we proposed a scheme for the precise control of a mobile robot supporting a task robot on the top. It is based upon the analysis of the images using the camera image caught by a camera attached at the end of the task robot. To measure the base position and orientation of the task robot, the image caught by a camera is analyzed by using the correspondence of the feature points on the image plane. Through this process, we estimated the internal parameter of a camera, i.e., the focal distance and the scale factor, and the position and orientation of the camera w.r.t the reference frame. By using the estimated pose of the camera and the actual pose of the task robot, the position/orientation of the top of the mobile robot is obtained. This estimated pose of the mobile robot is accurate enough to compensate for the pose error of the mobile robot caused by the slippage of the wheels on the ground. Our future research topic are reducing the estimation errors, and incorporation of the distortion of the lens in the estimation of the parameters of camera, which may improve our estimation accuracy. Also, we are pursuing a way of performing a task efficiently through the close cooperation of the mobile robot and the task robot, which may be our final goal on this topic.

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