

COMPENSATION OF POSE ERROR FOR A SCORA ER 14 ROBOT (SCARA) USING KINEMATIC ERROR MODEL

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Abstract

Now industrial robots are typically able to move with best positional accuracy. The accuracy of the robot can be asserted by measuring the position and orientation of robots. In order to achieve the best absolute accuracy, manufacturers usually offer a calibration. This work deals with inverse kinematic analysis of robot manipulator by using Denavit-Hartenberg (DH) parameters and also presents a methodology for finding geometric error using an error model based on all DH parameters. One of the sources of error in robots is the changes in DH parameters. Such as Joint angles, link lengths, offset distances and twist angles. In this work, DH parameters are optimized by using Jacobian approach. For a particular pose the minimum or required error at the end effector can be achieved through iterations. It can be inferred from the analyzed variations of DH parameters through the error model that, Variations in the DH parameter values for the poses are minimal and Variations in joint angles are least compared to other three DH parameters. SCORA ER14 Robot is used for the analysis. These errors have been compensated by incorporating in the robot controller, and the controller performance is analyzed through the help of numerical simulations.

Keywords: Robot manipulator, Denavit-Hartenberg parameters, Kinematic error model, Jacobian, Robot control.

I. INTRODUCTION

Today, industrial robots are often used in complex and capital intensive installations in big industries and their supplier companies. For an economic ratibility of these expensive installations, short programming and low cycle times are necessary. Nowadays industries are automated through the help of robots and computer-controlled machines. According to the automation level the robot and machines are involved in the industries. Calibration is used to enhance robot positioning accuracy, through software rather than changing the mechanical structure or design of the robot itself. As, robots similar to other mechanical devices can be affected by slight changes or drifts caused by wear of parts, dimensional drifts, tolerances and components replacement, calibration can minimize the risk of having to change application programs due to slight changes or drifts caused by the above mentioned factors in the robot system. This is useful in applications that may involve a rather large number of task points.

The literature survey for this work highlights the developments in the field of error analysis and robot calibration. Many researchers have devoted efforts for identification; measurement and compensation of end effector pose errors. Denavit-Hartenberg introduced four parameters to describe a lower pair mechanism kinematically [1], these were later used to represent and model robot and to derive their equations of motion. A common method of representing the relationship between two consecutive link coordinate frames is the homogeneous transformation matrix defined by Denavit

and Hartenberg [2]. Their representation uses four kinematic parameters to completely describe this relationship. Geometric errors in the manipulator's structure will produce corresponding errors in these kinematic parameters. The kinematic errors in the manipulator structure for modeling geometric errors can be divided into two categories: 1) errors in the joint variables, 2) errors in the fixed kinematic parameters. Author [2] introduced a kinematic tool for design and control of robot manipulator in 1984. C.Wu [3] studied the effect of joint errors on the accuracy of the operation using Stochastic model and also suggested for determining the optimum position error to aim at in a given manufacturing situation in 1988. This error analysis lead to the development of a feasible joint tolerance domain concept for use in computer aided design of robots. Author [4] proposed a new closed form solution for identifying the kinematic parameters of an active binocular head having four revolute joint and two prismatic joints by using 3 dimensional point measurement of a calibration point. This model is based on the complete and parametrically continuous (CPC) kinematic model, and can be applied to any kind of kinematic parameter identification problems with or without multiple and effectors, providing that the links are rigid. The general problems and present day calibration techniques are presented in [5].

This work presents the Kinematic error model of SCORA ER 14 manipulator has developed by using Jacobian approach and estimated in DH parameters for a particular pose error by solving the model using MATLAB program. Finally, these parameter errors are

compensated in the controller and the performance studies carried out.

II. BACKGROUND

A. Kinematics

Kinematics is the science of motion, which considers motion without regard to the forces causing it. A robot, in terms of kinematics, can be considered as a series of links connected by joints. The main relation describing the kinematics of a robot manipulator relates to the connection between Cartesian and joint coordinates. Forward kinematics is the problem of solving the Cartesian position and orientation of the end-effector to given knowledge of the kinematic structure and joint coordinates. Forward kinematics is easy always leads to unique solution, the inverse kinematics is far more mathematically involved and usually leads to several solutions. The limitation of forward kinematic technique is the inability to easily position end effector points at absolute positions in space. Inverse Kinematics is used to determine a set of joint angles in an articulated structure based up on the position of a given node in the hierarchical structure. Inverse kinematics problem is analytically complex and closed form of solution does not always exist.

B. Jacobian

Jacobian is one of the most important tools for characterization of differential motions of the manipulator. Generally, there are two forms of Jacobian (1) Tool Jacobian (2) Manipulator Jacobian. A transformation from tool configuration velocities to the joint velocity is known as called Tool Jacobian. Manipulator Jacobian is also used for describing the mapping between forces applied to the end effector and resulting torque at joints.

C. Singular Value Decomposition (SVD)

There exists a very powerful set of techniques for dealing with sets of equations or matrices that are either singular or else numerically very close to singular. In many cases where Gaussian elimination and (LU) decomposition fail to give satisfactory results, this set of techniques, known as singular value decomposition, or SVD, will diagnose precisely what the problem is. In some cases, SVD will not only diagnose the problem. Procedure for doing SVD as follows. Consider $m \times n$ matrix A , where $m \geq n$ and $\text{rank}(A) = r$, the singular value decomposition of A , denoted by SVD (A), is defined as

$$A = U \Sigma V^T \quad (1)$$

where, $U^T U = I_m$, $V^T V = I_n$ and $\Sigma = \text{diag}(\sigma_1, \dots, \sigma_n)$, $\sigma_i > 0$ for $1 \leq i \leq r$, $\sigma_j = 0$ for $j \geq r+1$.

The first r columns of the orthogonal matrices U and V define the orthonormal eigenvectors associated with the r nonzero Eigen values of AA^T and $A^T A$, respectively. U and V are referred to as the left and right singular vectors, respectively. The singular values of A are defined as the diagonal elements of Σ which are the non-negative square roots of the n eigen values of AA^T .

III. METHODOLOGY FOR KINEMATIC ERROR MODEL

In this paper the analytical expressions and physical interpretation of the linear combinations of the generalized errors are developed for any serial link manipulator. The six-parameter representation is used to define the errors, and the linear combination coefficients are expressed through the robot's D.H. parameters. The error combinations using the D.H. four-parameter error representation are also derived from the general expressions. A non-singular form of the Identification Jacobian matrix is then obtained using these expressions, allowing for systematic calibration with improved accuracy of any serial link manipulator.

This analytical approach has four main parts,

- (1) Inverse kinematic analysis
- (2) Calculation of Jacobian
- (3) Singular value decomposition and finally
- (4) Kinematic Error Model for Error calculation.

A. Modelling for Inverse Kinematic Analysis

A kinematic model is a mathematical description of the geometry and motion of a robot. A number of different approaches exist for developing the kinematic model of a robot manipulator. The most popular method, has been established by Denavit and Hartenberg . The method based on homogeneous transformation matrices. The procedure consists of establishing coordinate systems on each joint axis. Each coordinate system is then related to the next through a specific set of coefficients in the homogeneous transformation matrices. The D–H matrix is a transformation matrix from one coordinate frame to the next just like the homogeneous matrix. In SCORA ER 14, there are four links including gripper. Skeleton and photo of the robot is as shown in Fig. 1 and DH parameters are depicted in Table 1.

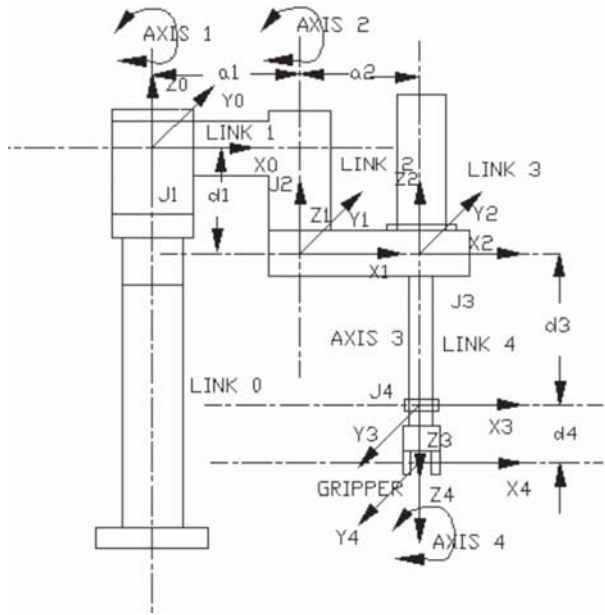


Fig.1. (a) Skeleton of the SCORA ER 14

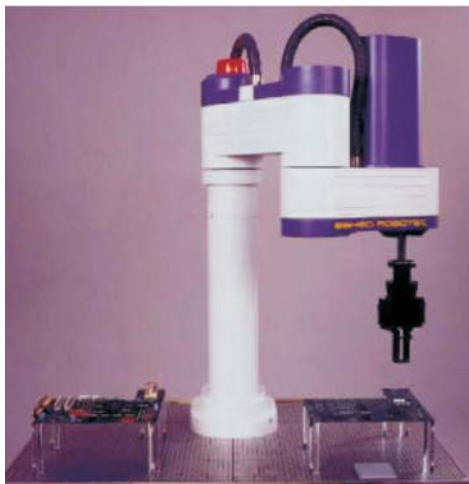


Fig.1. (b) Photo of the SCORA ER 14

Table.1 D – H parameters

Joint	θ (Deg)	a(mm)	d(mm)	α (Deg)
1	θ_1	a1 (270)	d1 (125)	0
2	θ_2	a2 (230)	0	0
3	0	0	d3	α_3 (180)
4	θ_4	0	d4 (140)	0

With the help of above parameters, the inverse kinematic model derived [6]. The final equations are as follows

$$\begin{aligned}
 P_x &= S_{12}d_4S\alpha_3 + a_2C_{12} + a_1C_1 \\
 P_y &= -C_{12}d_4S\alpha_3 + a_2S_{12} + a_1S_1 \\
 P_z &= d_1 + d_3 + d_4C\alpha_3
 \end{aligned} \tag{2}$$

B. Calculation of Jacobian

Jacobian is one of the most important tools for characterization of differential motions of the manipulator. Generally, there are two forms of Jacobian (1) Tool Jacobian (2) Manipulator Jacobian. A transformation from tool configuration velocities to the joint velocity is known as called Tool Jacobian. Manipulator Jacobian is also used for describing the mapping between forces applied to the end effector and resulting torque at joints.

The elements of the Jacobian can be derived analytically through use of the DH parameters [6, 7]. The Jacobian is as follows:

$$J = \begin{bmatrix}
 C_{12}d_4S\alpha_3 - a_2S_{12} - a_1S & C_{12}d_4S\alpha_3 - a_2S_{12} & 0 & C_1 & C_{12} & 0 & 0 & S_{12}S\alpha_3 & S_{12}d_4C\alpha_3 \\
 S_{12}d_4S\alpha_3 + a_2C_{12} + a_1C_1 & S_{12}d_4S\alpha_3 + a_2C_{12} & 0 & S_1 & S_{12} & 0 & 0 & -C_{12}S\alpha_3 & -C_{12}d_4C\alpha_3 \\
 0 & 0 & 0 & 0 & 0 & 1 & 1 & C\alpha_3 & -d_4S\alpha_3 \\
 e^{0.4/\pi}C_{12}S\alpha_3 & e^{0.4/\pi}C_{12}S\alpha_3 & \frac{1}{\pi}e^{0.4/\pi}S_{12}S\alpha_3 & 0 & 0 & 0 & 0 & 0 & e^{0.4/\pi}S_{12}C\alpha_3 \\
 e^{0.4/\pi}S_{12}S\alpha_3 & e^{0.4/\pi}S_{12}S\alpha_3 & -\frac{1}{\pi}e^{0.4/\pi}C_{12}S\alpha_3 & 0 & 0 & 0 & 0 & 0 & -e^{0.4/\pi}C_{12}C\alpha_3 \\
 0 & 0 & \frac{1}{\pi}e^{0.4/\pi}C\alpha_3 & 0 & 0 & 0 & 0 & 0 & -e^{0.4/\pi}S\alpha_3
 \end{bmatrix} \tag{3}$$

C. Kinematic Error Model for Error Correction

Various steps for the optimization or minimization of error in DH parameters are as follows: Standard DH parameterizations reveal the joint parameters, and to these sufficiently small synthetic deviations are introduced. The parameters considered were the joint angles, the link lengths, a, the link offsets, d, and twist angle, α . Thus, the actual position of the end effector can be calculated as a function of the joint angles, link lengths, link offsets and joint twists along with their corresponding deviations:

$$P_{\text{actual}} = f(\theta, a+a, d+d, \alpha+\alpha) \tag{4}$$

Whereas the positions calculated by the controller involve only the nominal parameters:

$$P_{\text{controller}} = f(\theta, a, d, \alpha) \tag{5}$$

The difference is computed vectorially and in three dimensional spaces:

$$\{P_{\text{xyz}}\} = P_{\text{actual}} - P_{\text{controller}} \tag{6}$$

This overall procedure is followed for each of the robot poses and then the data is concatenated into a final Jacobian matrix and a vector of end point deviations. The deviations of the joint parameters can be determined by use of the inverse of the Jacobian matrix:

$$\{q\} = [J(q)]^{-1} \{P_{\text{xyz}}\} \tag{7}$$

The pose values and DH parameters are taken for minimization process is tabulated and depicted in Table (2). Fig (2) shows the error correction in the DH parameters for the pose1 through this method, where the + is pointed the error in the DH parameters at initial or in other words before iteration. The * is indicating the final error after a certain iterations. From this, the error in the SCORAER 14 manipulator is changing at microns level for a particular pose error. MATLAB program gives the optimal DH parameters after 200 iterations. The error in DH parameters can be corrected by the controller using proper adequate software. This work mainly concentrated only on geometrical errors not on non-geometrical errors.

Table 2. DH parameters for various Poses of end effector

S.No	Pose / Point	$\theta 1$ (deg)	$\theta 2$ (deg)	$\theta 4$ (deg)	a1 (mm)	a2 (mm)	d1 (mm)	d3 (mm)	d4 (mm)	$\alpha 3$ (deg)
1	Initial	45	45	45	270	230	125	-65	-140	180
	Final	45.008	44.992	45.00	269.862	229.660	124.253	-65.60	-140	179.252
2	Initial	0	0	90	270	230	125	-65	-140	180
	Final	0.0085	-0.009	90	269.005	229.005	124.260	-65.62	-140	179.260
3	Initial	30	60	30	270	230	125	-65	-140	180
	Final	30.008	59.992	29.99	269.220	230.774	124.919	-65.38	-140	180.919
4	Initial	90	90	45	270	230	125	-65	-140	180
	Final	89.990	90.010	45	271.084	228.798	125.908	-65.74	-140	180.908
5	Initial	100	100	100	270	230	125	-65	-140	180
	Final	99.994	100.01	100	271.29	230.247	126.041	-63.11	-140	181.041
6	Initial	75	80	90	270	230	125	-65	-140	180
	Final	75.004	79.996	90	268.498	232.09	124.108	-64.79	-140	179.108

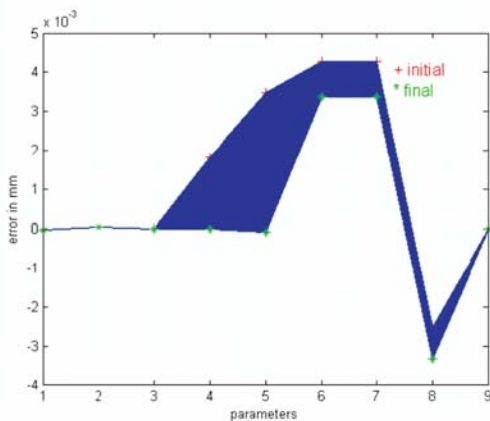


Fig.2. Pose Error Vs DH Parameters

IV. CONTROLLER DESIGN AND SIMULATION RESULTS

This section describes the design of the nonlinear tracking controller for the robot to track a given reference trajectory using the model-based control law.

The robot dynamic model is given by Eq. (8),

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + b(\dot{q}) + h(q) = \tau \tag{8}$$

where, $M(q)$ is the inertia matrix, $C(q, \dot{q})\dot{q}$ is the vector of centrifugal and Coriolis forces, $b(\dot{q})$ is the vector of frictional and damping forces, $h(q)$ is a vector of external forces and torques applied at the joints. The vectors q denote the position, \dot{q} velocity and \ddot{q} joint acceleration respectively.

The dynamic model Eq. (8) that characterizes the behavior of robot manipulators is in general it composed of nonlinear functions of the state variables (joint positions and velocities). This feature of the dynamic model might lead us to believe that given any controller, the differential equation that models the control system in closed loop should also be composed of nonlinear functions of the corresponding state variables. This intuition is confirmed for the case of all the control laws studied in previous chapters. Nevertheless, there exists a controller which is also nonlinear in the state variables but which leads to a closed-loop control system which is described by a linear differential equation. This controller is capable of fulfilling the motion control objective, globally and moreover with a trivial selection of its design parameters. It receives the name computed-torque control. The control law is given by,

$$\tau = \left\{ \begin{array}{l} \mathbf{M}(q)(\ddot{q} + K_D\dot{\tilde{q}} + K_P\tilde{q}) \\ + \mathbf{C}(q, \dot{q})\dot{q} + b(\dot{q}) + h(q) \end{array} \right\} \quad (9)$$

where, K_D and K_P are symmetric positive definite (SPD) design matrices, and are the velocity errors and position errors respectively.

The block-diagram that corresponds to computed-torque control of robot manipulators is presented in Fig. 3.

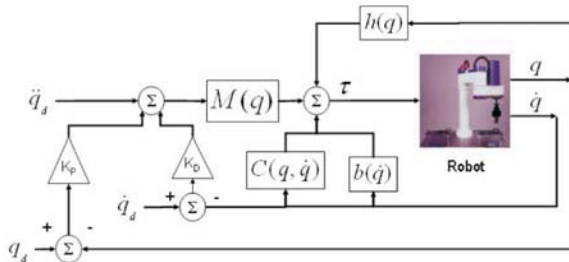


Fig.3. Block-diagram: computed-torque control

The simulation model that corresponds to robot control is presented in Fig.4. In that trajectory planner also included which will gives the desired robot path parameters such as joint acceleration, velocity and position. The interactive user screen for analysing the results is shown in Fig.5.



Fig.4. Robot Controller - Simulation Model

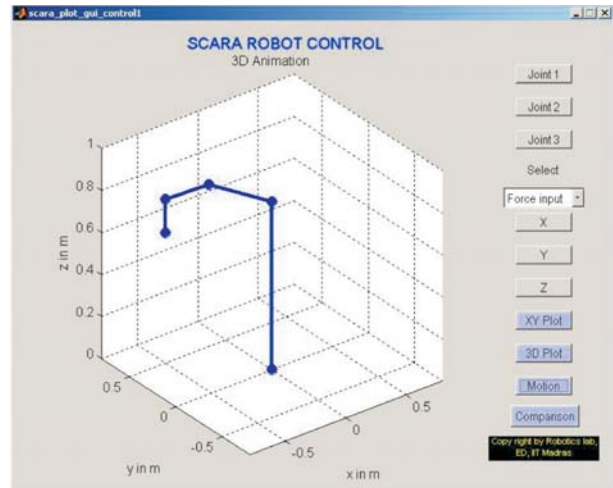


Fig.5. User interactive screen for robot controller analysis

The comparative trajectory tracking control results is presented in Fig.6. From this figure it shows that after the parameter error compensation the controller performance is improved and the tracking errors are significantly reduced.

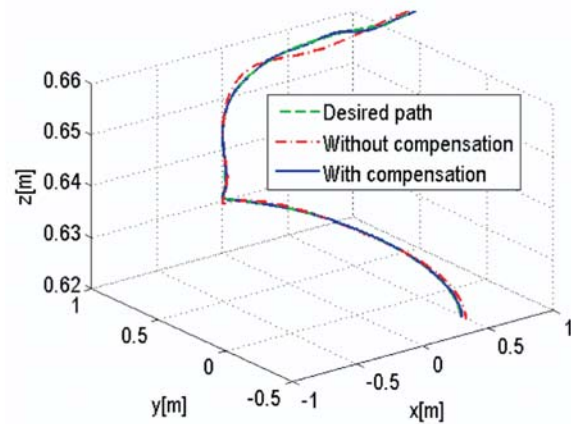


Fig.6. Comparative results of robot tracking control

V. CONCLUSION

It is clear from the result that the geometric error percentage varies from 0 - 5%. A kinematic error model has formulated in this work for analyzing the variations in DH parameters for a particular pose. Here non-geometric errors are not taken in account. In this work, the optimizations of error in DH parameters are also done.

It can be inferred from the analyzed variations of DH parameters through the error model that,

- Variations in the DH parameter values for the poses are minimal.

- Variations in joint angles are least compared to other three DH parameters.
- Maximum change is coming in Link length at the rate of approximately 2mm. This may be because of joint flexibility or bearing problem.
- Other two parameters variations like twist angle and offset distance variations are also minimal.

Further, the work can be carried out in following ways:

- Measuring the actual position and orientation by Coordinate Measuring Machine so that error can be predicted accurately.
- Calibration of robot by using Reconfigurable Binocular vision systems.
- Non geometrical errors like compliant error, errors due to environmental changes etc. can also be taken into account

This work can be carried out by dynamic closed loop system. By the help of sensors and feed back system to the controller.

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