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An Influence Based Error Identification for Kinematics Calibration of Serial Robotic Manipulators

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Abstract: *In serial robotic manipulators, due to the nature of the coupling of links, the influence of errors in joint parameters on pose accuracy varies with the configuration. Kinematics parameter's error identification in the standard kinematics calibration has been configuration independent which does not consider the influence of kinematics parameter on robot tool pose accuracy for a given configuration. Mutually dependent joint parameter errors cannot be identified at the same time, and hence error of one parameter in each pair is identified. In a pair of mutually dependent joint parameters, the effect of error in one parameter on positional error can be more than the other one depending on the configuration. Therefore, the error detection may be incorrect if the influence of joint parameters is ignored during the error identification. This research analyses the configuration dependent influences of kinematics parameters error on pose accuracy of a robot. Based on the effect of kinematics parameters, the errors in the kinematics parameters are identified. Kinematics model of the robot is composed of the modified DH method and an improved DH method to avoid the limitations of the original DH method. First, the robot is calibrated to identify errors in 17 kinematics parameters conventionally, and then errors are detected based on the proposed method.*

Keywords: *Calibration, Error identification, Kinematics, Measurement, Pose accuracy, Serial robots.*

1. INTRODUCTION

Serial robotic manipulators have numerous applications across various industries such as automobile, manufacturing, medical, space, and so forth. Various geometric factors such as inaccurate joint angles, joint twist, link lengths and non-geometric factors such as joint eccentricity, joint flexibility, dynamics and control errors introduce the difference between the model of a manipulator on the controller and an actual mechanism and hence accuracy of a robot decreases. [1] Robot calibration

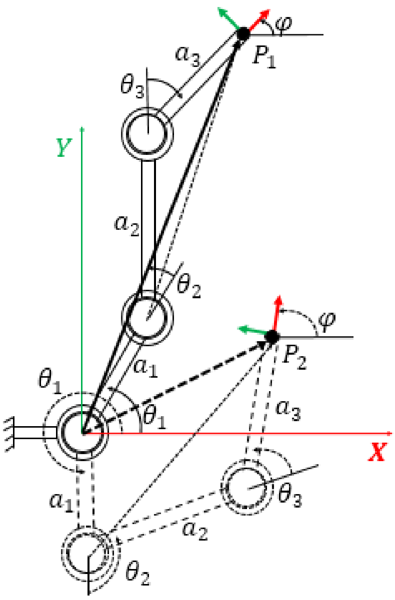

Figure 1 Mutually dependent parameters with variable influence

reduces this difference to improve accuracy. The geometric parameters errors can be systematically identified and compensated whereas other errors are difficult to model and identify. The main reason that causes the pose error is inaccurate geometric parameters used to calculate the pose. [2] So often geometric errors correction fulfils the desired pose accuracy for many applications. Geometric errors calibration is also known as a level 2 or a kinematics calibration. The current kinematics calibration includes four steps, namely kinematics and error modelling, end-effector's pose measurement, identification of error sources and compensation for the errors into a kinematic model. [3] The Level 2 calibration methods modify the kinematic parameters of the robot to minimize the difference between the kinematics model of a robot in the controller and actual mechanism. The modified kinematics parameters best fit the accuracy over the selected poses or small region of the robot's workspace. Completeness and continuity of kinematics model, precision of measurement system, accurate errors identification, proper error compensation scheme, and specification of the robot determine the effectiveness of the kinematics calibration process.

Kinematics modelling using Modified DH and improved DH method, the Complete and Parametrically Continuous (CPC) model, the Modified CPC model, and POE formula results into the complete and continuous kinematics model of the robot. [4] The large volume metrology such as Laser tracker is accurate up to 15 microns. [5] However, it is difficult to directly measure errors of individual kinematics parameter (i.e. joint-link parameter such as joint orientation or link length). An error identification in the contemporary kinematics calibration simultaneously approximate the errors of all kinematics parameters from a measured pose of robot end-effector for a given configuration using methods such as linear least squares, non-linear least squares, pseudo-inverse, genetic algorithm, and heuristic search method. [6] This process is repeated for few selected configurations to calculate a set of kinematics parameters which best fit the accuracy to all selected configurations. However, different pose errors occur for the same individual joint parameter over various configurations. For example, in Figure 1, θ_1, θ_2, and θ_3 are mutually dependent parameters whose errors cause positional error at end-point P. In configuration 1 (i.e. P_1), θ_1 is more influential than θ_2, and opposite in configuration 2 (i.e. P_2). Therefore, during the error identification more influential parameter in each pair must be considered at every selected configuration. However, contemporary error identification ignores the configuration dependency of the influence of kinematics parameters on a pose accuracy which leads to incorrect error identification at certain configurations of a robot. Therefore, this research analyses the influence of each kinematics parameters on the pose accuracy of a robot and proposes an influence based error identification. Section 2 prepares the kinematics model. Section 3 contains error identification and compensation. Section 4 performs experiments and Section 5 concludes the research.

2. KINEMATICS

This research combined the modified DH method and improved DH method to retain continuity of kinematics model of the robot considering the nominal values of the kinematics parameters listed in

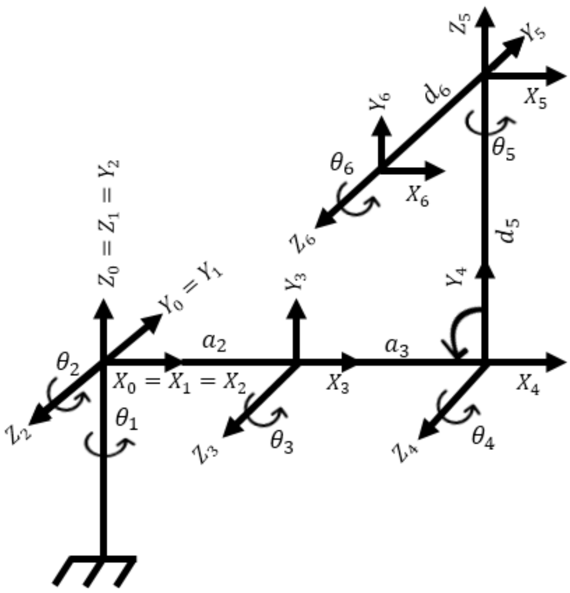

Figure 2 Frames assignment

Table 1. In the modified DH method, the frame i is rigidly attached to the link i, which rotates around joint i. The transformations ${}^{i-1}_{i}T$ between the frames $(i-1)$ and i is described with the help of two rotational parameters α_{i-1} and θ_i, and two translational parameters a_{i-1} and d_i.

Table 1 Kinematics parameters of Katana 450

Joint i	*α_{i-1} ^{o}*	*a_{i-1} mm*	*θ_i^o*	*β_{i-1} ^{o}*	*d_i mm*
1	0	0	+/-169.5	-	0
2	90	0	+102 / -30	-	0
3	0	190	+/-122.5	0	-
4	0	139	+/-112	0	-
5	-90	0	+/-168	-	147.3
6	90	0	Inactive	-	200

Therefore, the homogeneous link transformation matrix ${}^{i-1}_{i}T$ is obtained using the following transformations as:

$$ {}^{i-1}_{i}T = Rot(X,\alpha_{i-1})Trans(X,a_{i-1})Rot(Z,\theta_i)Trans(Z,d_i). \quad (1) $$

Joint 2,3 and 4 are parallel so the improved DH method must be employed with an additional parameter β to correlate frames 2,3 and 4 to avoid discontinuity. The transformation matrix is obtained using transformations:

$$ {}^{i-1}_{i}\boldsymbol{T} = Rot(X,\alpha_{i-1})Rot(Y,\beta_{i-1})Trans(X,a_{i-1})Rot(Z,\theta_i). \quad (2) $$

Eq. (2) correlate frames 2,3 and 4 using $\boldsymbol{T}_3^2$ and $\boldsymbol{T}_4^3$. The improved H method avoids the limitations of the modified DH method. The transformation ${}^{0}_{6}T$ between the robot base and the robot end-effectors is obtained by putting values of joint link parameters of Table 1 into transformation matrices as:

$$ {}^{0}_{6}T = {}^{0}_{1}T \cdot {}^{1}_{2}T \cdot {}^{2}_{3}\boldsymbol{T} \cdot {}^{3}_{4}\boldsymbol{T} \cdot {}^{4}_{5}T \cdot {}^{5}_{6}T \quad (3) $$

The homogeneous transformation matrix ${}^{0}_{6}T$ in (3) describes pose (i.e. position and orientation) of the robot end-effectors on the robot's nominal base. The kinematics model of the Katana 450 robot describes orientation of robot's end-effector as ZXZ Euler angles Φ, θ, and Ψ . Therefore, the pose P of robot is defined by the coordinates X, Y, and Z and orientation angles Φ, θ, and Ψ in the form of vector $P = [X\ \ Y\ \ Z\ \Phi\ \theta\ \ \Psi]^T$. The derived kinematic model of the robot has been verified against the robot's control software. For the calibration purpose, the positional error vector ΔP between the actual pose P_a and the theoretical pose P_t of the end-effectors can be described as:

$$ \Delta P = P_a - P_t = [\Delta X\ \ \Delta Y\ \ \Delta Z\ ]^T \quad (4) $$

3. ERROR IDENTIFICATION

3.1. Influence of kinematics parameters on positional accuracy

The coordinates of 118 poses are selected within the largest cube of the robot's workspace as per proposed performance criteria and related test methods in the ISO 9283:1998 [7] for the robotic manipulators. A deviation of +0.05 on angular parameters (θ_i ..., α_i ... β_i ...) and +0.1 mm on linear parameters (a_i.., d_i..) is imposed one by one at a given data point (i.e. configuration). This simulation provided the influence of each kinematics parameters for a given robot configuration. Same process is repeated over 118 configurations. The error of +0.1 mm in linear parameters causes an absolute positional error of 0.1 mm regardless of the configuration of the robot. However, an error of +0.05° in rotational parameters causes configuration dependent error on end-effectors position as shown in Figure 3. The common understanding is the influence of rotational parameters error decreases from the base towards end-effector in serial robot, i.e. error in θ_2 has a larger impact on positional accuracy than θ_3. However, error in θ_3 can have a larger impact on positional accuracy than θ_2 for some configurations as per analysis in Figure 3. Therefore, followings section proposes influence based error identification of kinematics parameters error.

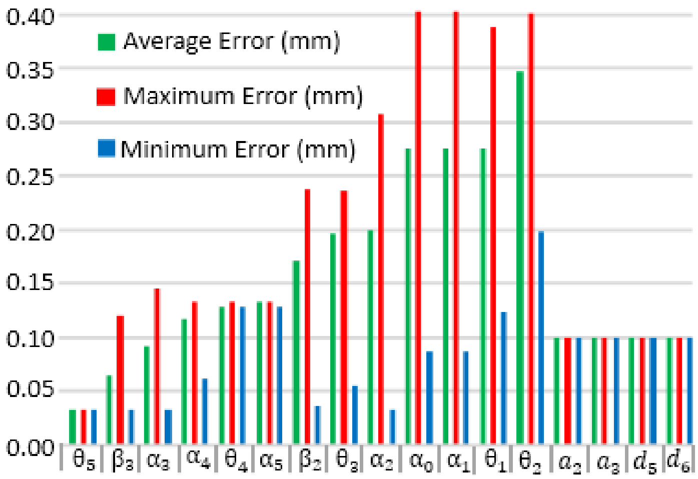

Figure 3 Influence of kinematics error on position accuracy

3.2. Influence based error identification

For the calibration purpose, positional errors vector $\Delta P = [\Delta X \;\; \Delta Y \;\; \Delta Z]$ is correlated to the kinematics parameters error vector ΔE with the help of the mapping matrix J as:

$$\Delta P = J.\Delta E. \tag{5}$$

Where, $J = \begin{bmatrix} \frac{\partial P_X}{\partial \theta_1} .. \frac{\partial P_X}{\partial \theta_5} & \frac{\partial P_X}{\partial \alpha_0} .. \frac{\partial P_X}{\partial \alpha_5} & \frac{\partial P_X}{\partial \beta_2} \frac{\partial P_X}{\partial \beta_3} & \frac{\partial P_X}{\partial a_3} \frac{\partial P_X}{\partial a_4} & \frac{\partial P_X}{\partial d_5} \frac{\partial P_X}{\partial d_6} \\ \frac{\partial P_Y}{\partial \theta_1} .. \frac{\partial P_Y}{\partial \theta_5} & \frac{\partial P_Y}{\partial \alpha_0} .. \frac{\partial P_Y}{\partial \alpha_5} & \frac{\partial P_y}{\partial \beta_2} \frac{\partial P_y}{\partial \beta_3} & \frac{\partial P_Y}{\partial a_3} \frac{\partial P_Y}{\partial a_4} & \frac{\partial P_Y}{\partial d_5} \frac{\partial P_Y}{\partial d_6} \\ \frac{\partial P_Z}{\partial \theta_1} .. \frac{\partial P_Z}{\partial \theta_5} & \frac{\partial P_Z}{\partial \alpha_0} .. \frac{\partial P_Z}{\partial \alpha_5} & \frac{\partial P_X}{\partial \beta_2} \frac{\partial P_y}{\partial \beta_3} & \frac{\partial P_Z}{\partial a_3} \frac{\partial P_Z}{\partial a_4} & \frac{\partial P_Z}{\partial d_5} \frac{\partial P_Z}{\partial d_6} \end{bmatrix}$ and

$\Delta E = [\Delta\theta_1 .. \Delta\theta_5 \;\; \Delta\alpha_0 .. \Delta\alpha_5 \; \Delta\beta_2 \; \Delta\beta_3 \;\; \Delta a_3 \; \Delta a_4 \;\; \Delta d_5 \; \Delta d_6 \,]^T.$

Eq. (5) correlates the kinematics parameters error vector ΔE with the positional error vector ΔP. Firstly, the kinematics parameters' errors are identified using the unique least square estimation [8] as:

$$\Delta E = \frac{J^T}{J \cdot J^T} \cdot \Delta P \tag{6}$$

Eq. (6) is iteratively used at each pose to correct the kinematics parameters error. In each iteration, a new ΔE is obtained which is compensated in (5) to obtain new ΔP. This process is repeated till the positional error is detectable by the measurement equipment being used (i.e. above 0.01 mm in this case) for the calibration. The same procedure identifies the kinematics parameters' errors for all poses. From the sets of errors in the kinematics parameters of all poses, a set of kinematics parameters is calculated that best fit the accuracy to all measured poses. However, the error detection may be incorrect if influence is not considered during the error identification. For example, in the configuration $\theta_1, \theta_2, \theta_3, \theta_5 = 0$ and $\theta_4 = 80^0$ influence of θ_4 is larger than θ_3.The positional error ΔP can be corrected by correcting θ_3 or θ_4. Even if influence of θ_4 is larger than θ_3 for that configuration, the conventional identification may identify larger error of θ_3 instead of smaller error in θ_4 for the same positional error ΔP. This incorrect identification of large error in θ_3 at this configuration would affect the set of best fit parameters in the end. Additionally, incorrect identification at few configurations may lead to significant positional error at uncalibrated points. Therefore, this research employs coefficient

C<1 in (8) to increase the numbers of iterations for errors identification at each pose. At each pose, in each of the iteration, error vector ΔE is multiplied influence vector $k = [k_1 .. k_{17}]$ as:

$$\Delta P = J.(\Delta E k), \tag{7}$$

and subsequent error vector ΔE is calculated as:

$$\Delta E = C \ \frac{J^T}{(JJ^T)} \cdot \Delta P. \tag{8}$$

Where, $k = [k_1 .. k_{17}]$ is obtained from the influence of kinematics parameters at a pose as explained in the Section 3.1. For example, assume that the parameters influence at one of the configuration is like average influence of kinematics parameters shown in Figure3. In this case θ_2 is the most influential with nearly 0.34 mm error leads to $k_2 = 1$. For this configuration, 0.34 mm is considered as 100%, and values for the remaining ks in that configuration can be found with reference to k_2. Like $k_8 = 0.59$ for α_2. For some of the configurations, where only θ_1 changes, vector k remains same, otherwise changes with the configurations. The proposed approach for error identification increases the computational cost, however, with the availability of low cost and faster computing power, an accurate error identification is desired. The following section performs experiments and identifies the errors in kinematics parameters with both conventional and influence based error identification approach with intensive experiments.

4. EXPERIMENTAL RESULTS

The measurement setup includes a five DOF Katana 450 robot, an Optotrack system with a volumetric resolution of 0.01 mm, active vibration isolation table, and a computer to control the robot. The end link of the Katana 450 robot is 118 mm long gripper, which is replaced with the 200 mm long and 0.5 Kg tailored attachment. The attachment imitates maximum payload of the robot, provide the ease for

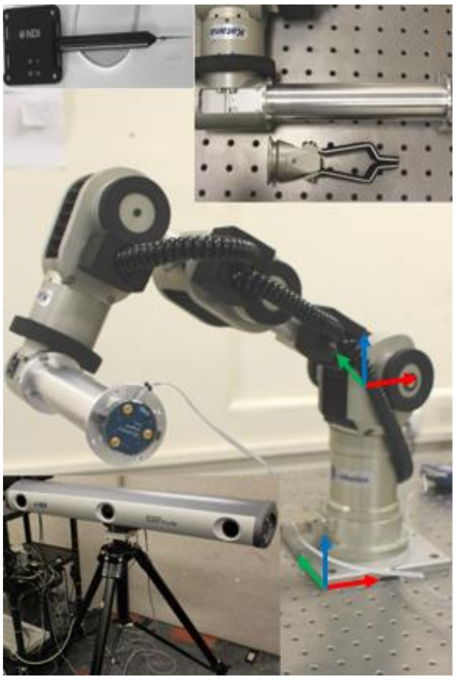

Figure 4 Experimental setup

attaching the measurement targets, and amplify the joint errors due to a larger length. The robot is controlled with the MATLAB using Katana Native Interface language for the calibration, and modification of the kinematic parameters after the calibration. The digitising probe shown in the top-left corner of Figure 4 used by the Optotrack system, it is easy to establish the global coordinate system for the measurements. The system measures Cartesian coordinates of three active markers on the established global coordinates system at the structural base of the robot. The coordinates of three markers are used to calculate the position as well as the orientation of the robot's end-effector on the structural base of the robot as shown in Figure 4. The translational transformation of [55 55 201.5]' mm transforms the coordinates of the structural base to the robot's nominal base as per design specification of the robot. The measurements are sequenced such that all five joints angle change when moving from one pose to another. Table 2 and Table 3 lists errors of 17 kinematics parameters identified with standard method and influence based approach respectively, and Table 4 compares the improvement in pose accuracy in term of various pose parameters. The overall positional accuracy improves significantly using proposed method for error identification. The current identification could reduce average positional error from 1.21 mm to 0.38 mm whereas influence based identification reduced error from 1.21 mm to 0.21 mm. Even though the orientation errors are not identified, the measurements show improvement in orientation accuracy as well.

Table 2 Standard simultaneous identification

Joint i	α_{i-1}^{o}	a_{i-1} *mm*	$\Delta\theta_i^{o}$	β_{i-1}^{o}	d_i *mm*
1	0	-	-0.061	-	-
2	89.92	-	0.0232	-	-
3	0.003	190.003	-0.057	0.0021	-
4	0.007	139.01	0.0641	0.0013	-
5	-90.01	-	-0.121	-	147.302
6	90.03	-	-	-	200.001

Table 3 Proposed influence based identification

Joint	α_{i-1}^{o}	a_{i-1}	$\Delta\theta_i^{o}$	β_{i-1}^{o}	d_i *mm*
1	0	-	-	-	-
2	90.05	-	0.034	-	-
3	-	190.0	0.066	0.005	-
4	0.062	139.0	0.023	-0.003	-
5	-	-	-0.01	-	147.30
6	90.01	-	-	-	200.00

Table 4 Calibration results

Average over 118 positions			
Pose parameter	Before the calibration	Simultaneous identification	Influence based identification
$\lvert\Delta X\rvert$	0.63	0.28	0.18
$\lvert\Delta Y\rvert$	0.44	0.13	0.10
$\lvert\Delta Z\rvert$	0.85	0.25	0.16
$\lvert\Delta P\rvert$	1.21	0.38	0.21
$\lvert\Delta \Phi\rvert°$	0.27	0.096	0.088
$\lvert\Delta \theta\rvert°$	0.17	0.027	0.022
$\lvert\Delta \Psi\rvert°$	0.26	0.084	0.079

5. CONCLUSION

The proposed approach for the identification of kinematics parameters errors has proven to be effective compared to the standard one. Consideration of influence of kinematics parameters during an error identification improved positional accuracy of a robot by nearly 14%. This approach can be further developed for improving the dynamic pose accuracy of the serial robotic manipulators.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Conrad KL, Shiakolas PS, Yih T, editors. Robotic calibration issues: Accuracy, repeatability and calibration. Proceedings of the 8th Mediterranean Conference on Control & Automation; 2000; Rio, Patras, GREECE.
2. Renders JM, Rossignol E, Becquet M, Hanus R. Kinematic calibration and geometrical parameter identification for robots. IEEE Transactions on Robotics and Automation. 1991;7(6):721-32. doi: 10.1109/70.105381.
3. Mooring BW, Roth ZS, Driels MR. Fundamentals of manipulator calibration: Wiley New York; 1991.
4. Chen-Gang C, Tong L, Ming C, Qing J, Xu S. Review on Kinematics Calibration Technology of Serial Robots, Int. Journal of Precision Engineering and Manufacturing. 2014;15(8):1759-74.
5. Nubiola A, Bonev IA. Absolute calibration of an ABB IRB 1600 robot using a laser tracker. Robotics and Computer-Integrated Manufacturing. 2013;29(1):236-45. doi: 10.1016/j.rcim.2012.06.004.
6. Wu Y, Klimchik A, Caro S, Furet B, Pashkevich A. Geometric calibration of industrial robots using enhanced partial pose measurements and design of experiments. Robotics and Computer-Integrated Manufacturing. 2015;35:151-68. doi: 10.1016/j.rcim.2015.03.007.
7. Johnsrud V. Improvement of the Positioning Accuracy of Industrial Robots [Masters]. Trondheim: Norwegian University of Science and Technology; 2014.
8. Roth Z, Mooring B, Ravani B. An overview of robot calibration. IEEE Journal on Robotics and Automation. 1987;3(5):377-85. doi: 10.1109/jra.1987.1087124.