Adaptation of the geometric model of a 6 dof serial robot to the task space

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Abstract. This work presents the results concerning the modeling and sensitivity analysis of the serial ABB IRB 6660 robot in a dedicated workspace. In this sense, this study is a first step to define a geometrical modeling method. The proposed method is based on the introduction of one parameter for each defect which affects the orientation and position of each robot joint and end-effector. Then, the parameters selection is realized with a sensitivity analysis with regard to the workspace and needed accuracy. This work is illustrated on an ABB IRB 6660 robot. The final aim of this approach is to improve the accuracy of a robot during the following of a tool path in a given workspace.

Key words: Sensitivity analysis, Direct kinematic analysis, Serial robot, geometric modeling.

1 Introduction

The use of serial robots for machining operations has become a robot development issue in recent years. The aim is to propose an alternative to machine tools. Thus, 6-axis heavy-duty robots are offered by robot manufacturers and designers. However, developed robots have toolpath following accuracy only near 0.1 mm, although their stiffness has been improved compared to robots used for less demanding operations. Indeed, the geometrical, static and dynamic behaviors of these robots do not allow machining to be performed with great accuracy and, finally, only 3% to 4% of industrial robots are dedicated to machining [1, 2].

The geometric model is the mathematical description of the geometrical behavior of the robot. This model expresses the pose of the center of the tool in the robot coordinate system with regard to the pose of the active joints [3]. The geometric models of robots are generally based on a set of mathematical equations allowing computing the pose of the final end-effector with regard to the values of the articular variables and geometric parameters. The most widely used modeling methods are generally based on the Denavit-Hartenberg (DH) formalism [4]. This formalism is enriched by various scientific works in order to be more adapted to the studied structure behavior [5]. However, the complexity of the models developed does not guarantee the improvement of robot geometric accuracy. Indeed, the addition of geometric parameters makes the model more sensitive to identification errors [6]. It is necessary to limit the number of geometric parameters to influential and identifiable parameters.

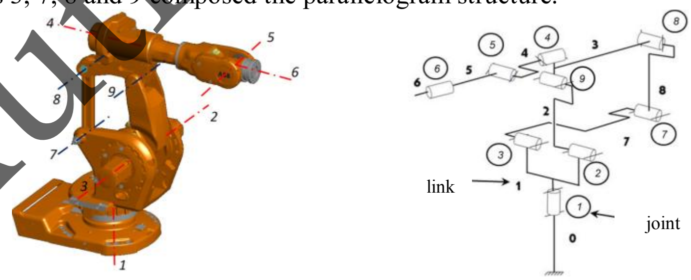
Similarly, in order to improve the accuracy of task realisation, it is necessary to study the influence of each geometrical parameter on the task and to identify its parameters under the conditions of realization of the task [6]. The objective is not to guarantee absolute accuracy of the robot throughout its working space but to focus on the task accuracy. In other words, it is necessary to focus only on the end-effector poses which have an influence on the accuracy of task realization in the task workspace. In the case of machining, the accuracy of the machined part is linked to the robot accuracy during the toolpath following in the part coordinate system.

We propose in this work to make a contribution on the definition of the number and the nature of the geometric parameters of a serial robot equipped with a spindle with regard to the needed workspace.

First, we introduce the ABB IRB 6660 robot and its characteristics. Then, methods for geometric modeling are presented. Finally, we perform the sensitivity analysis to select the most influential parameters and proposed a geometrical model adapted to a given workspace.

2 Presentation of the ABB IRB 6660 robot

The robot IRB 6660 is composed of a serial structure with a parallelogram structure to improve the overall rigidity of the robot [7, 8]. The robot is composed of six motorized joints (from 1 to 6) and three passive joints (7, 8 and 9) (Figure 1). Axes 3, 7, 8 and 9 composed the parallelogram structure.



(a) (b)

Fig. 1 (a) Joints of the ABB IRB 6660 robot. (b) Kinematic diagram of the robot.

This robot is a 6 dof serial robot with a simple closed kinematic chain. It is thus considered by Khalil as a complex robot [5] because it has at least one solid positioned by more than two joints.

The robot studied is also equipped with a spindle fixed at the last joint in order to carry out pre-machining operations. This spindle is a spindle MFW-1412 from Precise France Fisher.

A first analysis of the architecture of the robot is realised in order to determine the overconstrained degree of the mechanism [9]. The aim is to determine the dimensional and geometrics constraints which ensure to guarantee good working condition of the system [10].

According to this study, the robot IRB 6660 has an overconstrained degree of 3 [9]. This oversontrained degree is due to the parallelogram mechanism behavior. Indeed, the mechanism is in parallelogram the axes of joint 3, 7, 8, and 9 have to be parallel to transmit the movement from joint 3 to joint 9.

This mechanical constraint must be taken into account during the definition of the geometric parameters used in the geometric model of the robot. Thus, we consider that the orientation defect between the joints 3, 7, 8 , and 9 are not taken into account in the geometrical model of the robot as their parallelism is controlled by the manufacturing and assembly constraints and we also considered joint 2 is independent of joint 3, 7, 8 and 9.

This first analysis of the structure of the robot ensure us to realize geometric models closer to the mechanical behavior of the architecture of the robot.

3 Direct kinematic model analysis

The initial realized model is a 6-parametric model defined from DH method for serial robot (Figure 2). This model does not take into account the transformation of motion generated by the parallelogram mechanism and it is composed with the minimal number of parameters. The coordinate system linked to each active joint is defined and noted $R_i(\mathbf{X}_i, \mathbf{Y}_i, \mathbf{Z}_i)$ except for joint 9 which is $R_3(\mathbf{X}_3, \mathbf{Y}_3, \mathbf{Z}_3)$. The DH parameters are then : R_{L1}, d_2, d_3, d_4, R_{L4}, R_{L6}.

However, this model has to be completed by taking into account the parallelogram mechanism behavior in the movement transmission between joint 3 to joint 9.

Figure 2 presented the parameters used to described the geometrical behavior of the parallelogram mechanism.

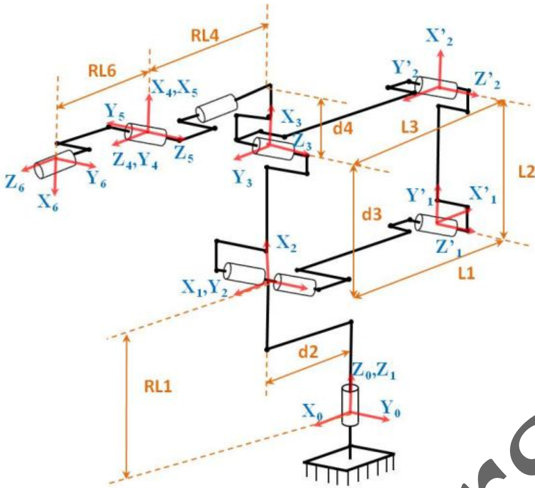
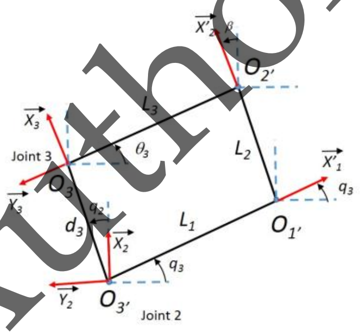


Fig. 2 Geometrical model of the robot.

The articular variable q_3 is located at the articulation 3, the relation between q_3, the geometrical parameters of the parallelogram and the angle θ_3 of the articulation 9 must then be determined.

Figure 33 illustrates the modeling of the parallelogram mechanism and the relationship between the values of the articular variables q_2, q_3, θ_3 and the introduced geometrical parameters (L_1, L_2, L_3) of the parallelogram. We assume from the overconstrained analysis that the system is plane and that all the axes of the bonds are parallel. Thus, the modelling hypothesis are consistent with the hypotheses of the Denavit-Hartenberg method.



$$\theta_3 = 2\tan^{-1}\left(\frac{2B \pm \sqrt{4B^2 + 4A^2 - 4C^2}}{2(A+C)}\right)$$

$$\text{With} \begin{cases} A = -L_1\cos(q_3) - d_3\sin(q_2) \\ B = -L_1\sin(q_3) - d_3\cos(q_2) \\ C = \dfrac{L_2{}^2 - A^2 - L_3{}^2 - B^2}{2L_3} \end{cases}$$

Fig. 3 Parameter relations of the parallelogram.

This model is thus completed to express geometric models taking into account each defect between non-overconstrained joints and the spindle coordinate system. Thus, 6 parameters are taken into account to express the position and orientation of ith joint coordinate system with regard to (i-1)th joint coordinate system:

$$ {}^{0}\mathbf{T}_6 = {}^{0}\mathbf{T}_1\ {}^{1}\mathbf{T}_2\ {}^{2}\mathbf{T}_3\ {}^{3}\mathbf{T}_4\ {}^{4}\mathbf{T}_5\ {}^{5}\mathbf{T}_6 \tag{1} $$

$$ {}^{0}\mathbf{T}_1 = \begin{bmatrix} \cos(q_1) & -\sin(q_1) & 0 & 0 \\ \sin(q_1) & \cos(q_1) & 0 & 0 \\ 0 & 0 & 1 & RL_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{1}\mathbf{T}_2 = \begin{bmatrix} \cos\left(q_2 - \pi/2\right) & -\sin\left(q_2 - \pi/2\right) & 0 & d_2 \\ 0 & 0 & 1 & 0 \\ -\sin\left(q_2 - \pi/2\right) & -\cos\left(q_2 - \pi/2\right) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{2}\mathbf{T}_3 = \begin{bmatrix} \cos(\theta_3 - q_2) & -\sin(\theta_3 - q_2) & 0 & d_3 \\ \sin(\theta_3 - q_2) & \cos(\theta_3 - q_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{3}\mathbf{T}_4 = \begin{bmatrix} \cos(q_4) & -\sin(q_4) & 0 & d_4 \\ 0 & 0 & 1 & RL_4 \\ -\sin(q_4) & -\cos(q_4) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{4}\mathbf{T}_5 = \begin{bmatrix} \cos(q_5) & -\sin(q_5) & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin(q_5) & -\cos(q_5) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{5}\mathbf{T}_6 = \begin{bmatrix} \cos(q_6 + \pi) & -\sin(q_6 + \pi) & 0 & 0 \\ 0 & 0 & 1 & RL_6 \\ -\sin(q_6 + \pi) & -\cos(q_6 + \pi) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Where ${}^{j-1}\mathbf{T}_j$ is the homogeneus transformation matrix to i articulation to j articulation. Then, 3 paramters are added to define the position and orientation of the spindle coordinate system with regard to the 6th joint coordinate system (x_{ef}, y_{ef} and z_{ef}) J_{tool} is the length of the tool used:

$$ {}^{6}\mathbf{T}_{spindle} = \begin{bmatrix} 0 & 0 & 1 & x_{ef} = x_{spindle} + J_{tool} \\ 0 & 1 & 0 & y_{ef} = y_{spindle} \\ -1 & 0 & 0 & z_{ef} = z_{spindle} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

A model with 45 parameters are then considered by taking into account errors of position and orientation of the coordinate systems of each non-overconctrained joints and the parallelogram mechanism parameters, these 45 parameters takes into account the position and orientation errors of each pivot link (6x6 parameters), the position and orientation errors of the final effector (6 parameters) and the 3 parameters of the parallelogram. These parameters are nomed t_ix, t_iy and t_iz for traslations errors on the x, y and z axe respectively of the i link; tit_i, psi_i and alf_i for angulars errors on the x, y and z axe respectively of the i link i; t_bx, t_by and t_bz for traslations errors on spindle and tit_b, psi_b and alf_b for angulars errors on spindle.

4 Sensitivity analysis

The sensitivity analysis will enable us to evaluate the influence of the geometric parameters on the position of the end effector of the robot. It will also allow us to discuss the number of optimum parameters to introduce. In the case of our study, we carry out the sensitivity analysis on the most complete model, the geometric model with 45 parameters. The MGD is represented by:

$$ \mathbf{X} = MGD(\mathbf{Q}, \xi) \tag{3} $$

Where $\mathbf{X}$ is the pose vector which corresponds to the coordinates of the piloted point of the robot end-effector and its orientataion in the robot base coordinate system and ξ the 45 parameters.

Q is the vector of the articular variables of the robot (q_1, q_2, q_3, q_4, q_5 and q_6).

In our case, we study the influence of the geometric parameters on the position of the tool for given values of the motor set points. Thus, if we consider the articular instruction to be perfectly repeatable, the sensitivity matrix **S** is then:

$$\mathbf{S} = \frac{d\mathbf{X}}{d\xi} = \frac{\partial MGD(\mathbf{Q},\xi)}{\partial \xi} \tag{4}$$

The matrix of sensitivity is a matrix of 3*45 elements where the term $\mathbf{S}_{ij}$ represents the influence of the parameter i on the coordinate j of the tool position.

In this first part we will carry out the sensitivity analysis on a given workspace which is used to realize the identification (Figure 4). After an analysis of the sensitivity matrix transformed with the Gaussian pivot method, we observe that the parameters *t2z*, *t3z*, *t4z*, *t5z*, *t6z*, *tbx*, *tby*, *tbz* and *psi5* are redundant parameters and we can establish relations between these parameters and the model parameters (Associated parameters). The maximum influence in this space is shown in Figure 5.

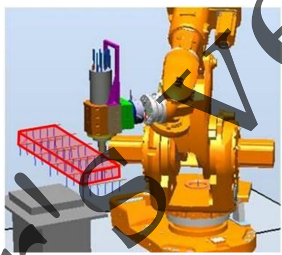
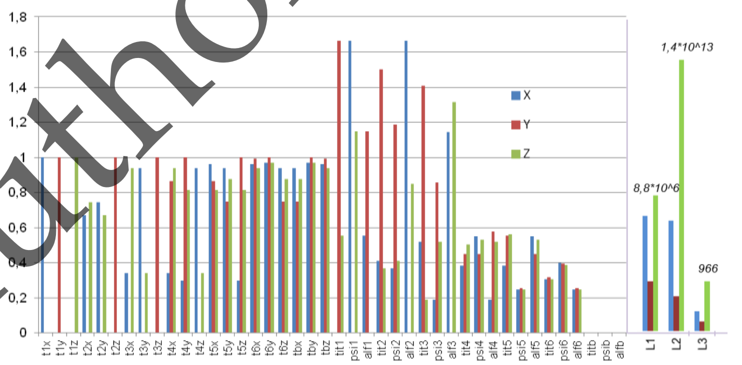


Fig. 4 Workspace used to the identification.



Redundant Parameters	*t2z*	*t3z*	*t4z*	*t5z*	*t6z*	*tbx*	*tby*	*tbz*	*alf6*
Associated Parameters	*t1y*	*t1y*	*t3y*	*t4y*	*t5y*	*t5y*	*t6y*	*t6x*	*psi5*

Fig. 5 Maximum influence of parameters in the X, Y and Z axis for 60 points and the redundant parameters and associated parameters.

On the basis of these results, we propose a new model without the redundant and zero parameters, that is to say without the parameters *t2z*, *t3z*, *t4z*, *t5z*, *t6z*, *tbx*, *tby*, *tbz*, *alf6*, *titb*, *psib* and *alfb*. The new model contains 33 parameters.

5 Identification of geometric parameters

To see, the impact of this model adapted to the workspace, a process of identification is realized. The identification phase of the robot consists of determining the values of the geometrical parameters related to the structure of the robot and the spindle.

For the identification of the 33 parameters model, the identification of the proposed model is carried out with 60 positions measured with a Laser Tracker measurement system, Leica ATD-901 with accurate performance measurement of the position of the test pattern of ±15µm+6µm/m and compared with the positions simulated with the direct kinematic model (figure 6). Thus, by minimizing the cost function with Matlab's *lsqnonlin* function, we obtain the identified geometric parameters of the model.

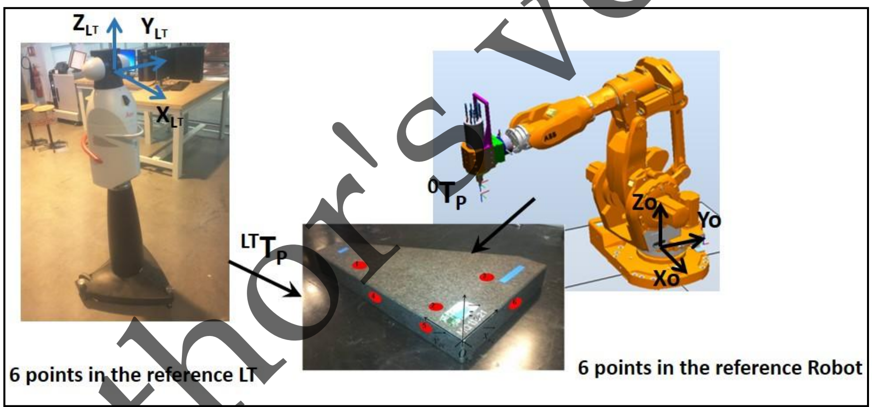


Fig. 6 Reconfiguration of reference system.

After the measurement of 60 points the maximum residual error values are: 0.09566 mm on the X-axis, 0.1222 mm on the Y-axis and 0.09191 mm on the Z-axis, with a maximum spatial position error of 0.1803 mm for the model with 33 parameters sans compensation de la gravité.

6 Conclusions

The goal of this study is to analyze the influence of the geometrical parameters use to define the ABB IRB 6660. A new approach for the identification of the influential geometric parameters of a serial robot is developed. Despite the sensitivity study and the reduction of the model of 45 parameter to 33 parameters the error of position remains always important. Indeed, taking into account parameters of a different nature in the parameter model can explain this deviation as well as the fixed orientation of the tool in the space under consideration. However, the proposed modeling method can be applied to different working spaces in position and orientation.

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