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SCREW KINEMATIC MODEL FOR ROBOT CALIBRATION WITH PC-ROBOT COMMUNICATION OVERVIEW

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Abstract. *This paper presents an alternative way to represent a serial robot kinematic model with screw theory and its calibration, considering joint and link offsets. To calibrate an industrial robot a set of procedures is proposed: performance evaluation before and after calibration, model definition, kinematic parameter estimation, and correction. Moreover, a pc-robot communication is implemented to reduce robot path programming and measurements time-consuming.*

Keywords: *robot calibration, screw theory, robot communication*

1. INTRODUCTION

Robot calibration consists in estimate kinematic model parameter to reduce pose deviances caused by joint and link errors (Zhuang, 1993), for example. This process can be divided into four steps: Modeling, measurement, estimation, and correction (Mooring et al., 1991; Ginani and Motta, 2011; Nguyen et al., 2013) and (Nubiola and Bonev, 2013). The first step can be made over Denavit-Hartenberg (DH) method, screw theory (Tsai, 1999), product of exponentials (He *et al,* 2015) or quaternions (Wang, 215). This work is focused on the second method comparing its advantages over DH.

After the kinematic model is defined, the measurement process has to be chosen. A contact or non-contact measurement machine is used to get the TCP pose with high accuracy. The most common contact equipment is the coordinate measuring machine with Cartesian or anthropomorphic (measuring arm) configuration. The non-contact ones have many varieties, like laser tracker, laser scanner, cameras and indoor positioning systems (Veischegger, 1988; Pinto, 2001). In this work, a measuring arm system is chosen, because of its availability on the laboratory.

The next step is defining an optimization method to estimate kinematic parameters that minimize the TCP pose error when the model is corrected. In general, industrial robots don't have its controller system available to change kinematics parameters, but it has a procedure to reset encoder readings moving all joints and aligning its marks visually. Consequently, the robot accuracy is impaired. So the kinematic model is formed considering this manual and visually procedure.

After the estimation, the robot is moved to its initial position, called *home position*, and each joint is moved considering these estimations. Before and after the calibration, a performance evaluation should be made according to (ISO 9283, 1998). Considering the time consuming on measurements, an automated process is important to be applied, so TCP/IP protocol is used to communicate the robot controller to the interface implemented on PC. The next section explains why the kinematic model was chosen based on advantages of screw theory and the overall calibration.

2. SCREW THEORY APROACH FOR ROBOT CALIBRATION

Despite the method used to set the joints encoder readings to zero in an industrial robot, a kinematic model is formed considering joint and link offsets, since they are the main sources of robot inaccuracy (Judd and Knasinski, 1990; Ginani and Motta, 2011). The next subsection explains an advantage of screw theory over DH.

2.1 Parameter issues on calibration

The kinematic model of serial robots is commonly formulated by DH convention (Erthal, 1992; Santolaria et al., 2009; Sciavicco, 2012) and (Souza, 2014), but the screw based model has some advantages over DH convention in terms of calibration. This method consists in defining links coordinate systems with a minimum number of parameters, which are four. Two are linear and the others, angular. When consecutive joints axis are aligned their coordinate systems coincides with the joint center position.

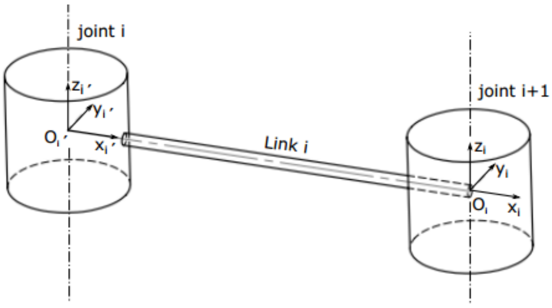


Figure 1. Aligned joints with its coordinate systems

In a real mechanism, despite gear clearances, assembly and fabrication errors, consecutive joints on the configuration of Figure 1 go to near parallel configuration. According to DH method, one of the coordinates systems goes to distant pose divergence comparing Figure 1 with Figure 2. The two angular parameters are related to a rotation around "joint i" axis (θ) and another one around x_i' axis, between joints i and i+1.

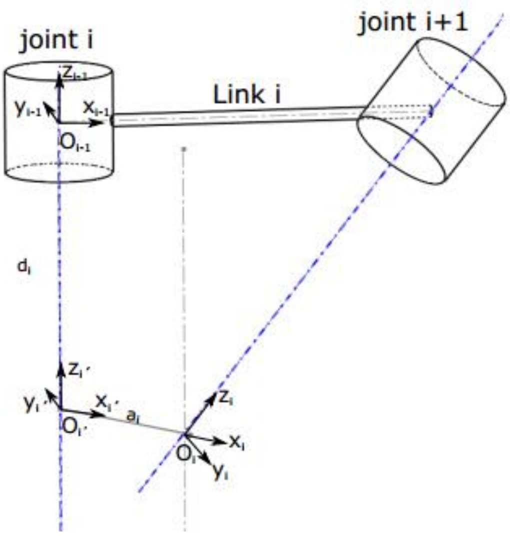


Figure 2. Misaligned joints

The problem emerges when the link frame presents its pose with more rotations components, i.e. to faithfully represent all coordinates movements, it is necessary more than four parameters to describe a motion. If a calibration procedure is made using this four parameter model (Siciliano *et al*, 2010), and a considerable error is presented in a rotation of O_i on the y axis of $O_{i'}$, which has not its correspondent parameter, the correction on robot parameters will be insufficient to reduce the robot pose deviance. To overcome this problem, the screw model can be used (Davidson and Hunt, 2004), because it represents a motion in all tridimensional space, with three rotations and three translations in a single vector, as described in Eq. (1).

$$\$ = \begin{bmatrix} s \\ s_0 \times s + h \cdot s \end{bmatrix} = \begin{bmatrix} \omega \\ v \end{bmatrix} \quad (1)$$

The vector S is the joint axis direction; S_0 is the position vector of any point of joint axis related to a base frame. Commonly, this position is defined in the joint center. The scalar h is the screw step, associating both velocities. When a revolute joint is considered, this value is set to zero. In this case, the screw has the two velocities: linear (v) and angular (ω).

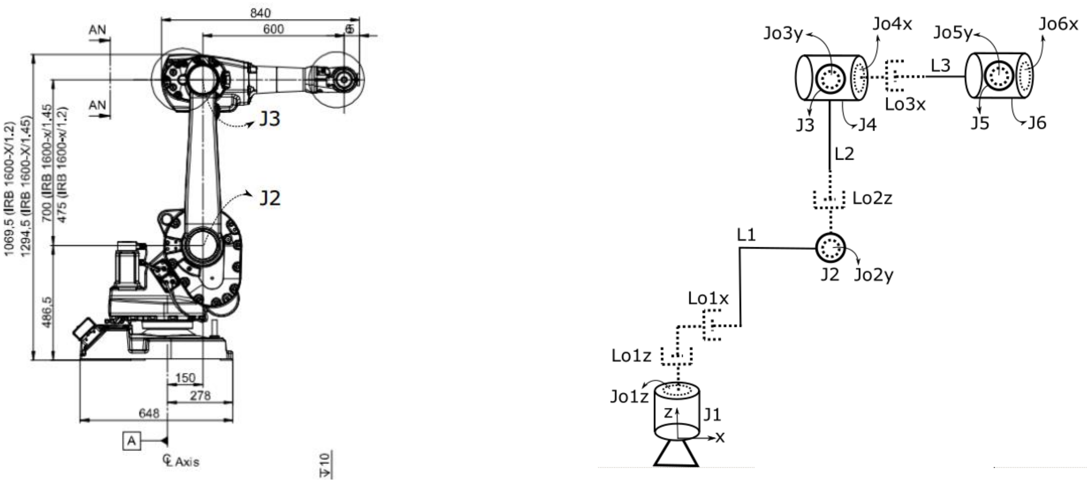
The cross product between S_0 and S is the tangential velocity on a circle, which center is located on the reference frame. If the screw belongs to a prismatic joint the step value is set to infinity, so the cross product is irrelevant because there is no angular velocity.

Also, in terms of poses, a screw can represent a rigid body motion by a homogenous matrix like in DH. This process is known by Rodrigues formula (Tsai, 1999). Each joint has its homogenous matrix and to find the robot tool center point (TCP) related to its base frame, the Successive Screw method is implemented (Tsai, 1999).

Others advantages of screw method are that the base frame can be located arbitrarily and the Jacobian is formed by normalized screws directly after the Rodrigues parameters identification (Rocha, 2010).

2.2 Kinematic model on an industrial robot

The robot model used to the calibration is in Figure 3(b), which is based on the nominal model in Figure 3(a). The joints and links nomenclatures are *L* (link), *J* (joint), *o* (offset), 1 to 6 (joint or link number) and x, y, z (joint or link direction). Each joint or link offset is added to the nominal model as virtual joints. On each robot configuration, the nominal joint variables are defined and the error sources are distributed in these virtual joints that have to be estimated. At this step, the kinematic model must be defined to be incorporated in the objective function (OF) of the next section. The model relates virtual joints parameters (θ or t), for revolute or prismatic joint, respectively.



(a) Nominal robot – ABB1600 (b) Model with joint and link offsets

Figure 3. Robot Models

The model is based on Rodrigues Formulas for screw movements, their parameters are shown in Table 1.

Table 1. Rodrigues parameters for the serial robot ABB 1600 considering virtual joints

Joint/link	s	s0	θ	t
J1	[0 0 1]	[0 0 0]	θ1	0
Jo1z	[0 0 1]	[0 0 0]	θ*o*1	0
Lo1z	[0 0 0]	[0 0 0]	0	*to*1*z*
Lo1x	[0 0 0]	[0 0 0]	0	*to*1*x*
J2	[0 1 0]	[150 0 486.5]	θ2	0
Jo2y	[0 1 0]	[150 0 486.5]	θ*o*2	0

Lo2z	[0 0 0]	[150 0 486.5]	0	*to*2*z*
J3	[0 1 0]	[150 0 961.5]	θ3	0
Jo3y	[0 1 0]	[150 0 961.5]	θ*o*3	0
J4	[1 0 0]	[150 0 961.5]	θ4	0
Jo4x	[1 0 0]	[150 0 961.5]	θ*o*4	0
Lo3x	[0 0 0]	[150 0 961.5]	0	*to*3*x*
J5	[0 1 0]	[750 0 961.5]	θ5	0
Jo5y	[0 1 0]	[750 0 961.5]	θ*o*5	0
J6	[1 0 0]	[750 0 961.5]	θ6	0
Jo6x	[1 0 0]	[750 0 961.5]	θ*o*6	0

Once all parameters are specified, the transformation matrix can be formed and the successive screw method can be applied. Also, this model has 16 variables, 6 (nominal joints) of them are known and 10 must be estimated. As the system of equations created cannot be solved because of the unknown virtual parameter, in terms of forward kinematics, it is possible to solve with the inverse kinematics.

2.3 Objective function and optimization techinique

The inverse kinematic has its input variables the robot task space, or TCP pose values, and the output, the joint space, or rotation angles of each joint. The difference between a simple inverse kinematic and a calibration is the number of poses calculated simultaneously and its error in position and orientation, once the desired virtual joints variables must reduce the TCP pose for many robot configurations (Beyer and Wulfsberg, 2004; Siciliano *et al*, 2010).

Since the kinematic model is defined and the error poses measured with an accuracy system, the OF must be defined to use a linear or non-linear optimization technique. For this problem, the Newton method for n-variable OF is applied. When position and orientation are considered a magnitude problem emerges between these components because the length error (mm) has magnitudes of hundred times bigger than orientation errors (radians). So a weight value α is applied to these components and it is defined over calibration simulation results.

The objective function is formed in terms of the position and orientation error, where E_p on Eq (2) stands for position error of N measurements, NE_p on Eq. (3), the norm of each position, and Eq.(4), the maximum norm value. The similar way is made for orientation error E_o, which is described in Row, Pitch and Yaw angles.

$$E_p = \begin{bmatrix} e_{px1} & \dots & e_{pxN} \\ e_{py1} & \dots & e_{pyN} \\ e_{pz1} & \dots & e_{pzN} \end{bmatrix} \tag{2}$$

$$NE_p = \left[\|E_{p1}\| \quad \dots \quad \|E_{pN}\| \right] \tag{3}$$

$$ME_p = \max\left[NE_{p1} \quad \dots \quad NE_{pN} \right] \tag{4}$$

$$OF: \quad Min \quad \alpha\left[\sum_{i=1}^{N} \frac{NE_{pi}}{ME_p}\right] + (1-\alpha)\left[\sum_{i=1}^{N} \frac{NE_{oi}}{ME_o}\right] \tag{5}$$

To identify the α value the measuring data was simulated with forward kinematics. The joint and link offset was used according to recently researches (Gao *et al*, 2014 and Kamali *et al*, 2016) on the same robot model (ABB 1600). The joint space values used to simulate robot poses are composed of three components: nominal value, systematic and random error. The second element represents the encoder error readings in its zero position and the third one represents joint clearances, which vary according to robot pose. For the links, only the nominal and a systematic error are considered because link deflection is disregarded.

The robot poses quantity simulated is chosen according to Klimchik *et al* (2014), who analyses a similar anthropomorphic robot and evaluates the minimum number (40) of calibration experiments to achieve desired parameter identification accuracy, for example, the joint offset of 0.01°.

With these simulated poses, the estimation procedure can be made varying the weight values of the O.F. and the results are shown in Table 2.

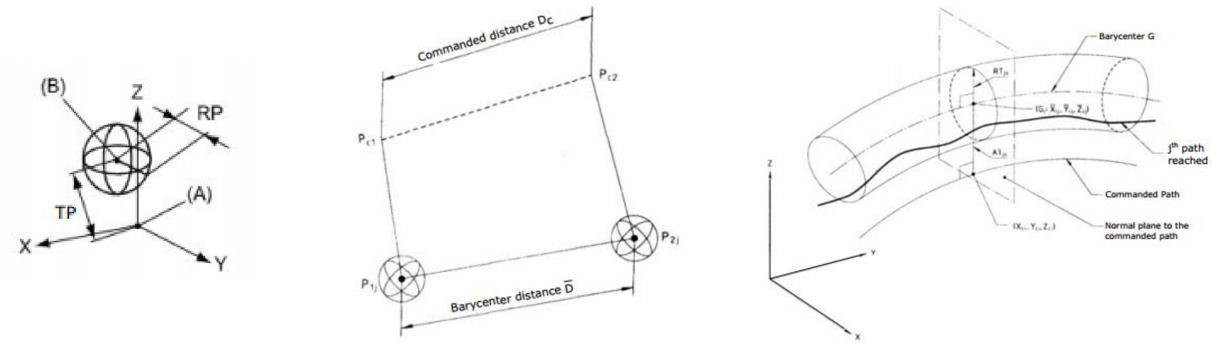
Table 2. Selection of weight value of Objective function

			Orientation error [°]				
		Euclidean Distance Error (EDE) [mm]	R_x(Yaw)	R_y(Pitch)	R_z(Row)	Orientation Error Norm (OEN)	EDE + OEN
α	0	0.771	0.032	0.036	0.022	0.053	0.824
	0.25	0.682	0.028	0.035	0.028	0.053	0.735
	0.5	1.016	0.028	0.037	0.030	0.056	1.072
	0.75	1.686	0.043	0.055	0.048	0.085	1.771
	1	2.996	1.342	0.352	0.615	1.518	4.514

The Euclidean distance error is calculated in terms of TCP position in the robot base frame. Since the position and orientation errors are normalized, the maximum value admitted among distances and orientations is one, so the magnitudes dimension divergences are reduced. According to the Euclidean distance and orientation error norm, the best value of α is 0.25.

2.4 Performance evaluation

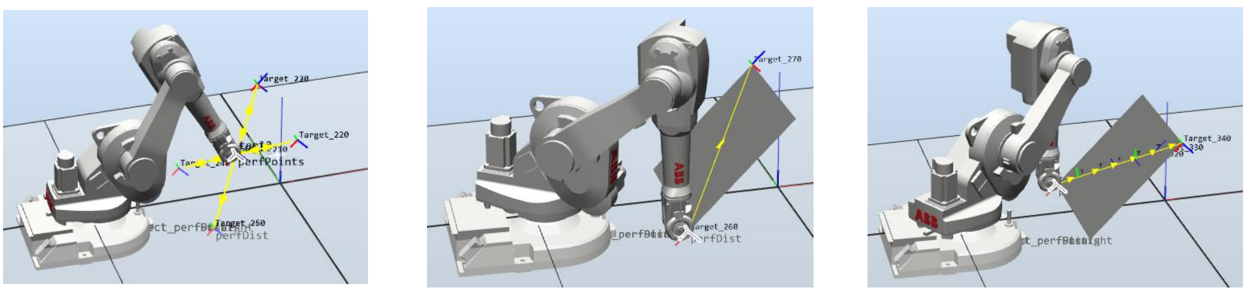
The ISO 9283 (1998) norm establishes methods to evaluate the robot performance criteria, like pose accuracy and repeatability, which can be made in terms of TCP poses, distances and paths shown in Figure 4.



(a) Pose (b) Distance (c) Path

Figure 4. Performance criteria

The pose accuracy, according to this norm, is measured on an oblique plane with dimensions that permits robot achievements far from its singularity regions. These positions are programmed with RobotStudio® (Figure 5) and they are commanded over Matlab® program.



(a) Path for pose accuracy (b) Path for distance accuracy (c) Path for straightness accuracy

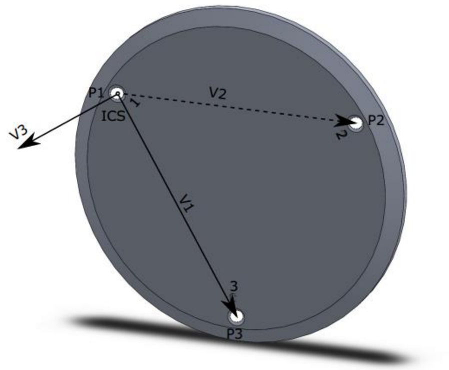
Figure 5. Robot paths for performance evaluation

Both distance and pose accuracy must be measured under positions achieved with the same movement direction as the previous measurement. Also, each pose is measured five times to reduce the measure equipment uncertainties.

2.5 Measurement system

For the performance evaluation or calibration procedure, the TCP pose must be acquired by an accurate measuring system. The system chosen to get these poses is the FaroArm® with accuracy up to 0.02mm (Faro, 2009). As the equipment gets only positions from the center of its spherical probe, a flange with three cavities is made in order to define an intermediate coordinate system. This tool is shown in Figure 6.

(a) Data acquisition on flange



(b) Intermediate Coordinate System

Figure 6. Flange for measurements

The intermediate coordinate system (ICS) is on point P1 (Figure 7b) and it is defined according to Gram-Schmidt orthogonalization with vector V1, V2 and V3. V1 forms X axis, V3, Z axis and Y is formed by the cross product of V3 and V2 in order to have accordance to the right-hand rule.

As the pose used to form the objective function is based on the robot end effector, this information must be found by matrix transformations considering the ICS. On Eq. (6) and (7) show how the robot pose is identified based on the measurements.

$$T_B^F = T_B^{EF} T_{EF}^F \quad (6)$$

$$T_B^{EF} = T_B^F \left(T_{EF}^F\right)^{-1} \quad (7)$$

Where, B is the base coordinate system (CS), EF, the end effector CS, F, the ICS and T, the transformation matrix.

3. PC – ROBOT COMMUNICATION

To minimize time consuming on measurements on calibration and performance evaluation, a communication between the robot controller and the Matlab program is implemented over TCP/IP protocol. The controller has all programed poses for calibration and performance evaluation. On the other side, the matlab has the human machine interface (HMI), presented on Figure 7 that send messages to the controller informing what the operator wants to do and it calculates the joint offset estimation with the measurement data.

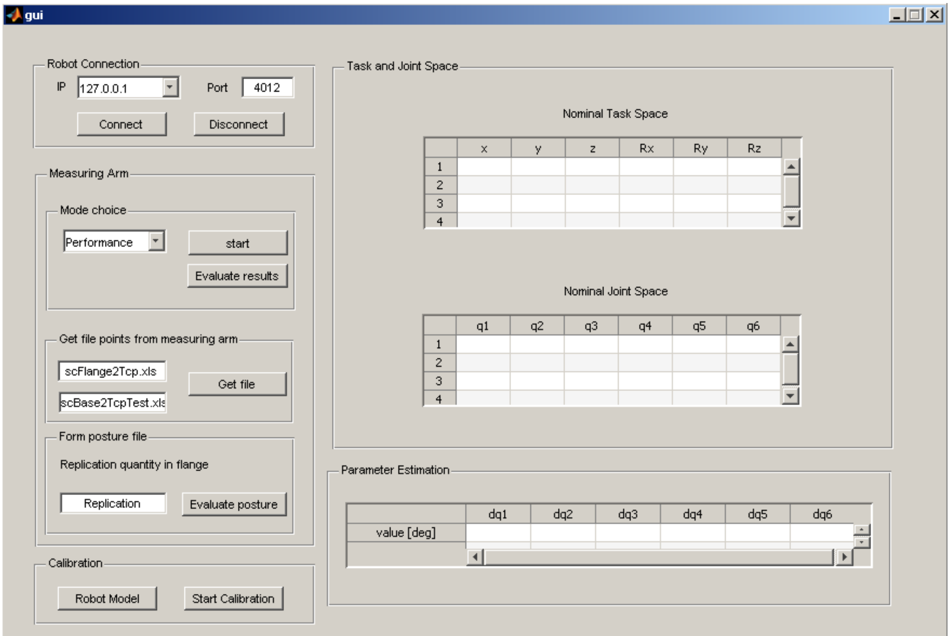


Figure 7. HMI for pc-robot communication

The interface has 6 modules: Communication (Robot Connection), selection of poses to calibrate or evaluate the performance (Mode choice), process data from measuring machine (Form posture file), nominal joint and task space given by the controller (Task and Joint Space), robot kinematic model and start the parameter estimation (Calibration), and finally, the joint space estimation result (Parameter Estimation).

The ABB controller (IRC5) uses the RAPID programming language, which is structured into modules. So it is easy to organize the robot targets, path, variables and other functions. The program structure is depicted on Figure 8.

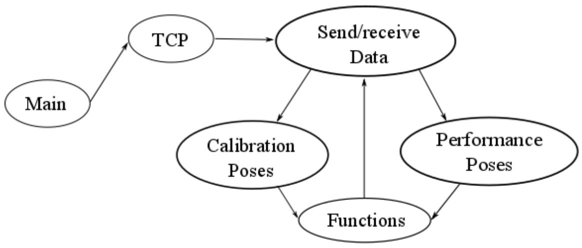


Figure 8. RAPID modules for calibration and performance evaluation

All TCP poses defined for calibration and performance are programmed on RobotStudio and saved on robot controller. The data are encapsulated into datagrams to permit the Matlab application identify if the information sent by controller. On Table 3 shows how the datagram is defined.

Table 3. Datagram for communication

Id	Pose data	Control
p	$[x, y, z, R_x, R_y, R_z]$	{0, 1, 2, 3}
j	$[\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]$	

There are three data fields on the datagram: Id, pose data and control. The first one, shows if the required data is on joint or task space, the second, the pose or joint data, and the last one, the control number, which informs the Matlab if the data sent is the first robot configuration {1}, intermediate {0}, last {2} or end of robot movements {3}.

4. CONCLUSION

The kinematic model presented on this work shows advantages over the conventional DH method, since it is possible to identify kinematic parameters related to any kind of body rotations, on the other hand, the model becomes a non-minimal model, with more parameters than DH. After the robot model definition, an objective function was defined in terms of pose error including position and orientation. This function has a weight value specified according to the influence of angular or distance errors and is defined over simulation.

For the measurements, a tool flange was designed to get the measurement system data with its spherical probe. Also to make these data acquisition with less time consuming, a robot controller-pc communication was implemented over Rapid and Matlab programs.

The next step for this work applies these procedures on an industrial robot (ABB 1600) with performance evaluation and correcting its zero encoder readings over estimation parameter results.

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