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GLOBAL KINEMATIC RELIABILITY INDEX OF ROBOTIC MANIPULATORS

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Abstract.*This paper proposes a performance criterion to evaluate the kinematic accuracy of robotic manipulators based on reliability concepts. The proposed performance index applies kinematic reliability concepts to analyze how the kinematic error of the joint clearances affects the kinematic accuracy of the end-effector over a required workspace. The proposed global kinematic reliability criterion is applied to analyze the serial 3R serial manipulator with joint clearances.*

Keywords: *kinematics, robotics, reliability, performance index.*

1. INTRODUCTION

The design indices or design criteria are estimations of mechanical properties to quantify the performance of robotic manipulators. The kinematic criteria quantify the kinematic behavior considering the kinestatics performance and they are based on the Jacobian matrix (Lipkin and Duffy, 1988). In addition, the workspace and singularities are widely used as performance indices in the design procedure of manipulators (Wang *et al.*, 2010). The design criteria can be local criteria and global criteria; local criteria evaluate the performance at a fixed pose of end-effector; moreover, global criteria evaluate the performance over the workspace of the manipulator. These design criteria are widely used to carry out the optimal design of manipulators (Gosselin and Angeles, 1991; Liu *et al.*, 2006; Lara-Molina *et al.*, 2018b).

On the other hand, the robotic manipulators are subjected to uncertainties produced by manufacturing and assembly errors of the links, positioning errors of the actuators, and clearances of joints. Several methods have been proposed to deal with the effects of uncertainty in the geometric parameters. Therefore, the calibration reduces the consequences of manufacturing and assembly errors of the links. However, the calibration methods can not compensate for the errors produced by the joint clearances (Zhuang, 1997). Thus, the joint clearances are the most important source of error that affects the accuracy and repeatability (Chebbi *et al.*, 2009). The uncertainties have been considered in the clearances to analyze the kinematic accuracy of manipulators (Lara-Molina *et al.*, 2018a). Moreover, advanced motion control techniques have been applied to minimize the positioning errors of the actuators (Cetin *et al.*, 2019; Costa *et al.*, 2018).

The kinematic reliability of manipulators determines the probability of obtaining positioning errors within acceptable limits. The kinematic reliability has recently emerged as alternative criteria to evaluate the effects of uncertainties in manipulators (Xu, 2018). Kim et al (2010) evaluate the kinematic reliability of manipulators using the advanced first-order second-moment (AFOSM) method. Pandey and Zhang (2012) used the fractional moments to efficiently compute the kinematic reliability such that the positioning error remains within acceptable limits. Cui et al. (2015) computed the kinematic reliability using the Monte Carlo simulation method and they evaluated three error sensitivity criteria based on the singular value decomposition of the error translation matrix. The research works mentioned above evaluated the reliability as a local property, i.e. the kinematic reliability was assessed at a specific pose of the manipulator. However, it is necessary to compute the kinematic reliability as a global criterion.

This paper is organized into four sections. Initially, the axisymmetric model of joint clearances with uncertainties and the error propagation method is presented. Then, the global kinematic reliability criterion is defined. Afterward, the proposed global kinematic criterion is applied to the serial 3R spatial manipulator through numerical simulations. Finally, the conclusion and further work are presented.

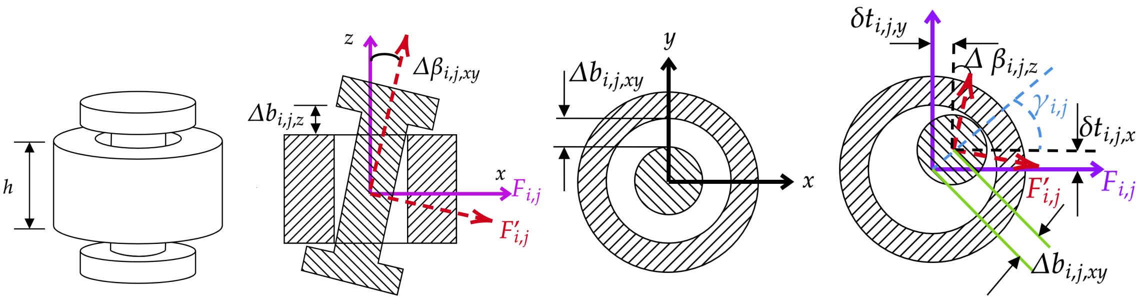
2. CLEARANCES AND ERROR PROPAGATION

2.1 Joint Clearance Model

The axisymmetric model of the joint clearance is inspired by the model shown by Meng et al. (2009) and Binaud et al. (2010). Clearances introduce additional and uncontrollable degrees of freedom within the joints according to the axisymmetric joint clearance model that considers the joint axis along the z-axis (see Fig. 1). These additional degrees of freedom can be either rotational and translational; consequently, the pose error at the local frame $F_{i,j}$ of the joint can be modeled using the error screw $\delta\mathbf{e}_{i,j}$, thus:

$$\delta\mathbf{e}_{i,j} = \begin{bmatrix}\delta\mathbf{r}_{i,j} & \delta\mathbf{t}_{i,j}\end{bmatrix}^T \tag{1}$$

where i is the index of the kinematic chain, and j is the index of the joint in the respective i^{th} kinematic chain, $\delta\mathbf{r}_{i,j} = \begin{bmatrix}\delta r_{i,j,x} & \delta r_{i,j,y} & \delta r_{i,j,z}\end{bmatrix}^T$ is the orientation error, and $\delta\mathbf{t}_{i,j} = \begin{bmatrix}\delta t_{i,j,x} & \delta t_{i,j,y} & \delta t_{i,j,z}\end{bmatrix}^T$ is the translational error produced by the clearances of the auxiliar frame $F'_{i,j}$ with respect to the local frame $F_{i,j}$ (see Fig. 1).



(a) Isometric view. (b) Definitions of the zx plane. (c) yx plane. (d) Definitions of the yx plane.

Figure 1. Joint Clearance Model.

The translational clearance along the axis joint z, and the rotational clearance with respect to the axis z are defined as $\Delta b_{i,j,z}$ and $\Delta\beta_{i,j,xy}$, respectively. Moreover, the translational clearance in the xy plane and the rotational clearance related to the z axis are defined as $\Delta b_{i,j,xy}$ and $\Delta\beta_{i,j,z}$. Therefore, the elements of the error screw $\delta\mathbf{e}_{i,j}$ of Eq. (1) are defined in Eq. (2).

$$\begin{cases}\delta r_{i,j,x} = \Delta\beta_{i,j,xy}\cos(\gamma_{i,j})\\ \delta r_{i,j,y} = \Delta\beta_{i,j,xy}\sin(\gamma_{i,j})\\ \delta r_{i,j,z} = \Delta\beta_{i,j,z}\end{cases} \qquad \begin{cases}\delta t_{i,j,x} = \Delta b_{i,j,xy}\cos(\gamma_{i,j})\\ \delta t_{i,j,x} = \Delta b_{i,j,xy}\sin(\gamma_{i,j})\\ \delta t_{i,j,z} = \Delta b_{i,j,z}\end{cases} \tag{2}$$

with $0 \leq \gamma_{i,j} \leq 2\pi$. Following this definition, the positioning and orientation error should meet the following constraints: $\delta r^2_{i,j,x} + \delta r^2_{i,j,y} \leq \Delta\beta^2_{i,j,xy}$ and $\delta t^2_{i,j,x} + \delta t^2_{i,j,y} \leq \Delta b^2_{i,j,xy}$. The uncertainties are introduced in the following five parameters that define the clearances of the joints: $\Delta\beta_{i,j,z}$, $\Delta\beta_{i,j,xy}$, $\gamma_{i,j}$, $\Delta b_{i,j,xy}$ and $\Delta b_{i,j,z}$. These uncertainties are modeled as random variables according to the expression presented in Eq. (3).

$$\begin{array}{ccc}\Delta\beta_{i,j,z}(\Omega) = \beta_z + \beta_z\xi(\Omega) & \Delta\beta_{i,j,xy}(\Omega) = \beta_{xy} + \beta_{xy}\xi(\Omega) & \gamma_{i,j}(\Omega) = \gamma + \gamma\xi(\Omega)\\ \Delta b_{i,j,xy}(\Omega) = b_{xy} + b_{xy}\xi(\Omega) & \Delta b_{i,j,z}(\Omega) = b_z + b_z\xi(\Omega) & \end{array} \tag{3}$$

with β_z, β_{xy}, γ, b_{xy}, and b_z being the mean values of each uncertain parameter, $\xi(\Omega)$ is a Gaussian random variable, and Ω represents a random process.

The vector of the set of uncertain clearance parameters from a serial kinematic chain is defined based on the Eq. (3) as:

$$\mathbf{c} = \begin{bmatrix}\mathbf{c}_1 & \mathbf{c}_2 & \dots & \mathbf{c}_i & \dots & \mathbf{c}_{n_{i,f}}\end{bmatrix} \tag{4}$$

where $i = 1, \dots, n_i$, and $n_{i,f}$ represents the number of joints of the kinematic chain; $\mathbf{c}_j$ are the uncertain parameters of the $j - th$ joint clearance, thus $\mathbf{c}_j = \begin{bmatrix}\Delta\beta_{j,z}(\Omega) & \Delta\beta_{j,xy}(\Omega) & \gamma_j(\Omega) & \Delta b_{j,xy}(\Omega) & \Delta b_{j,z}(\Omega)\end{bmatrix}$. More details about the clearances model with uncertainties are given in (Lara-Molina and Dumur, 2020a).

2.2 Error Propagation Method

The error propagation method of serial manipulators is based on the method proposed by Binaud et al. (2010). Initially, the Denavit-Hartenberg method is used to obtain the pose of the end-effector considering no clearances. Thus, the homogeneous transformation matrix, $\mathbf{S}_{i,j}$, is defined as:

$$\mathbf{S}_{i,j} = \begin{bmatrix}\mathbf{R}_{i,j} & \mathbf{t}_{i,j}\\ \mathbf{0}_{1\times 3} & 1\end{bmatrix} \tag{5}$$

with $i = 1, \ldots, m$ and $j = 1, \ldots, n_{i,f}$, respectively; m is the number of kinematic chains (for a single kinematic chain $m = 1$), and $n_{i,f}$ is the total number of frames. $\mathbf{S}_{i,j}$ represents the transformation matrix from the frame $\mathbf{F}_{i,j}$ to the frame $\mathbf{F}_{i,j+1}$, $\mathbf{R}_{i,j}$ is the (3x3) rotation matrix and $\mathbf{t}_{i,j}$ is the (3x1) position vector. The pose of the end-effector related to the $i-th$ kinematic chain, $\mathbf{P}_i$, is defined as:

$$\mathbf{P}_i = \prod_{j=1}^{n_{i,f}} \mathbf{S}_{i,j} \tag{6}$$

However, the pose of the end-effector considering the joint clearances, $\mathbf{P}'_i$, will not be equal to the pose $\mathbf{P}_i$ presented in Eq. (6). The adjoint map transformation matrix of $\mathbf{S}_{i,j}$ maps the error screw onto the end effector at a specific pose as presented in Eq. (7).

$$adj(\mathbf{S}_{i,j}) = \begin{bmatrix} \mathbf{R}_{i,j} & \mathbf{0}_{3\times3} \\ \mathbf{T}_{i,j}\mathbf{R}_{i,j} & \mathbf{R}_{i,j} \end{bmatrix} \tag{7}$$

where $\mathbf{T}_{i,j}$ is the screw matrix of the vector $\mathbf{t}_{i,j}$; $\mathbf{t}_{i,j}$ and $\mathbf{R}_{i,j}$ can be extracted from the transformation matrix of Eq. (5). Moreover, the adjoint of the inverse transformation matrix, $adj(\mathbf{S}_{i,j})^{-1}$, permits to express screws at the frame $\mathbf{F}_{i,j+1}$ from $\mathbf{F}_{i,j}$.

The error screw, $\delta\mathbf{e}_{i,j}$, in the local frame $\mathbf{F}_{i,j}$, can be expressed in the end-effector frame, $\mathbf{F}_{i,n_{i,f}}$, by multiplying all the inverse adjoint transformation matrices from $n_{i,f}$ to $j+1$, thus: $\left(\prod_{k=n_{i,f}}^{j+1} adj(\mathbf{S}_{i,k})^{-1}\right)\delta\mathbf{e}_{i,j}$.

The following expression quantifies the pose error of the end-effector considering all the joint clearances:

$$\delta\mathbf{p}_i|\mathbf{F}_{i,P} = \sum_{j=1}^{n_i} \prod_{k=n_{i,f}}^{j+1} adj(\mathbf{S}_{i,k})^{-1}\delta\mathbf{e}_{i,j} \tag{8}$$

with n_i being the number of joints, and $n_{i,f}$ the number of frames; note that $n_{i,f} \geq n_i$. $\delta_{\mathbf{P}_i}|\mathbf{F}_{i,P}$ is the pose error in the frame attached to the end-effector $\mathbf{F}_{i,P}$.

The pose error in the end-effector should be expressed in the reference frame attached to the fixed base $F_{i,1}$. Thus,

$$\delta\mathbf{p}_i|\mathbf{F}_{i,1} = \prod_{j=1}^{n_{i,f}} (\mathbf{N}_{i,j})\, \delta\mathbf{p}_i|F_{i,P} \tag{9}$$

where $\mathbf{N}_{i,j} = \begin{bmatrix} \mathbf{R}_{i,j} & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{R}_{i,j} \end{bmatrix}$. Therefore, an expression for $\delta\mathbf{p}_i|\mathbf{F}_{i,1}$ is obtained by substituting Eq. (8) into Eq. (9).

$$\delta\mathbf{p}_i|\mathbf{F}_{i,1} = \sum_{j=1}^{n_i} \prod_{l=1}^{n_{i,f}} (\mathbf{N}_{i,l}) \prod_{k=n_{i,f}}^{j+1} adj(\mathbf{S}_{i,k})^{-1}\delta\mathbf{e}_{i,j} \tag{10}$$

The expression of Eq. (10) can be written in the following compact form:

$$\delta\mathbf{p} = \mathbf{M}_i\delta\mathbf{e}_i = \begin{bmatrix} \delta\mathbf{p}_r & \delta\mathbf{p}_t \end{bmatrix}^T \tag{11}$$

where $\mathbf{M}_i = \begin{bmatrix} \mathbf{M}_{i,1} \ldots \mathbf{M}_{i,ni} \end{bmatrix}$, and

$\delta\mathbf{e}_i = \begin{bmatrix} \delta\mathbf{e}_{i,1}^T \ldots \delta\mathbf{e}_{i,n_i}^T \end{bmatrix}$, $\mathbf{M}_{i,j} = \prod_{l=1}^{n_{i,f}} (\mathbf{N}_{i,l}) \prod_{k=n_{i,f}}^{j+1} \left(adj(\mathbf{S}_{i,k})^{-1}\right)$; $\delta\mathbf{p}_r$ and $\delta\mathbf{p}_t$ are the orientation and translational errors of the end effector, respectively. Additional details about this method are given in (Lara-Molina and Dumur, 2021).

3. GLOBAL KINEMATIC RELIABILITY CRITERION

Kinematic reliability is the probability that the mechanism performs a specific motion not exceeding an error limit. These motion errors can be produced by uncertainties in the geometric parameters and clearances of the manipulator (Rao and Bhatti, 2001).

As presented in the previous section, the uncertain parameters of the joint clearances can be modeled as random variables. These random variables are grouped in the random vector $\mathbf{c}$ of Eq. (4) associated to the joint probability density function $f_{\mathbf{c}}(\mathbf{c})$. The kinematic error or the performance function is defined as $e_T(\mathbf{c})$ based on the error screw definition of Eqs. (11). It is worth to mention that the kinematic error for the performance function, e_T, can consider the orientation error ($e_T(\mathbf{c}) = ||\delta\mathbf{p}_r||$) or the translational error ($e_T(\mathbf{c}) = ||\delta\mathbf{p}_t||$) separately, where $||.||$ represents the magnitude of the vector. The kinematic reliability is quantified by the probability of the positioning error, $e_T(\mathbf{c})$, exceeding the maximum admissible limit, e_{max}, thus:

$$p_f = pr\{e_T(\mathbf{c}) > e_{max}\} \tag{12}$$

where $pr\{.\}$ represents the probability.

Several methods have been used in the literature to evaluate the kinematic reliability as stated in the literature review of the introduction (Zhang *et al.*, 2014; Wu *et al.*, 2021). In this contribution, the failure probability is computed by using the Monte Carlo simulation method.

The kinematic reliability according to Eq. (12) is only evaluated in a specific configuration; therefore, it represents the probability of the kinematic error exceeding the maximum limit only in this particular configuration.

The concept of the global criteria has been used to evaluate kinematic properties of the manipulator such as the global conditioning index (GCI) (Gosselin and Angeles, 1991). Consequently, the global reliability index (GRI) aims at evaluating the behavior of the kinematic reliability over the workspace of the manipulator. Therefore, the following global reliability index is proposed:

$$GRI = \frac{\int_w p_f dw}{\int_w dw} \tag{13}$$

where p_f is the probability that the kinematic error exceeds the maximum limit at a single point of the workspace w; this probability is evaluated by using the expression of Eq. (12). The denominator represents the volume of the workspace. The failure probability, p_f, is bounded as follows:

$$0 \leq p_f \leq 1 \tag{14}$$

that also produces a bounded global performance index defined as:

$$0 \leq GRI \leq 1 \tag{15}$$

where the desired performance of a manipulator consists of minimizing the failure probability and the global reliability index. Additional details about the kinematic reliability can be found in (Lara-Molina and Dumur, 2020b).

4. NUMERICAL RESULTS

Initially, the rotational joint clearances used in all the applications are defined. The parameters of the active joint clearances, according to the model of Eq. (3), are defined as $\beta_{xy} = 0.1^o$, $\beta_z = 0.05^o$, $b_{xy} = 5 \times 10^{-5}$m, $b_z = 5 \times 10^{-5}$m, and $\gamma_{i,j} = 180^o$. The passive joints have same parameters; nevertheless, no clearance around the axial axis is considered, thus $\beta_z = 0^o$. Then, the performance function is defined according to the expression of Eq. (12). Thus, the positioning error is considered in the analysis, thus $e_T(\mathbf{c}) = ||\delta \mathbf{p}_t||$, and $e_{max} = 1 \times 10^{-3}$m. Finally, the following hardware was used: i7 Intel i7-7500U CPU processor (2.9 GHz) and RAM 8.0 GB.

The global conditioning index is a criterion widely used in the literature to assess the kinematic dexterity of manipulators (Gosselin and Angeles, 1991). This index was also evaluated to establish a basis to compare the results and behavior of the global reliability index proposed in the present contribution.

The 3R serial arm is presented in Fig. 2, and its D-H parameters are defined in Tab. 1. According to the error propagation method $i = 1$ and $j = 1, \ldots, 3$. The link lengths and maximum limits of the rotational joints are defined as $a_2 = 0.15$m, $d_3 = 0.01$m, $d_4 = 0.10$m, $-100^o \leq \theta_1 \leq 90^o$, $-90^o \leq \theta_2 \leq 45^o$ and, $-90^o \leq \theta_3 \leq 90^o$.

Initially, the failure probability of the kinematic reliability is evaluated by using the Monte Carlo simulation (MCS) method. The failure probability, p_f, is evaluated at several positions within the workspace as showed in Fig. 3. Figure 3a presents the selected positions over the xz plane considering the y-coordinate fixed at $y = d_3$. Figure 3b presents the positions for the xy plane considering the z-coordinate fixed at $z = 0$.

The outcomes of the failure probability, p_f, are presented in table 2.

The kinematic reliability is also evaluated over the usable workspace as showed in Fig. 4. The p_f increases in the outer limit of the usable workspace that corresponds to poses in which the 3R manipulator is extended. The increment of p_f is produced by the increasing of the kinematic error in the outer borders of the usable workspace. The left side of the usable workspace corresponds to poses in which the manipulator is retracted; therefore, the kinematic error and p_f decreases (see Figs. 4a and 4b).

Moreover, the kinematic dexterity based on the condition number of the Jacobian matrix is also computed over the usable workspace as presented in Fig. 5. The local kinematic dexterity corresponds to $1/\kappa(\mathbf{J})$, where $\kappa(.)$ is the condition number of a matrix, and $\mathbf{J}$ is the Jacobian matrix. For this specific application, an inverse relationship between kinematic reliability (see Fig. 4) and kinematic dexterity is observed (see Fig. 5) for the poses in which the manipulator is extended,

Table 1. D-H parameters of 3R manipulator.

j	α_{j-1}	a_{j-1}	d_j	θ_j
1	0	0	0	θ_1
2	-90^o	0	0	θ_2
3	0	a_2	d_3	θ_3
4	-90^o	0	d_4	0

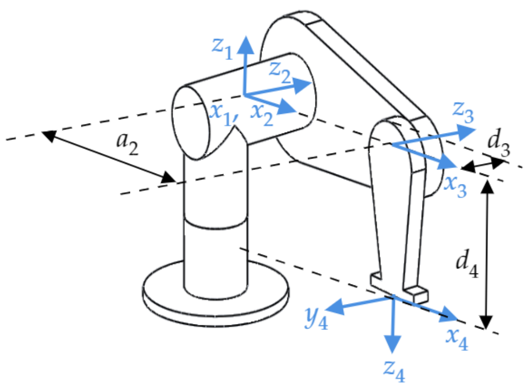
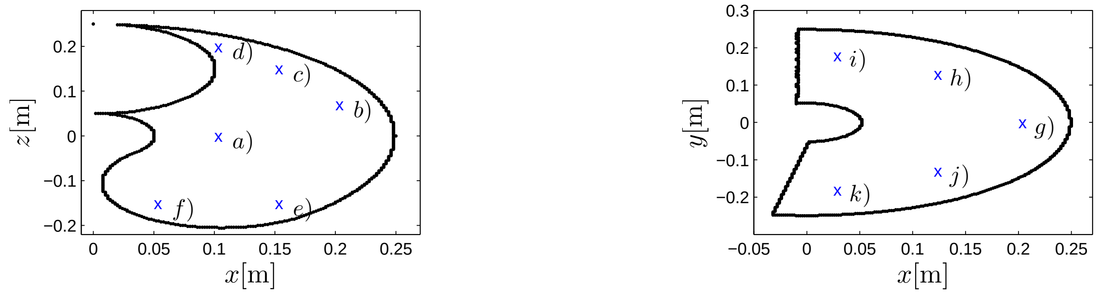


Figure 2. 3R serial manipulator.



(a) xz plane.

(b) xy plane.

Figure 3. Usable workspace of the 3R serial manipulator.

i.e. p_f increases and $1/\kappa(\mathbf{J})$ decreases. Nevertheless, this behavior is not observed for the poses in which the manipulator is retracted.

The definition of both the probability of failure and the kinematic dexterity is related to positioning error. The augment of the probability of failure p_f implies the increase of the end effector positioning error, as defined in Eq. (12). The kinematic dexterity depends on the rank of the Jacobian matrix that measures the impact of the joint error on the positioning error of the end effector. Thus, a high kinematic dexterity implies a small effect of the joint errors on the end effector positioning error. Consequently, an inverse relationship between the probability of failure and the kinematic dexterity is observed for this application.

Finally, the global reliability index (GRI) is also evaluated as follows. The volume of the workspace for the computation of the GRI is defined as a torus part, w, (see Fig. 6a). The volume w is inscribed within the usable workspace; it is defined as a function of the link lengths as follows:

$$w = \pi r_w^2 c_w \theta_w \tag{16}$$

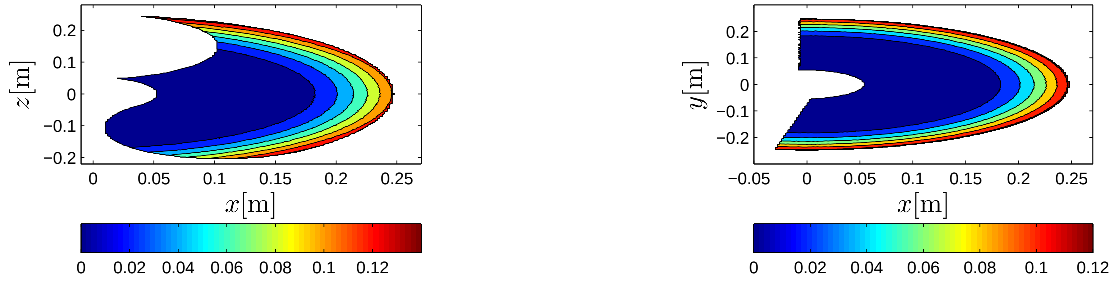
where r_w is radius of the tube; c_w is the distance of the center of the torus to the center of the tube; θ_w is the angle of the torus part. The geometric parameters of the torus part are defined as a function of the link lengths, thus: if $a_2 \leq d_4$, then $r_w = d_4/4$, and $c_w = a_2$; and, if $a_2 < d_4$, then $r_w = a_2/4$, and $c_w = d_4 + a_2/2$.

For this analysis, the link legnths a_2 and d_4 are considered as variables. Thus, $0 \leq a_2 \leq 0.25$m and $0 \leq d_4 \leq 0.25$m; moreover, the following geometric constraint is imposed:

$$a_2 + d_4 = 0.25\text{m} \tag{17}$$

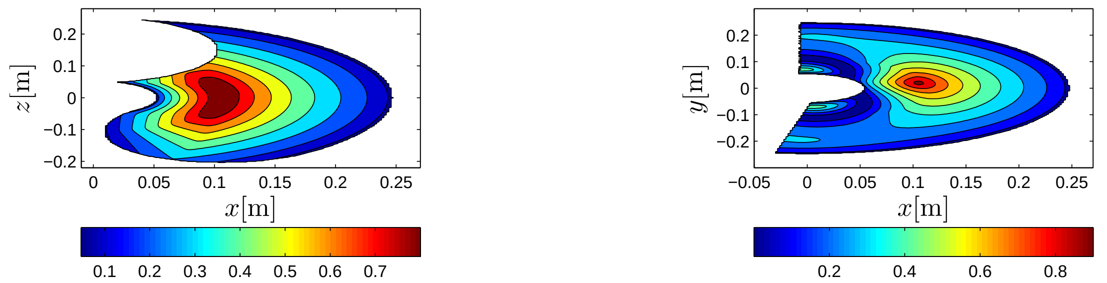
Table 2. Reliability outputs.

p	$a)$	$b)$	$c)$	$d)$	$e)$	$f)$	$g)$	$h)$	$i)$	$j)$	$k)$
p_f	4.0×10^{-5}	0.0908	0.0664	0.0934	0.0704	0.0014	0.0036	0.0019	0.0037	0.0020	0.0039
Time [sec]	0.5863	0.5184	0.5429	0.5802	0.5460	0.5462	0.5442	0.5948	0.5831	0.5686	0.5420



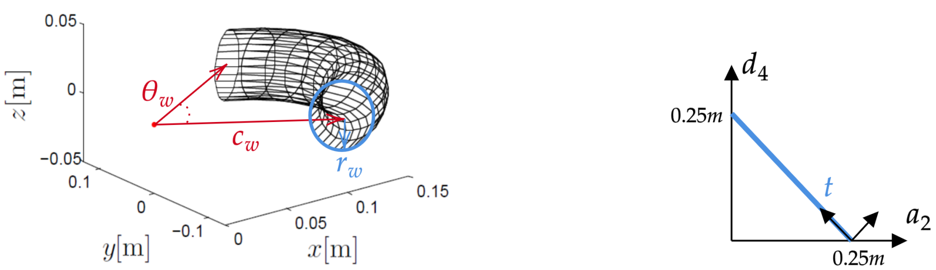
(a) xz plane. (b) xy plane.

Figure 4. p_f over the usable workspace.



(a) xz plane. (b) xy plane.

Figure 5. $1/k(\mathbf{J})$ over the usable workspace.



(a) Torus part workspace. (b) t coordinate definition.

Figure 6. Dimensional definitions.

Based on this geometric constraint, an auxiliar coordinate, t, is defined to evaluate all the possible combinations of the link lengths, thus $t = 2/\sqrt{2}a_2$ (see Fig. 6b).

The GRI is assessed for all the combinations of the link lengths subject to the imposed geometric constraint of Eq.(17) based on the definition of the auxiliary coordinate t (see Fig. 7). Moreover, the global conditioning index (GCI) is also computed. One can observe that the behavior of the GRI is inversely proportional to the GCI, i.e., the increasing of the global failure probability decreases the global kinematic dexterity. The maximum value of the GRI is 0.02974 for $t = 0.1768$m.

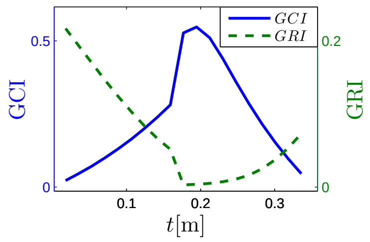


Figure 7. GCI and GRI of the 3R manipulator.

5. CONCLUSIONS

The global reliability index was evaluated based on the error produced by clearances over a required workspace. Initially, random uncertainties were introduced within the axisymmetric model of the clearances. Then, a method to propagate the joint clearances was proposed; finally, the global reliability index was formulated. The numerical results demonstrated that the global reliability index permitted the evaluation of the positioning error considering the errors of the joint clearances.

The proposed approach allows quantifying the kinematic reliability that takes into account the effect of clearances. The proposed global reliability index demonstrated to be an alternative design criterion to take into account the effect of clearance in the kinematic accuracy of the manipulators. The kinematic criterion based on the Jacobian matrix does not present the effects of uncertain clearance on the kinematic performance.

Future work will encompass the robust optimal design of manipulators based on the proposed reliability method criterion.

6. ACKNOWLEDGEMENTS

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