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Robustness Indices of a Serial Manipulator

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Abstract: Taguchi's robust design aims at minimizing the sensitivity of performances to variations without controlling the causes of these variations. A mechanism is robust when the sensitivity of its performances to variations is a minimum .In order to obtain a robust solution independently of the amount of variations in design variables and design parameters an appropriate robustness index is required .This paper focuses on the determination of robustness indices of Serial manipulators. For case study two revolute jointed(2R) serial manipulator with different link lengths have been considered, for which the appropriate robustness indices were calculated with help of norm of Jacobian.
Keywords: Robustness index, sensitivity, robust design, serial manipulator, tolerance synthesis

I. INTRODUCTION

In industries specific robots perform several tasks such as picking and placing objects, movement adapted from observing how similar manual tasks are handled by a fully-functioning human arm. Such robotic arms are also known as robotic manipulators. These manipulators were originally used for applications with respect to bio-hazardous or radioactive materials or for use in inaccessible places. A series of sliding or jointed segments are put together to form an arm-like manipulator that is capable of automatically moving objects within a given number of degrees of freedom. Every commercial robot manipulator includes a controller and a manipulator arm. The performance of the manipulator depends on its speed, payload weight and precision. However, the reach of its end-effectors, the overall working space and the orientation of the work is determined by the structure of the manipulator.

A robot manipulator is constructed using rigid links connected by joints with one fixed end and one free end to perform a given task (e.g., to move a box from one location to the next). The joints to this robotic manipulator are the movable components, which enables relative motion between the adjoining links. There are also two linear joints to this robotic manipulator that ensure non-rotational motion between the links, and three rotary type joints that ensure relative rotational motion between the adjacent links.

II. SERIAL MANIPULATOR

Serial manipulators are the most common industrial robots. They are designed as a series of links connected by motor-actuated joints that extend from a base to an end-effectors. Often they have an anthropomorphic arm structure described as having a "shoulder", an "elbow", and a "wrist”. Serial robots usually have six joints, because it requires at least six degrees of freedom to place a manipulated object in an arbitrary position and orientation in the workspace of the robot. The success of this robot was possible due in the main to the following factors:

1) Precision;
2) High speed due to simple structure
3) Small dimensions
4) Smooth motion;
5) Simple and reliable structure
6) Ease of installation and use;
7) Very small back lash
8) This robot is used in different sizes in all kinds of industries such as automotive, electronics, and pharmaceutical. The mo common applications are:
9) Pick and place operations;
10) Assembly operations;
11) Palletizing;
12) Packing operations.

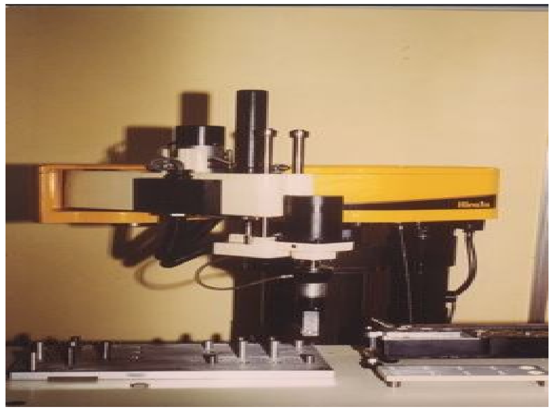

Fig.1The Hirata AR-300, one of the first model of a SCARA

The main advantage of a serial manipulator is a large workspace with respect to the size of the robot and the floor space it occupies. The main disadvantages of these robots are:

A. The low stiffness inherent to an open kinematic structure,

1) Errors are accumulated and amplified from link to link,
2) The fact that they have to carry and move the large weight of most of the actuators, an
3) The relatively low effective load that they can manipulate.

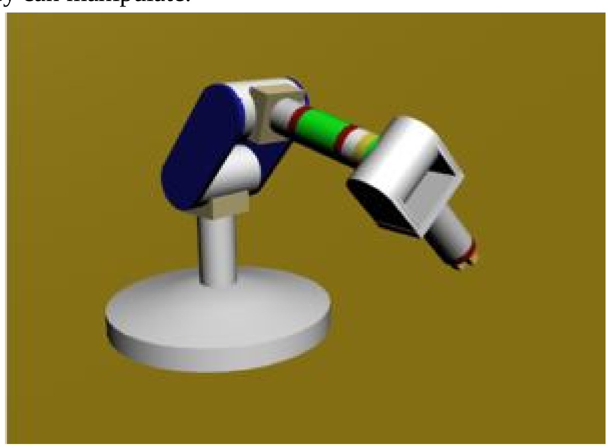

Fig.2 Structure of serial manipulator

B. Kinematics Of Serial Manipulator

Position analysis is an essential step in the design, analysis and control of robots. In this article, a basic introduction to the position analysis of serial manipulators is given. This topicis invariably covered in all the textbooks on this subject. Therefore, instead of repeating the standard details of forward kinematics, such as, the designation of the reference frames, determination of the Denavit-Hartenberg (DH) parameters, multiplication of the 4_4 transformation matrices to get the end-effector position and orientation etc., more emphasis is laid on the inverse problem, which is relatively more complicated in such manipulators. Simple examples, such as a planar 2-R and a spatial 3-R serial robot are discussed in detail

C. 2-R Planar Manipulator

Let us consider one of the simplest possible manipulators in this section, namely, the 2-Rplanar serial robot. The robot is shown in Fig.2 The designation “2-R" derives from the fact that the robot has one rotary actuator at each of its joints. The problem of position kinematics (also known as zeroth-order kinematics) can be further divided in two sub-problems: forward and inverse kinematics.

D. Forward Kinematics Of The Planar 2-R Manipulator

Forward kinematics refers to the problem of finding the position of the end-effector (in this case, represented by the point in Fig. 2, given the link lengths, and the inputs. For this manipulator, the forward kinematics problem is trivially solved

$$x = l_1 \cos\theta_1 + l_2 \cos\theta_{12} \quad (1)$$

$$y = l_1 \sin\theta_1 + l_2 \sin\theta_{12} \quad (2)$$

Eqs. (1, 2) are also referred to as the forward kinematic map1, as they map the joint angles to the tip coordinates. As this map is nonlinear in nature, the inverse of it, i.e., finding the inverse kinematic map, is generally more complicated.

III.METHODOLOGY

Every engineering design is subject to variations that can arise from a variety of sources, including manufacturing operations, variations in material properties, and the operating environment. When variations are ignored, non-robust designs can result, which are expensive to produce or fail in service. Besides, the robustness of a mechanism is important when calibration is necessary because the lower the sensitivity of the mechanism to dimensional variations, the easier its calibration.

The concept of robust design may be first used by Taguchi. He introduced the concept of parameter design to improve the quality of a product whose manufacturing process involves significant variability or noise. Robust design aims at minimizing the sensitivity of performances to variations without controlling the causes of these variations. In the last decades, several authors have contributed to the formulation and the improvement of robust design problems.

The project focuses on mechanisms, which are assemblies of moving parts performing a complete functional motion.

A. Robust Design Problem

In a robust design problem, the distinction is made between three sets: (i) the set of design variables (*DV*) whose nominal values can be selected between the range of upper and lower bounds, they are controllable; (ii) the set of design parameters (*DP*) that cannot be adjusted by the designer, they are uncontrollable; (iii) the set of performance functions. The *l*-dimensional vector of design variables is denoted by $\mathbf{x} = [x_1 x_2 \cdots x_l]^T$. The*m*-dimensional vector of design parameters is denoted by $\mathbf{p} = [p_1 p_2 \cdots p_m]^T$. Performance functions are grouped into the *n*-dimensional vector $\mathbf{f} = [f_1, f_2 \cdots f_n]^T$.*DV* are, however, subject to uncontrollable variations because of manufacturing errors, wear, or other uncertainties, although their nominal value is fixed.A system is robust when its performance is as little sensitive as possible to variations. Performance function f depends on *DV* and *DP*, which are supposed to be independent.

$$f = f(x, p) \quad (3)$$

Here, the study of the sensitivity of the system to variations is based on the theory of performance sensitivity distribution.

$$\delta f = [Jx\ Jp][\delta x^T\ \ \delta p^T]^T = J\ dX \quad (4)$$

In this theory, a Jacobian matrix J describes the effect of the component variations to the system performance, as depicted by eq. (4.2) where $\mathbf{J}_x = \partial \mathbf{f} / \partial \mathbf{x}, \mathbf{J}p = \partial \mathbf{f} / \partial \mathbf{p}, \mathbf{J} = [\mathbf{J}_x \mathbf{J}_p], \mathbf{X}^T = [\mathbf{x}^T \mathbf{p}^T]$. δ_x and δ_p are the variations in *DV* and in *DP*, respectively. $\mathbf{J}_x$ And $\mathbf{J}_p$ are the $(n \times l)$ sensitivity Jacobian matrix of fwith respect to x and the $(n \times m)$ sensitivity Jacobian matrix of fwith respect to p, respectively. If variations in DV are not taken into account, then $\mathbf{J} = \mathbf{J}_p$ and X = p. On the contrary, $\mathbf{J} = \mathbf{J}_x$ and X = x when only variations in DV are considered.

The performance distribution is characterized in the variation space by a set of Eigenvalues and eigenvectors, *i.e.*: by a hyper-ellipsoid. Without loss of generality, assuming that variations in *DV* are negligible and that there are only two *DP*, this design sensitivity hyper-ellipsoid is an ellipse. σ_1 and σ_2 are the smallest and the largest singular values of J, respectively, and q_1, q_2 are their corresponding eigenvectors. Lengths of semi-axes are inversely proportional to singular values of J. Points on the ellipse surface lead to the same norm of performance variation, $\|\delta f\|_2$ where $\|\bullet\|_2$ depicts the Euclidean norm. Moreover, the performance is the least sensitive to variations in the direction of q_1 and the most sensitive to variations in the direction of q_2.

A mechanism is robust when the sensitivity *S* of its performances to variations is a minimum. Therefore, *S* can be defined as the ratio of the Euclidean norm of variations in its performances, $\|\delta f\|_2$ and the Euclidean norm of variations in *DV* and *DP*, $\|\delta X\|_2$. *S* represents a variation transmission ratio and means the amount of variations transmitted from the sources to the design. Besides, eq.

(4) follows from eq. (3) and means that *S* is bounded by the smallest singular value, $\sigma_{\min}$ and the largest singular value, $\sigma_{\max}$ of sensitivity Jacobian matrix J.

$$\sigma_{\min} \leq S = \frac{\|\delta f\|_2}{\|\delta f\|_2} \leq \sigma_{\max} \qquad (5)$$

B. Choice Of An Appropriate Robustness Index

In order to obtain a robust solution independently of the amount of variations in *DV* and *DP*, a judicious robustness index is required. The robustness indices usually found in the recent literature are the condition number and the Euclidean norm of the sensitivity Jacobian matrix, **J**. Al-Widyan and Angeles [14], Ting and Long [15] used the condition number of **J**. Zhu [12] and Hu et al. [16] suggested the use of the Euclidean norm of **J**. In this section, it is shown that the Euclidean norm of **J** is more appropriate for the robust design of mechanisms. The condition number of a matrix is the ratio of its largest singular value to its smallest singular value. Let RI_1 be the condition number of **J**.

$$RI_1 = \|J\|_2 \left\|J^{-1}\right\|_2 = \frac{\sigma_{\min}}{\sigma_{\max}} \qquad (6)$$

A singular value of **J** corresponds to the error transmission factor in the direction of its corresponding eigenvector and in the space of variations. The ideal solution is the minimization of all the singular values of **J**, but is not easy to obtain. According to eq. (4), a compromise solution is to minimize the upper bound of *S*, which is the largest singular value of **J**. Thus, a second robustness index, RI_2, is defined by eq. (7).

$$RI_2 = \sigma_{\max} \qquad (7)$$

C. Dimensioning Of The 2r Manipulator

Let S_T be defined as a set of *n* points $P_1, P_2, \cdots, P_n$. First, *E* can hit all points in S_T if and only if l_1 and l_2 satisfy the following conditions:

$$\begin{cases} |l_1 - l_2| \leq r \\ l_1 + l_2 \geq R \end{cases}$$

with $r = \min_i d(A,Pi)$, $R = \min_i d(A,Pi)$, $i = 1, \cdots, n$ where $d(A,Pi)$ is the distance between *Pi* and *A*. These conditions bound the feasible design variables space. The formulation of a robust design problem was given in section 2. For the manipulator under study, the set of design variables, **x**, and the set of performance functions, **f**, are given by eqs. (8, 9).

$$x = [l_1\, l_2]^T \qquad f = \left[e_1^T \ldots. e_i^T \ldots. e_n^T\right]^T \qquad (8)$$

$$e_i = l_1\left[C_{\theta_{1i}}\ S_{\theta_{1i}}\right]^T + l_2\left[C_{\theta_{1i}+\theta_{2i}}\ S_{\theta_{1i}+\theta_{2i}}\right]^T \qquad (9)$$

Where e_i is the vector of the Cartesian coordinates of E at P_i. $C_{\theta_{ji}} = \cos\theta_{ji}, S_{\theta_{ji}} = \sin\theta_{ji}, \theta_{ji}$, Where θ_{ji} is the j[th] actuated joint variable at P_i, j =1,2The relation between the positioning error of end-effecter at P_i, $\delta f_{i,\text{ and}}$ dimensional variations δl_1 and δl_2 follows from eq.(9) and is given by eq.(10)

$$\delta f_i = J_{x_i}\delta x \text{ With } J_{x_i} = \begin{bmatrix} C_{\theta_{1i}} & C_{\theta_{1i}+\theta_{2i}} \\ S_{\theta_{1i}} & S_{\theta_{1i}+\theta_{2i}} \end{bmatrix}; \delta x = \begin{bmatrix} \delta l_1 \\ \delta l_2 \end{bmatrix} \qquad (10)$$

The norm of $\delta f = \left[f_1^T \ldots. f_i^T \ldots. f_n^T\right]^T, \|\delta f\|$, is the global positioning error of E on $\mathbf{S}_T$. The sensitivity jacobian matrix of the manipulator $\mathbf{J}_x$ is a (2n×2) matrix composed of matrices J_{x_i}. The relation between δ**f**, $\mathbf{J}_x$ and dimensional δ**x**, is given by eq.(11)

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$$\delta f_i = J_{x_i} \delta x \text{ with } J_x = \left[J_{x_1}^T \ldots. j_{x_i}^T \ldots. j_{x_n}^T \right]^T \quad (11)$$

The robustness of the manipulator with respect to dimensional variations is quantified by robustness index *RI*2, defined in section 3. RI_2 is the maximum singular value of $\mathbf{J}_x$and corresponds to the maximum norm of positioning error of *E*,||δ**f**||*max*, when the norm of dimensional variations is unitary, i.e.: $\delta l_1^2 + \delta l_2^2 = 1$

Let $S_T$bemade up of four points, P_1,P_2,P_3,P_4, whose Cartesian coordinates are (1,5), (2,7), (3,7), (4,6), respectively. Fig.9shows the iso-contours of RI_2 in the feasible design variable space. We can notice that RI_2iso-contours form a family of ellipses and that RI_2 is a minimum when design variables belong to the circle Crob. In fact, the algebraic expression of RI_2 can be derived as shown in eq. (12):

$$RI_2 = \sqrt{n + \left| \sum_{i=1}^{n} \cos \theta_{2i} \right|} = \sqrt{n + \left| \sum_{i=1}^{n} \frac{x_1^2 + y_1^2 - l_1^2 - l_2^2}{2 l_1 l_2} \right|} \quad (12)$$

Where $x_i$and $y_i$are the Cartesian coordinates of point Pi. Thus, the set of solutions (l_1, l_2), satisfying eq. (5.7) for a fixed RI2, is either ellipse ε1 or ellipse ε2whose equations are $L_1^2 / a_1^2 + L_2^2 / b_1^2 = c$ and $L_1^2 / a_2^2 + L_2^2 / b_2^2 = c$, respectively, where $a_1 = b_2 = 1 / RI_2$, $a_2 = b_1 = 1 / \sqrt{2n - RI_2^2}$. L_1 and L_2 are the expressions of l_1 andl_2 in the coordinate frame rotated of 45deg with respect to the reference frame of the design variable space. Thus, ε_1 and ε_2, depicted are the iso-contours of robustness index RI_2.

$$l_1^2 + l_2^2 = \frac{1}{n} \sum_{i=1}^{n} x_i^2 + y_i^2 = \frac{1}{n} \sum_{i=1}^{n} d^2(A, P_i) \quad (13)$$

According to eq.(9), $RI_2$is a minimum when eq.(13) is satisfied ,i.e.: when dimensioning (l1,l2) belongs to the circle of radius the square root of the mean of square distances between points A and P_i and centred at the origin of the design space variable. Therefore, this circle corresponds to C_{rob}. Its radius is equal to 6.87. Thus, there exists an infinite number of dimensioning (l_1,l_2) that minimize RI_{2s}.,.

According to eq. (10), the maximum global positioning error ofE is a minimum when cosines of angles θ_{2i}tend towards zero. It means that the links of a robust 2R manipulator should be almost perpendicular. That is apparent in Fig.11. The obtained robust dimensions are independent of the amount of variations and tolerate globally the largest variations.

As there are several robust manipulators, the designer can choose another criterion to be optimized. For instance, he can take into account the cost or the complexity of the mechanism. Here, the optimal robust manipulator is supposed to be the one with the best dexterity. This criterion is frequently used in manipulator design. It evaluates the ease of a manipulator to execute motions or arbitrary motions in all directions. It is quantified by the condition number of its kinematic Jacobian matrix. The smaller this condition number, the higher the dexterity. Besides, the manipulator is isotropic when its condition number is equal to one. Let $\mathbf{J}_k$be the kinematic Jacobian matrix of the 2*R*manipulator:

$$\mathbf{J}_k = \begin{bmatrix} -l_1 \sin(\theta_1) - l_1 \sin(\theta_1 + \theta_2) & -l_2 \sin(\theta_1 + \theta_2) \\ l_1 \sin(\theta_1) + l_1 \sin(\theta_1 + \theta_2) & l_2 \sin(\theta_1 + \theta_2) \end{bmatrix} \quad (14)$$

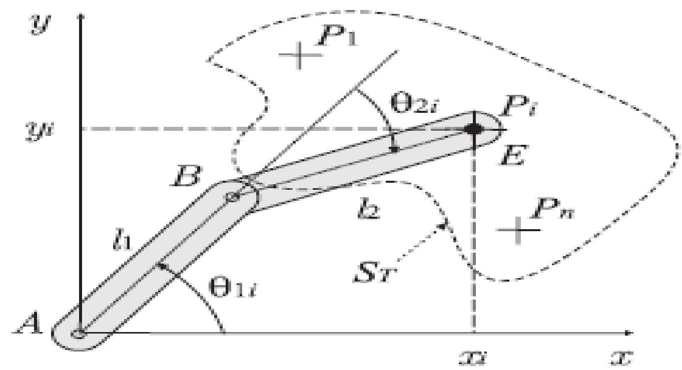

Fig.4. A 2R Manipulator and its target S_T

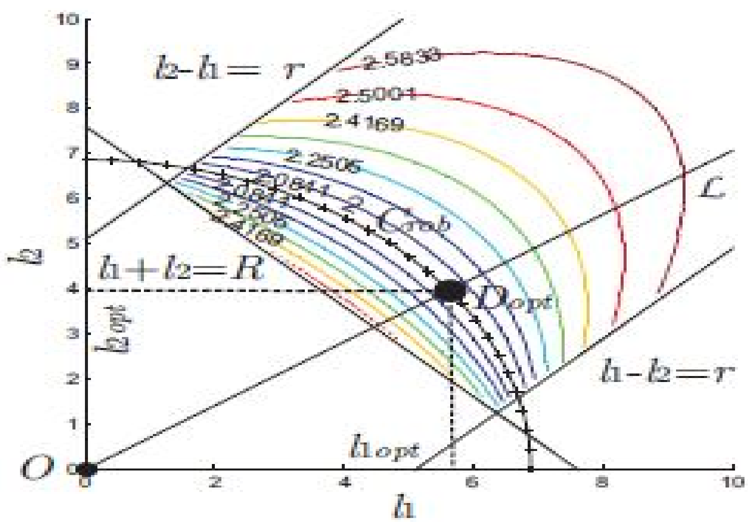

Fig.5. $RI_2 = f(l_1+l_2)$

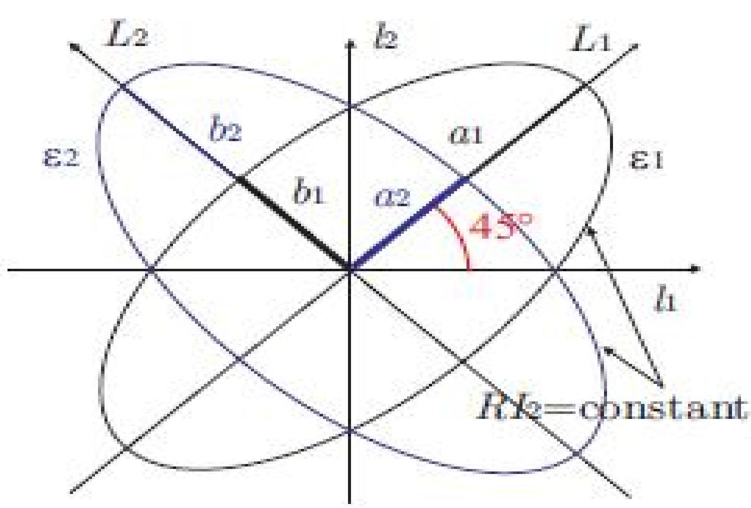

Fig.6. Design Variables(l_1+l_2) corresponding to the same RI_2

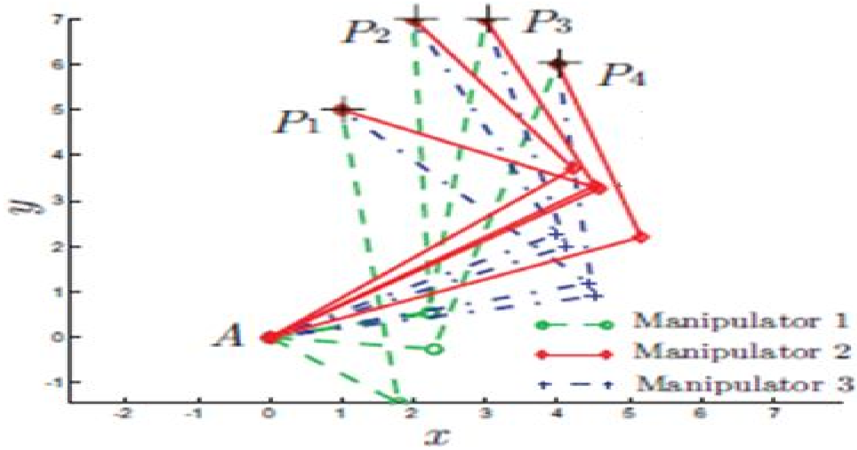

Fig.7. Robust manipulators

IV. RESULTS

(l_1,l_2)	(x,y)	(θ_1,θ_2)	RI_1	RI_2
(1,1)	(1,1.05)	(12.5409, 87.0623)	19.4900	8.4506
(1,1)	(1.05,1)	(-24.5695, 87.0623)	5.2108	2.0221
(1,1)	(1,1.1)	(10.1467, 83.9728)	1.6181	1.1022
(1,1)	(1.1,1)	(5.1386, 83.9728)	77.3789	0.9403
(1,1)	(1,1.15)	(-26.0200,80.7205)	5.2099	2.0221
(1,1)	(1.15,1)	(-46.4372, 80.7205)	4.8511	1.9941
(1,1)	(1,1.2)	(22.2551,77.2910)	1.9937	1.3753
(1,1)	(1.2,1)	(13.9882, 77.2910)	7.4665	1.2946
(1,1)	(1,1.25)	(-9.000e+01,73.6652)	72.1904	2.4087
(1,1)	(1.25,1)	(-9.000e+01+1.6914e+0.2i, 73.6652)	1.6823e+16	3.2942e+73
(1,1)	(1,1.3)	(31.6014, 69.8182)	2.0708e+04	1.6633e+04
(1,1)	(1.3,1)	(20.9567, 69.8182)	6.8538	2.1050
(1,1)	(1,1.35)	(-28.0919, 65.7166)	3.9408	1.0006
(1,1)	(1.35,1)	(-54.6330+36.3195i, 65.7166)	21.2903	4.3368e+15
(1,1)	(1,1.4)	(90.000e+95.9613i, 31.3146)	2.2146e+16	5.9037
(1,1)	(1.4,1)	(-9.000e+1.1974e+02i, 61.3146)	3.9054e+04	1.2534e+52
(1,1)	(1,1.45)	(28.1507, 56.5472)	10.0254	2.2201
(1,1)	(1.45,1)	(7.9510,56.5472)	3.3273e+03	1.9477
(1,1)	(1,1.5)	(36.9168, 51.3178)	4.3663	1.9474
(1,1)	(1.5,1)	(18.2659, 51.3171)	4.3690	2.2360

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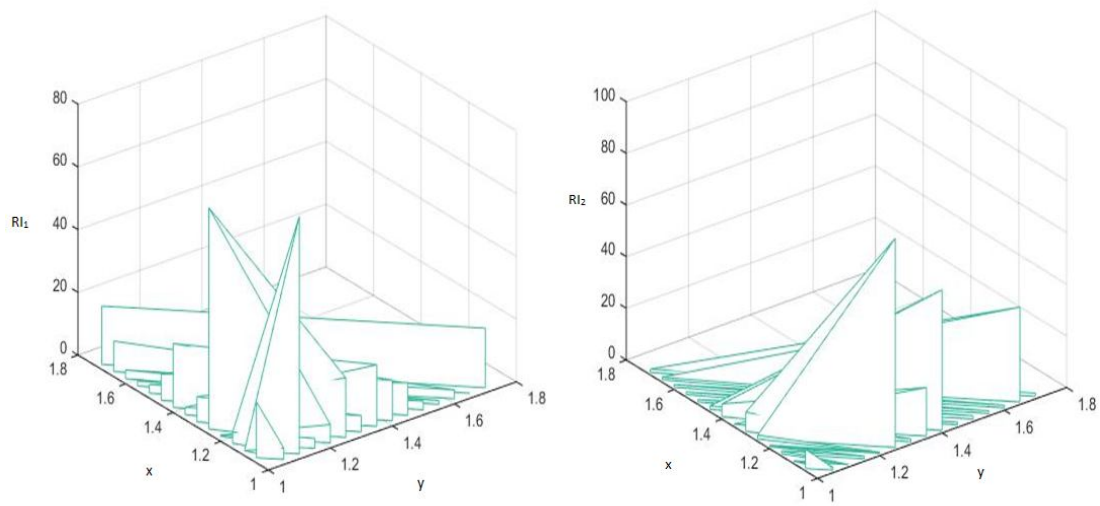

Fig.8. Graphs representing the robustness indices accordingly to results obtained

V. CONCLUSIONS

This present work deals with the Robustness indices of a 2R – planar serial manipulator. for given link lengths (l1, l2) by considering certain point p(x, y). In the work space the joint displacements for a posture are calculated. By using these joint displacements jacobian is calculated, which would be the main consideration for calculating the Robustness indices. Hence by using jacobian the robustness indices RI 1 and RI2 are calculated.

The point in the work space at which the lowest robustness index 1 is obtained is considered to be as the most accurate point in the work space which the manipulator can reach with minimum error. Also the point in the work space at which the robustness index RI2 is minimum is considered as the point at which the manipulator's manipulating ability is more.

VI. FUTURE SCOPE

Obtaining the robustness indices this work can be further extended in computing the optimal dimensional tolerance of the 2R serial manipulator by means of tolerance synthesis method. Also this theory of robustness indices can be applied to parallel manipulators.

A. Matlab Program

1) x=input(' enter the value of x:');
2) y=input(' enter the value of y:');
3) l1=input(' enter the value of l1:');
4) l2=input('enter the value of l2');
5) q=(x.^2)+(y.^2)-(l1.^2+l2.^2)
6) b=2*l1*l2
7) r2=acosd(q/b)
8) disp(r2);
9) l3=[l1^2+l2^2-2*l1*l2*cos(180-r2)]^0.5
10) disp l3
11) sye=asind((l2*sind(r2))/l3)
12) w1=acosd(x/l3)
13) r1=w1-sye
14) disp sye
15) j=[-l1*sin(r1)-l2*sin(r1+r2) -l2*sin(r1+r2);-l1*cos(r1)-l2*cos(r1+r2) -l2*cos(r1+r2)]
16) disp j
17) o=inv(j)
18) RI1=norm(j,2)*norm(o,2)
19) RI2=norm(j,2)

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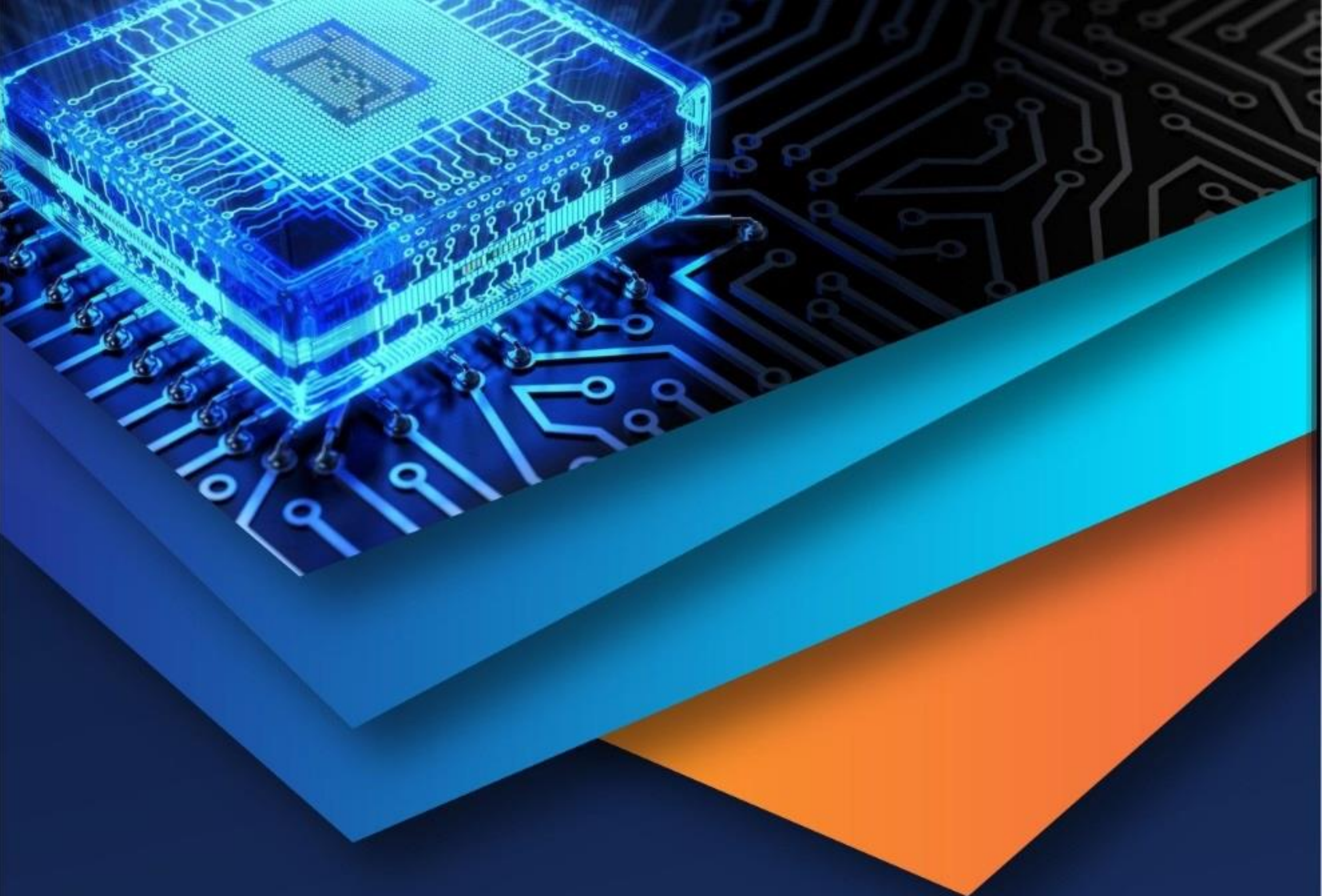

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