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CONDITION NUMBER ANALYSIS OF A THREE DEGREES OF FREEDOM TRANSLATIONAL PARALLEL CUBE MANIPULATOR

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Robot manipulators are geometrically classified into parallel, serial, and hybrid configurations, with parallel manipulators demonstrating superior characteristics including enhanced payload-to-weight ratios, increased structural stiffness, and improved operational accuracy compared to their serial counterparts. This research investigates a three-degree-of-freedom translational parallel cube manipulator through comprehensive kinematic analysis. The study successfully resolves the inverse kinematics problem and derives the corresponding Jacobian matrix, establishing the mathematical foundation for performance evaluation. The condition number serves as a fundamental performance index for quantifying manipulator dexterity and assessing system sensitivity to geometric parameter variations, including link dimensions and moving platform radius, calculated as the ratio between the highest and lowest singular values of the Jacobian matrix. Condition number values are systematically computed across the entire workspace for various geometric parameter ratios, introducing the concept of "well-conditioned" workspace regions where the condition number remains within acceptable bounds. The percentage of well-conditioned workspace area is calculated to evaluate overall manipulator performance. A specialized Python implementation facilitates comprehensive manipulator analysis and computational processing. Results are presented through graphical visualization, demonstrating the relationship between design parameters and workspace performance characteristics, providing valuable insights for optimal manipulator design and operational planning.

Key words: parallel manipulator, condition number, well-conditioned, Jacobian matrix.

1. Introduction

Parallel mechanisms have gained widespread adoption across various fields, thanks to their notable advantages including exceptional accuracy, an excellent ratio between load-bearing capability and self-weight, as well as superior structural stiffness. The fundamental design of these mechanisms - possessing n degrees of freedom - consists of two rigid bodies: a movable platform and a stationary base, which are interconnected through n number of open or closed kinematic chains (linkages). Among these chains, a specific number of kinematic pairs are actuated to provide the platform with n degrees of freedom relative to the base. Back in 1947, Gough [1] established the basic principles of a mechanism with a closed loop kinematic structure, his prototype machine allows to test tire wear and tear by changing the position and orientation of a moving platform, however the first use of this kind of robots was during the 1960's, at the time of aeronautics industry development, due to pilots' training increasing costs and the need to test equipment on the ground lead the researchers to look into mechanism with several degree of freedom that could simulate a heavily loaded platform with good speed and acceleration performance thus the first flight simulators were built, After the introduction of the flight simulator with closed loop kinematics chains in 1965 [2], parallel manipulators received more attention due to their good characteristics like high accuracy, high speed, high load capacity/mass ratio and rigidity etc. and rigidity etc. increasingly parallel manipulators with a certain number and type of degrees of freedom have been proposed.

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One type of parallel manipulator are the ones with 3 DOF, these kind of manipulators are good in pick and place and machining operations, the most famous ones with are the *delta robot*, that was initially developed by Clavel [3] with a kinematic chain of RRP_aR type, another one from this family is the *Tricept* which is developed by Neumann [4]with 3 RRPS chains used in machine tool applications, Reboulet suggests *the Speed-R-Man* robot which is similar to the delta but the rotary actuators are replaced by two linear ones [5], which exhibits a good speed characteristics and good maneuverability, another member of the 3 DOF translational family is the *orthoglide* robot developed for machining applications [6], This robotic system demonstrates consistent and uniform kinematic behavior throughout its operational workspace. The parallel cube manipulator belongs to the Orthoglide family, featuring three PRPRR kinematic chains. In this configuration, PR represents a planar four-bar parallelogram mechanism comprising four revolute joints, as illustrated in Fig.1. The linear actuators are positioned according to a Cartesian framework, meaning that the three actuation axes are perpendicular to one another. The joints that attach to the movable platform are situated on three faces of a cubic structure, which is why this particular manipulator design is referred to as the parallel cube-manipulator. The manipulators also have three translational DOFs as in the cases of DELTA robot and Tsai's manipulator, this robot has an application of micro-motion robots, remote center compliance (RCC) devices, and precise assembly machine [7].

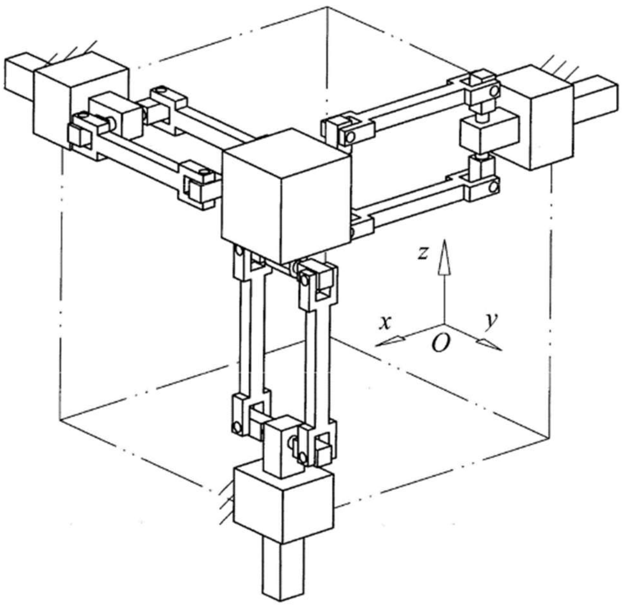

Fig.1. Parallel cube manipulator.

There are many performance indices for parallel manipulators to consider like dexterity, accuracy, stiffness, speed and accelerations, choosing one of these indices depends on the required application and design objectives of robot. This study concentrates on examining the Jacobian condition number, referred to simply as the condition number. This metric represents the ratio between the maximum and minimum singular values of the Jacobian matrix. Its primary benefit lies in providing a single numerical value that characterizes the complete kinematic performance of a robotic system. This index serves multiple purposes: it evaluates the precision and maneuverability of robots, indicates how close the system is to reaching a singular configuration, acts as a benchmark for achieving optimal designs and comparing different robotic platforms, and helps establish the practical operating region of a manipulator [8].

2. Work space analysis

One of the primary limitations of parallel manipulators is their restricted operational space. Beyond this fundamental constraint, several additional factors further reduce the available workspace volume, including the range limitations of passive joints, physical collisions between the linkages and the moving platform, and the occurrence of singular configurations within the workspace boundaries. Therefore, calculating the workspace volume becomes essential for several reasons: to verify that the manipulator can achieve the required positions and orientations for specific tasks, to locate singular zones where the system experiences degraded accuracy and controllability, and to map out areas where the manipulator exhibits strong performance based on various performance metrics. For instance, considering the workspace volume of parallel cube manipulators with specific geometric parameters such as $\rho_{max} = -774$ and $\rho_{min} = -1746$ where ρ_{min}, ρ_{max} are the min and max actuators strokes respectively, so that $|\rho_{max} - \rho_{min}| = 972$, the moving platform radius $r = 200$, and the length of the links $L = 1000$ is $809557568\ mm^3$. The method of calculating the workspace is explained in [7].

3. Kinematic model

Figure 2 illustrates the kinematic model that has been established. In each of the three chains, the central point of the linkage connects to the stationary base through prismatic joints, designated as B_i (where $i = 1, 2, 3$). The midpoint between the pair of spherical joints that attach the moving platform in each chain is labeled as P_i (where $i = 1, 2, 3$), and these points are positioned on three different faces of the cubic moving platform. Both B_i and P_i represent the centers of revolute joints within each chain. A fixed global coordinate frame *A*: *O-xyz* is established at the point where the three actuation axes intersect, with the *x*, *y*, and *z* axes aligned along the first, second, and third actuation directions respectively, as depicted in Fig.2. An additional coordinate frame A' $: o' - x'y'z'$ is located at the center of the cubic moving platform. The *xyz* axes are along the P_2O', P_3O', P_1O' respectively, the geometric parameters are $OP_i = r$ and $B_iP_i = L$, where $i = 1, 2, 3$.

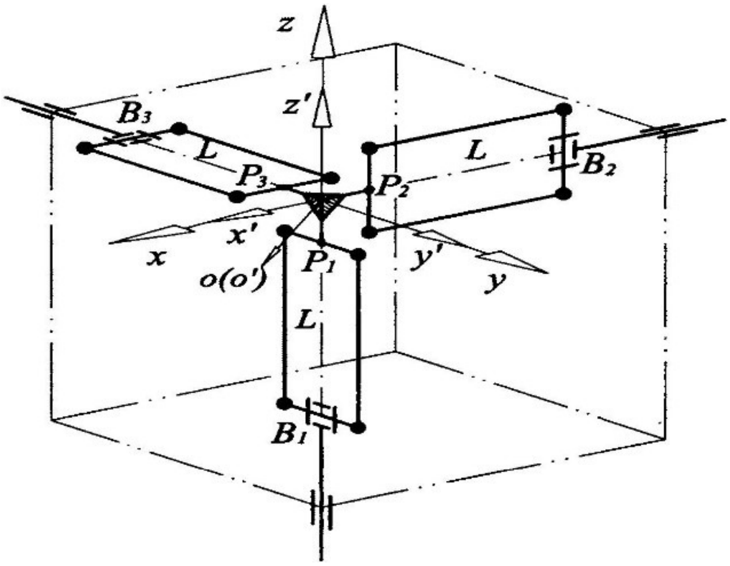

Fig.2. kinematic model of the 3 PRP$_R$R parallel manipulator.

4. Inverse kinematics model

The inverse kinematics objective is to find the joint coordinates if the required position of the end effector is given, deriving the inverse kinematics model is important for position control. There are two methods for deriving the inverse kinematics model the analytical and geometrical methods [9-15]. We use the former one because of the derivation simplicity of parallel cube manipulator.

Referring to Fig.2, the position vector S_R of the end effector can be written as:

$$S_R = [x \quad y \quad z]^T . \tag{4.1}$$

P_i coordinates in the moving frame $\{A'\}$ can be written as $P_{iA'}$ ($i = 1,2,3$) which can be expressed as:

$$P_{1A'} = \begin{bmatrix} 0 \\ 0 \\ -r \end{bmatrix}, \qquad P_{2A'} = \begin{bmatrix} -r \\ 0 \\ 0 \end{bmatrix}, \qquad P_{3A'} = \begin{bmatrix} 0 \\ -r \\ 0 \end{bmatrix}. \tag{4.2}$$

The vector P_i can be written in the fixed frame $\{A\}$ *O-xyz* as:

$$P_{iA} = P_{iA'} + S_R . \tag{4.3}$$

Also, the coordinates of point B_i can be written w.r.t the fixed frame $\{A\}$ *O-xyz* as:

$$b_{1A} = \begin{bmatrix} 0 \\ 0 \\ \rho_1 \end{bmatrix}, \qquad b_{2A} = \begin{bmatrix} \rho_2 \\ 0 \\ 0 \end{bmatrix}, \qquad b_{3A} = \begin{bmatrix} 0 \\ \rho_3 \\ 0 \end{bmatrix}. \tag{4.4}$$

Where ρ_1, ρ_2, ρ_3 are the manipulator's inputs, now the inverse kinematics problem can be solved be writing the following closure loop equation:

$$\| P_{iA} - b_{iA} \| = L \qquad \text{where} \qquad i = 1,2,3 . \tag{4.5}$$

Algebraically the above constraint equation can be written as:

$$x^2 + y^2 + (z - \rho_1 - r)^2 = L^2 , \tag{4.6}$$

$$(x - \rho_2 - r)^2 + y^2 + z^2 = L^2 , \tag{4.7}$$

$$x^2 + (y - \rho_3 - r)^2 + z^2 = L^2 . \tag{4.8}$$

From which we can solve for the manipulator's input if the position of the moving cube platform is known:

$$\rho_1 = \pm\sqrt{L^2 - x^2 - y^2} + z - r , \tag{4.9}$$

$$\rho_2 = \pm\sqrt{L^2 - y^2 - z^2} + x - r , \tag{4.10}$$

$$\rho_3 = \pm\sqrt{L^2 - z^2 - x^2} + y - r . \tag{4.11}$$

One can see from the above equations that there are eight solutions for the inverse kinematics problem, but only three of them are valid which are by taking the '–' sign only from the above equations, the other ones are invalid because of the interference problems between the legs and the moving platform.

5. Jacobian matrix

The Jacobian matrix relates the input velocities of the prismatic joints to the output velocities of the moving platform, in general calculating the Jacobian matrix is not a trivial task because of the inverse matrix calculation, except for planar robots which can be determined by direct differentiation of the closure loop equations as shown in [16-19]. Differentiating (4.6)-(4.8) equations give us the following:

$$x\dot{x} + y\dot{y} + (z - \rho_1 - r)\dot{z} = (z - \rho_1 - r)\dot{\rho}_1, \tag{5.1}$$

$$(x - \rho_2 - r)\dot{x} + y\dot{y} + z\dot{z} = (x - \rho_2 - r)\dot{\rho}_2, \tag{5.2}$$

$$x\dot{x} + (y - \rho_3 - r)\dot{y} + z\dot{z} = (y - \rho_3 - r)\dot{\rho}_3. \tag{5.3}$$

By some algebraic manipulation of the above equations, and rewriting them in a matrix form gives us the following:

$$A\dot{\rho} = B\dot{p} \tag{5.4}$$

where $\dot{p}$ is the moving platform velocity and can be expressed as follows:

$$\dot{p} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} \end{bmatrix}^T \tag{5.6}$$

and $\dot{\rho}$ is the prismatic joint velocity and can be expressed as follows:

$$\dot{\rho} = \begin{bmatrix} \dot{\rho}_2 & \dot{\rho}_3 & \dot{\rho}_1 \end{bmatrix}^T. \tag{5.7}$$

Matrices A and B are 3×3 inverse and forward Jacobian matrices respectively, and can be written as:

$$A = \begin{bmatrix} x - \rho_2 - r & 0 & 0 \\ 0 & y - \rho_3 - r & 0 \\ 0 & 0 & z - \rho_1 - r \end{bmatrix}, \quad B = \begin{bmatrix} x - \rho_2 - r & y & z \\ x & y - \rho_3 - r & z \\ x & y & z - \rho_1 - r \end{bmatrix}.$$

And if matrix A is non-singular, the equation (5.7) can be written as :

$$\dot{\rho} = J\dot{p} \tag{5.8}$$

where J is the manipulator's Jacobian matrix:

$$J = A^{-1}B = \begin{bmatrix} 1 & y/(x - \rho_2 - r) & z/(x - \rho_2 - r) \\ x/(y - \rho_3 - r) & 1 & z/(y - \rho_3 - r) \\ x/(z - \rho_1 - r) & y/(z - \rho_1 - r) & 1 \end{bmatrix}. \tag{5.9}$$

6. Condition number analysis

The condition number is Jacobian matrix highest to lowest singular value ratio, It is a well-known theorem in numerical analysis that the condition number measures the sensitivity of a system to small input changes, a matrix is called “ill-conditioned” if a small changes in the input cause large changes in the output and called “well-conditioned” if small changes in the input cause small change in the output, the values of the condition number goes from 1 to infinity where 1 indicates an isotropic configurations, An isotropic manipulator is superior in kinematic accuracy and does not have singular configurations [10]. and infinity means that the robot is in singular configurations, Singular configurations are particular poses of the end-effector, for which parallel robots lose their inherent infinite rigidity, and in which the end-effector will have uncontrollable degrees of freedom [9].

The term “well-conditioned” workspace is used and it is defined as the workspace where the condition number values varies from 1-2, one been isotropic and two is within the region where the robot is more stable and precise in its movement with less error multiplying factor and more predictable in all directions of its motion with no singular configuration around.

The links length and the cubic moving platform radius are crucial geometric parameters for parallel manipulators design; it plays a major role in the robot’s characteristics like workspace dexterity and singularities within the workspace [19-21].

By taking the different ratios of the above-mentioned geometric parameters, the results show that the higher *L/r* ratio is the better kinetostatic performance the manipulator is, algebraically the reason behind this is because of the structure of the Jacobian matrix, the higher the links length *L* compared to the moving platform radius r the bigger denominators values of the Jacobian matrix off-diagonal elements are, which leads to smaller off-diagonal magnitude values, means the manipulator is closer to the isotropic configurations, and this indicates the stability of the condition number over the workspace. Mechanically it indicates within the same actuators limits the manipulator has a higher reachability inside the workspace because the legs extensions are bigger, and also leads to higher percentage of the “well-conditioned” workspace. Also, the higher the ratio is the lower the max condition number is which means less or no singular configurations inside the workspace.

The sum of the above-mentioned parameters is kept constant $=1200\ mm$, *X*-axis and *Y*-axis indicate the moving platform position; the plots are at fixed value of $Z=0$.

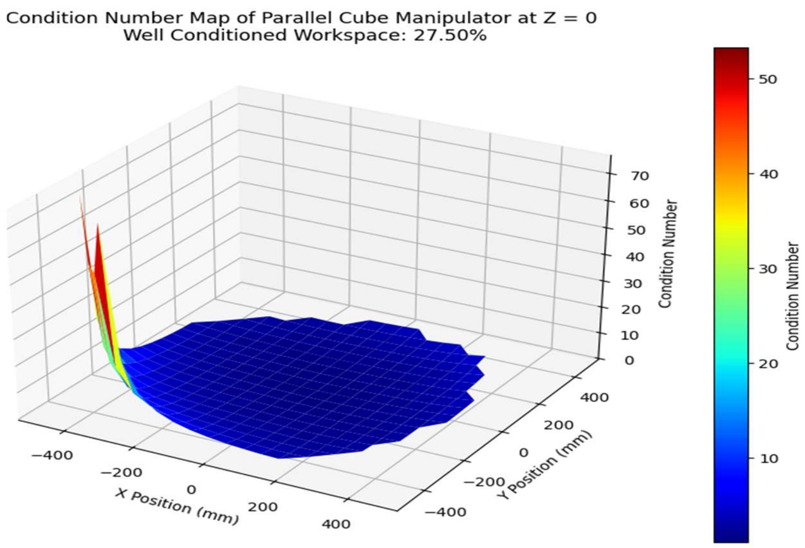

Fig.3. Condition number of 3 PRP_RR manipulator at $L=600$ and $r=600$.

1) First ratio $\left(L/r=1\right)$.

As shown in Fig.3 the condition number is evaluated over the whole workspace at $L=600$ and $r=600$, and the results are as following:

- The a “well-conditioned” workspace $=27.5\%$.
- The max condition number >50.

2) Second ratio $\left(L/r=1.4\right)$.

As shown in Fig.4 the condition number is evaluated over the whole workspace at $L=700$ and $r=500$, and the results are as following:

- The a “well-conditioned” workspace $=37\%$.
- The max condition number >20.

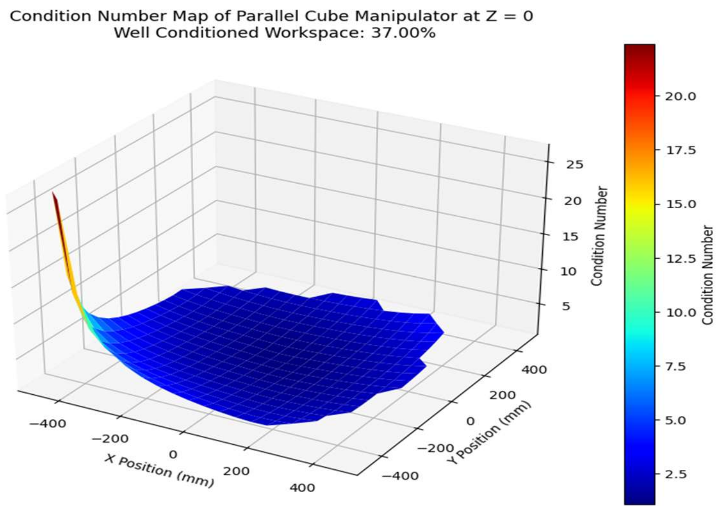

Fig.4. Condition number of 3 PRP$_R$R manipulator at $L=700$ and $r=500$.

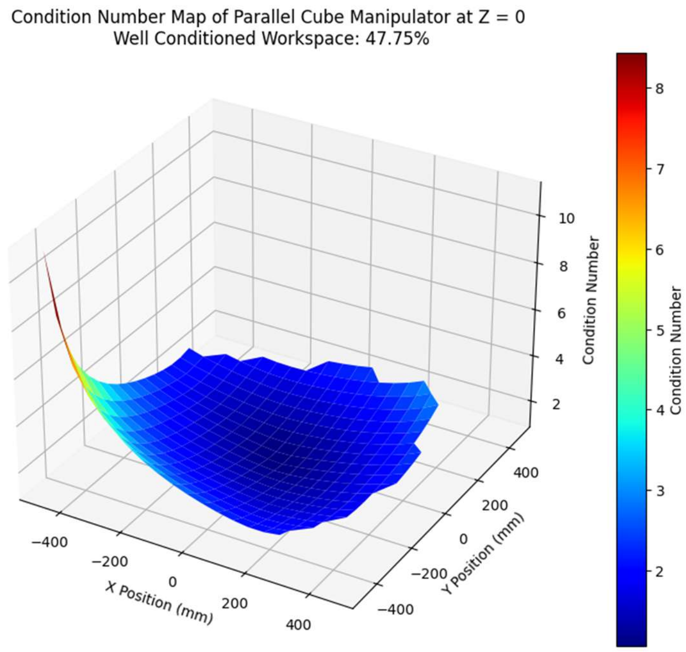

Fig.5. Condition number of 3 PRP$_R$R manipulator at $L=800$ and $r=400$.

3) Third ratio $(L / r = 2)$.

As shown in Fig.5 the condition number is evaluated over the whole workspace at $L = 800$ and $r = 400$, and the results are as following:

- The a "well-conditioned" workspace $= 47.75\%$.
- The max condition number > 8.

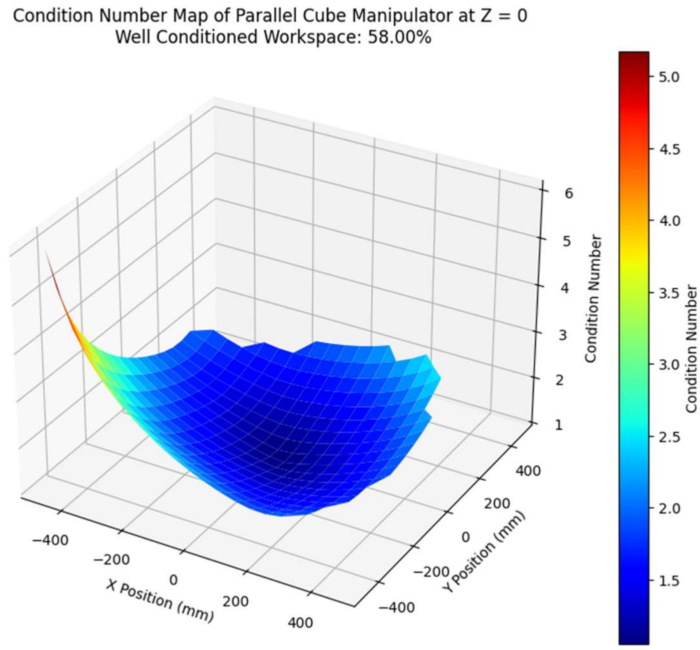

Fig.6. Condition number of 3 PRP_RR manipulator at $L = 900$ and $r = 300$.

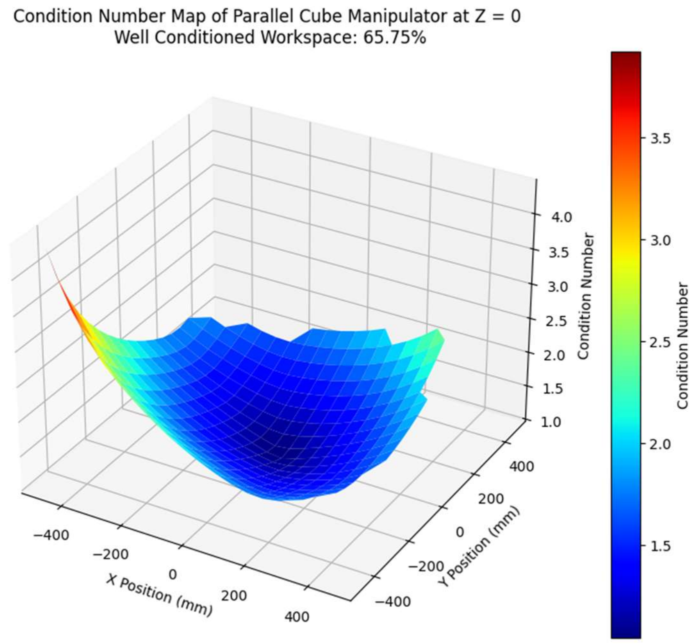

Fig.7. Condition number of 3 PRP_RR manipulator at $L = 1000$ and $r = 200$.

4) Fourth ratio $(L/r=3)$.

As shown in Fig.6 the condition number is evaluated over the whole workspace at $L=900$ and $r=300$, and the results are as following:

- The a "well-conditioned" workspace $=58\%$.
- The max condition number >5.

5) Fifth ratio $(L/r=5)$.

As shown in Fig.7 the condition number is evaluated over the whole workspace at $L=1000$ and $r=200$, and the results are as following:

- The a "well-conditioned" workspace $=65.75\%$.
- The max condition number >3.5.

6) Sixth ratio $(L/r=11)$.

As shown in Fig.8 the condition number is evaluated over the whole workspace at $L=1100$ and $r=100$, and the results are as following:

- The a "well-conditioned" workspace $=71.5\%$.
- The max condition number >3.

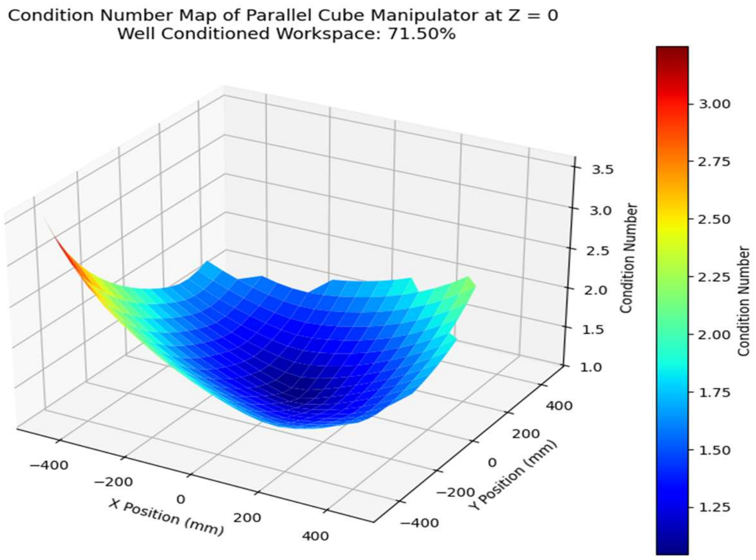

Fig.8. Condition number of 3 PRP_RR manipulator at $L=1100$ and $r=100$.

7. Results and discussions

The condition number analysis of the 3 PRP_RR manipulator parallel cube manipulator considering links length to the moving platform radius ratio = *11* reveals the best results in terms of a "well-conditioned" workspace (over *70%*) and the maximum condition number (less than *4*). It is observed that the higher the link length compared to the moving platform radius yield the best results. However, increasing the links length may introduce some mechanical drawbacks such as increases inertia. The condition number analysis provides valuable insights into its performance under different design parameters. Conducting this analysis allows designers to optimize the link lengths and the moving platform radius based on desired performance criteria. By carefully selecting appropriate link lengths, and moving platform radius the manipulator's sensitivity, accuracy and overall effectiveness can be enhanced.

The condition number variations over a fixed 2D workspace study was conducted by varying two geometric parameters which are the links length and the cubic moving platform radius while keeping their sum constant $(L + r = 1200)$, the ratio of the abovementioned parameters was varied from *1* to *11*, the results indicate that at $L / r = 1$ the maximum condition number was over *50* in some workspace regions and the "well-conditioned" workspace was only 27.75% from the whole workspace, as L / r increase the "well-conditioned" workspace increase also and the maximum condition number decrease. At $L / r = 11$ the "well-conditioned" workspace is over 71% and the maximum condition number is less than *4*.

8. Conclusions

This study was conducted to examine the effect of varying two geometric parameters ratios on the Jacobian's condition number, the results clearly show that the higher the ratio is the better the results are, meaning the manipulator is less sensitive to inputs change and more accurate. Additionally, the "well-conditioned" workspace is defined as the region where the condition number is in the range [1, 2], it increases as the L / r ratio increases. these geometric parameters selections are very important in the design process to optimize the kinetostatic performance of the manipulator. Overall, the study provides a clear quantitative and geometric basis on the best L / r ratio within practical mechanical constraints. This insight contributes directly to the design optimization of stable, precise, and high-performance parallel cube manipulators.

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Nomenclature

A – fixed global coordinate reference frame
A' – reference frame located at the center of moving platform
B_i, P_i – coordinates of the revolute joints in the fixed frame
J – Jacobian matrix
k – condition number
k_{max} – max condition number
L – length of the links
r – moving platform radius
x, y, z – Cartesian coordinates of the moving platform
$\dot{\rho}$ – prismatic joint velocity
ρ_{max} – max actuators stroke
ρ_{min} – min actuators stroke

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