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# Condition Number Analysis of 3$\underline{R}$RR Planar Parallel Manipulator by Varying Link Lengths

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## Abstract

Robot manipulators are categorized into parallel and serial manipulators based on their kinematic structure. Serial manipulators typically have less load transportation capabilities compared to parallel manipulators. The 3$\underline{R}$RR planar parallel robot manipulator is considered in this paper. The 3$\underline{R}$RR manipulator has three actuated joints and six passive revolute joints base platform is connected to the moving platform with three serial chains, with the kinematic relations the Jacobian matrix is derived. The condition number is the ratio of highest singular value to the lowest singular value. The condition number analysis plays a major role while selecting the best pose of end effector. By varying the link lengths, the condition number of the manipulator is calculated. This condition number serves as a measure of sensitivity to changes in the manipulator's input parameters. The plotted results are compared for different lengths and the best link size is estimated.

## Keywords

Robot manipulators, 3$\underline{R}$RR planar parallel manipulators, Condition number, Workspace, Jacobian matrix

## Introduction

Robotic industries and researchers are concentrating fast pick and place robots for packaging applications, the delta robots especially suited for fast picking and place processes. The delta robot is a blend of serial as well as parallel robots, the researchers also concentrating on the base of a delta or any positioning robot, the base platforms of the any device which need precise positioning the parallel manipulators are best suited. As parallel manipulators have good motion performance characteristics i.e., dynamic performance characteristics, optimum weight to load ratio, no error accumulation like serial robots and easy inverse kinematics, although these many advantages there are drawbacks like singularity, complicated manufacturing, need more accessories to control manipulator.

Gough and Stewart developed a parallel linkage based kinematic chain mechanism called Stewart Gough Platform [1, 2], which has many applications among all field of technology and engineering, this platform developed for tire testing with Six Degrees of Freedom. The Gough platform is used for base for parallel manipulator study, After the Farooq [3] proposed various parallel manipulator problems and laid foundations for developments of parallel manipulators, further these problems are solved and designed for specific applications and patented by various designers. The Delta robots [4] used in fast packaging applications in various packaging industries are an example of such design. To assess the performance of these robots many performance indices are proposed the related works are consolidated in the [5, 6].

There are many studies that address the Jacobian matrix and performance measures like condition number, stiffness indices [7], manipulability indices, robustness indices, dexterity indices, workspace [8, 9], dynamic performance [10, 11], etc., but the primary link (connects to ground/ fixed platform) and second link (connected to primary link and moving platform) are same in size. This work examines the variations in condition number with different link lengths as the change of link lengths are more flexible while manufacturing the planar parallel robots, and high potential to reduce the singularities in the workspace. The problems linked with condition numbers were studied in detail in this work.

## Experimentation

### About 3RRR planar parallel manipulators

Three revolute joints make up the 3RRR manipulator, one of which is an actuated joint. The movable triangular plate acts as a moving platform connected to fixed base with the help of links. There are two links in each connection. A total of six links are used in the mechanism, after adding two platforms the total links are eight and joints are nine with zero higher pairs. The R indicates the revolute joint and R indicates the actuated revolute joint. The 3RRR contains three actuated revolute joints and six binary joints.

Planar parallel manipulators (PPMs) have a particular feature that their motion takes place in a plane, rather than in three-dimensional space. This feature makes them well suited for tasks that require planar motion, such as pick-and-place operations or printing tasks. One advantage of PPMs over serial manipulators is their high stiffness, which allows for high precision and accuracy. They also have a smaller workspace, which makes them more compact and easier to control. PPMs had a lot of applications in the manufacturing, assembly, and inspection processes, where high accuracy, speed, and reliability are required. The 3RRR PPMs is a widely used mechanism in robotics due to its simple structure and high precision [12]. This indicates that the manipulator becomes more sensitive to perturbations in the input data as its size and range of motion increase. The paper also discusses the practical implications of the condition number analysis, such as the effect of measurement errors on the accuracy of the manipulator, and the importance of choosing appropriate input data to minimize the condition number. Overall, this paper provides a comprehensive analysis of the 3RRR PPM and presents useful insights for its design and control [13].

Nanorobots, also known as nanobots or nanomachines, are hypothetical miniature robots or machines that operate on a nanoscale, typically at the molecular or atomic level. The concept of nanorobots has captured the imagination of scientists, engineers, and science fiction writers for many years. While nanorobots are not yet a reality, there has been significant research and development in the field of nanotechnology. Nanorobots are incredibly small, with dimensions in the order of nanometers (1 nanometer is one billionth of a meter). This tiny size allows them to interact with individual molecules and cells. To potentially apply concepts from numerical analysis and linear algebra to assess the stability and precision of nanorobotic systems. When dealing with nanorobots or any nanoscale systems, precision and stability are crucial due to the small scale and sensitivity of these devices [14-16].

The control algorithms and systems used to guide nanorobots must be designed to account for uncertainties, disturbances, and variations in the environment. Nanorobots may require advanced sensing and feedback mechanisms to detect their position and orientation accurately. This information can be used for real-time control and adjustments. The materials used to build nanorobots should have consistent properties to avoid variations that could affect their performance. Precise manufacturing processes are essential. Nanorobots operating in fluid environments, such as inside the human body, may be subject to external forces like fluid flow, Brownian motion, or biochemical interactions. These factors must be considered in the design and control of nanorobots. Nanorobots will need a reliable and sustainable energy source to operate over extended periods, especially if used in medical or environmental applications. Error-correction techniques may be required to compensate for deviations or inaccuracies that can occur at the nanoscale [17-19].

While condition number in the traditional numerical analysis sense may not directly apply to nanorobots, the stability and precision of nanorobotic systems would be assessed using principles from control theory, mechanics, and nanotechnology. Researchers would need to consider these factors to ensure that nanorobots can perform their intended tasks accurately and reliably in various applications [20].

Robotics and its related topics have been studied using a variety of performance measures that have been proposed. These performance metrics are acknowledged in robot research and development as well as in industrial applications. A robot manipulator is a type of robot that is designed to manipulate or move objects in a specific way. It typically consists of a series of linked segments (called links), which are connected by joints. The joints can be controlled by a computer, allowing the robot to move and manipulate objects with precision.

A robot manipulator is also known as an industrial robot arm and is commonly used in manufacturing and other industries where repetitive tasks are performed. Robot manipulators are capable of performing a wide range of tasks, including welding, assembly, material handling, painting, and inspection. Robot manipulators can be either stationary or mobile. Stationary manipulators are fixed in place and typically operate in a designated workspace. Mobile manipulators, on the other hand, can move around the workspace and perform tasks in different locations. Robot manipulators can be controlled by a human operator using a control panel, or they can be programmed to perform tasks autonomously using computer software. Some robot manipulators are also equipped with sensors and cameras, which allow them to detect and respond to changes in their environment.

### Geometry of 3RRR PPM

The 3RRR PPM consists of three kinematic closed loops kinematic chains, each of which is composed of a revolute joint followed by another revolute joint, and then a third revolute joint that is connected to a common moving platform. The three chains are connected to the base at three fixed points that form an equilateral triangle. The 3RRR PPM is shown in figure 1 and the extended arm loop is shown in figure 2. The moving platform of the 3RRR parallel manipulator is capable of planar motion and can move in any direction within the plane of the triangle formed by the fixed points. The kinematic design of the 3RRR parallel manipulator provides a high degree of accuracy and stiffness, making it well suited for applications that require precise positioning and manipulation, such as micro-manufacturing, surgery, and inspection tasks. One advantage of the 3RRR PPM is that it has a big workspace for its size, which makes it suitable for tasks that require a large range of motion. Additionally, the 3RRR parallel manipulator is relatively easy to control and has low power consumption compared to other types of manipulators. 3RRR PPM is a popular design due to its high precision and accuracy, large workspace, and low power consumption.

The loop closure equations are generated from figure 2. These loop closure equations are arranged in the form of $J_x\dot{x} = J_q\dot{q}$ gives the relation between joint velocities and head velocities, in other words the Jacobians are correction co-efficients which relates the joint velocities of manipulator to angular velocities of manipulator.

$$x_B = x_A + h\cos\phi \tag{1}$$

$$y_B = y_A + h\sin\phi \tag{2}$$

and

$$x_C = x_A + h\cos\left(\phi + \frac{\Pi}{3}\right) \tag{3}$$

$$y_C = y_A + h\sin\left(\phi + \frac{\Pi}{3}\right) \tag{4}$$

$$y_A = \alpha_1\sin\theta_1 + b_1\sin\left(\theta_1 + \varphi_1\right) \tag{5}$$

$$y_A = \alpha_1\sin\theta_1 + b_1\sin\left(\theta_1 + \varphi_1\right) \tag{6}$$

By removing passive joint angles, the equation 7 is generated:

$$x_A^2 + y_A^2 - 2x_A a_1\cos\theta_1 - 2y_A a_1\sin\theta_1 + a_1^2 - b_1^2 = 0 \tag{7}$$

## Jacobian matrix of 3RRR PPM

The Jacobian matrix plays a crucial role in relating the velocities of joint angles to the velocities of the moving platform in a planar parallel manipulator. It is a 3xN matrix, N represents the number of joints in the manipulator. To compute the Jacobian matrix, forward kinematics equations are utilized. These equations establish the relationship between the moving platforms position, orientation, and the joint angles. These forward kinematics equations are expressed as a set of nonlinear equations. Numerical methods can be employed to solve these equations and obtain the expressions for the Jacobian matrix, which are specific to the geometry and kinematics of the particular parallel manipulator being analyzed. The structure and arrangement of the manipulator's links, joints, and the end-effector determine the precise form of the Jacobian matrix. By computing the Jacobian matrix, engineers and researchers gain valuable insights into the relationship among joint velocities and end-effector (moving platform) velocities. This information is crucial for tasks such as trajectory planning, inverse kinematics, and control of the parallel manipulator.

$$J_x\dot{x} = J_q\dot{q} \tag{8}$$

Where,

$$J_x = \begin{bmatrix} b_{1x} & b_{1y} & K_{1x}.b_{1y} - K_{1y}.b_{1x} \\ b_{2x} & b_{2y} & K_{2x}.b_{2y} - K_{2y}.b_{2x} \\ b_{3x} & b_{3y} & K_{3x}.b_{3y} - K_{3y}.b_{3x} \end{bmatrix};$$

$$J_q = \begin{bmatrix} a_{1x}.b_{1y} - a_{1y}.b_{1x} & 0 & 0 \\ 0 & a_{2x}.b_{2y} - a_{2y}.b_{2x} & 0 \\ 0 & 0 & a_{3x}.b_{3y} - a_{3y}.b_{3x} \end{bmatrix}$$

and where,

$$\dot{x} = \left[v_{gx}, v_{gy}, \dot{\phi}\right]^T \text{ and } \dot{q} = \left[\dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3\right]^T$$

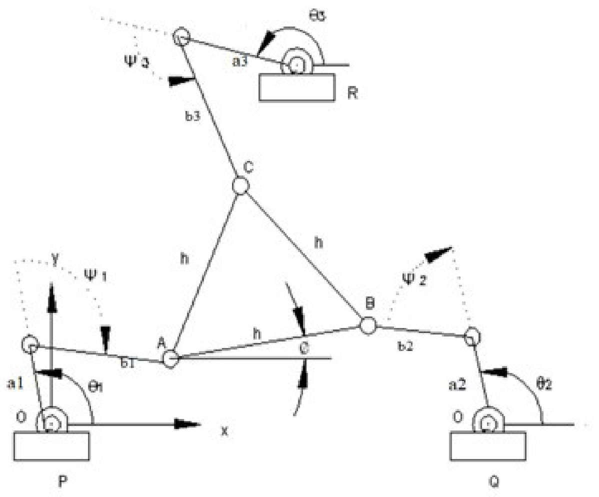

**Figure 1:** Kinematic model of 3RRR PPM.

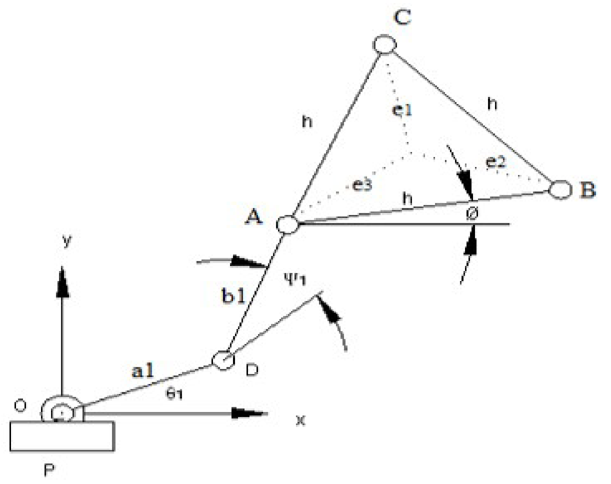

**Figure 2:** Single loop of the parallel manipulator.

The Jacobian of the 3RRR is as follows,

$$J = J_q^{-1} J_x$$

## Workspace of manipulators

The workspace of a robot manipulator refers to the physical region in which the end-effector (the tool or gripper attached to the robot arm, moving platform in case of parallel manipulators) can reach and operate. It is often defined by the maximum and minimum positions that the robot arm can reach in terms of its joint angles or Cartesian coordinates. The workspace of a robot manipulator can vary depending on several factors, such as:

### Robot configuration

The number of joints and their range of motion greatly affects the workspace. For example, a robot with more joints and larger joint ranges has a larger workspace compared to a robot with fewer joints or limited joint ranges.

### Robot kinematics

The kinematic structure of the robot arm, such as the length of the links and the arrangement of the joints, determines the reachable workspace. Different arm configurations allow for different ranges of motion and, therefore, different workspaces.

### Obstacles and constraints

The presence of obstacles or physical constraints in the robot's environment can limit its workspace. For instance, if there are walls, objects, or other robots in close proximity, the workspace might be restricted to avoid collisions.

### Singularities

Singular configurations are specific joint angles or poses where the robot's end-effector loses one or more degrees of freedom. At these points, the workspace can be significantly reduced or distorted.

To analyze and visualize the workspace of a robot manipulator, several techniques are commonly used, including geometric methods, kinematic simulations, or numerical algorithms. By considering the robot's kinematics, joint limits, and any external constraints, it is possible to determine the boundaries and reachable regions within the workspace. It's important to note that the workspace is typically defined based on the robot's reachability and does not take into account other factors such as payload capacity, joint torque limitations, or sensor reach. These additional considerations may further restrict the effective operational workspace of a robot manipulator in practical applications. The 3RRR PPM workspace is generated by drawing three circles with straight arm. Figure 3 is the common area between the three circles representing the workspace of the 3RRR PPM.

## Performance indices of 3RRR PPM

The performance indices of a 3RRR parallel manipulator can vary depending on the specific design, kinematics, and objectives of the manipulator system. Here are some commonly used performance indices for evaluating the performance of parallel manipulators, including the 3RRR configuration.

### Dexterity

Dexterity measures the manipulator's ability to move the end-effector to different positions and orientations within its workspace. It is often quantified using metrics like manipulability, condition number, or Jacobian-based indices. Higher dexterity implies better maneuverability and flexibility.

### Accuracy

Accuracy evaluates the precision with which the manipulator can achieve desired positions and orientations. It can be measured by assessing factors such as positioning errors, repeatability, or end-effector trajectory tracking. Factors like joint clearances, manufacturing tolerances, and control systems play a role in determining accuracy.

### Stiffness

Stiffness refers to the rigidity of the manipulator structure. It indicates how the manipulator resists deflection or deformation when subjected to external forces or moments. Higher stiffness is desirable for maintaining positional accuracy and stability during operation.

### Speed and acceleration

Performance indices related to speed and acceleration evaluate the manipulator's ability to perform tasks quickly. Metrics such as maximum achievable velocities, accelerations, and dynamic response time can provide insights into the manipulator's dynamic capabilities.

### Energy efficiency

Energy efficiency considers the amount of energy consumed by the manipulator system to perform a given task. It can be quantified by evaluating factors like power consumption, torque requirements, or energy consumption per unit of work accomplished.

These performance indices can be calculated analytically

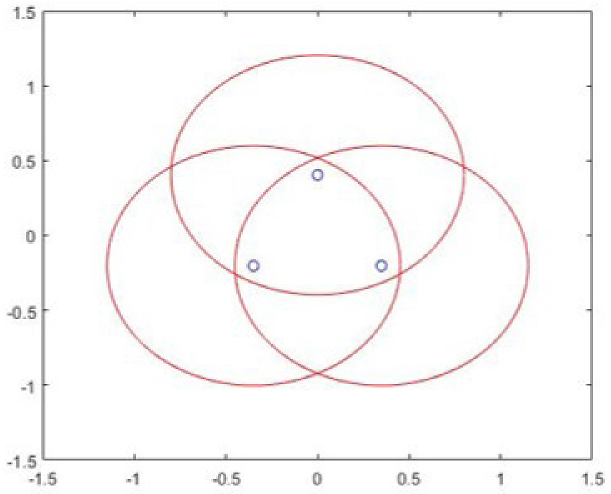

**Figure 3:** The workspace of 3RRR PPM. **Case-I:** The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.2 and b1 = 0.8 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

using mathematical models or assessed through simulation or experimental testing. Workspace also plays a major role. It's important to note that different indices may be prioritized based on the specific application requirements and design objectives of the 3RRR parallel manipulator.

## Condition number

Condition number is the ratio of the highest singular value to the lowest singular value or product of double norm (Frobenius Norm) of Jacobian matrices. The condition number of the Jacobian matrix provides valuable information about the sensitivity of a 3RRR PPM to small changes in its input parameters, such as the lengths of its links. The Jacobian matrix, which relates the velocities of the joint angles to the velocities of the end-effector, has singular values that correspond to the lengths of the semi-axes of an ellipse representing the end-effector motion in joint space.

The condition number, calculated as the ratio of the maximum and minimum eigenvalues of the Jacobian matrix [21, 22], indicates the elongation of this ellipse. A larger condition number suggests that the manipulator's motion is more sensitive to small changes in the joint angles. This sensitivity can lead to reduced accuracy and stability.

The configurations with more similar link lengths tend to result in higher condition numbers, indicating greater sensitivity to parameter changes. On the other hand, configurations with more diverse link lengths tend to have lower condition numbers, indicating reduced sensitivity to parameter variations. A high condition number implies that the manipulator is more challenging to control and may have decreased accuracy, while a low condition number suggests better controllability and accuracy. By analyzing the condition number, designers and engineers can make informed decisions regarding the link lengths of the 3RRR PPM to achieve desired performance characteristics, such as improved accuracy, stability, and ease of control. By varying the link lengths, figure 4, figure 5, figure 6, figure 7, figure 8, and figure 9 are the condition number distribution in the workspace, the X axis and Y axis combined region shows the robot workspace grid or region and along the Z axis the variation in the condition number plotted.

### Case-I

The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.2 and b1 = 0.8 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

### Case-II

The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.2 and b1 = 0.2 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

### Case-III

The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.8 and b1 = 0.8 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

### Case-IV

The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.2 and b1 = 1 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

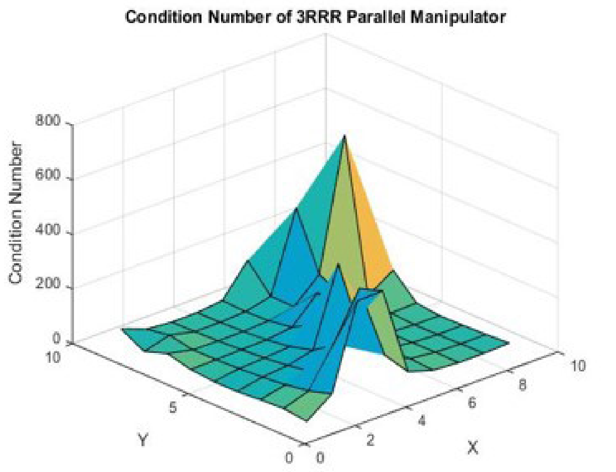

**Figure 4:** The condition number spread on the workspace of 3RRR PPM (plot X axis and Y axis indicates the movement of end effector (moving platform CG). **Case-II:** The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.2 and b1 = 0.2 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

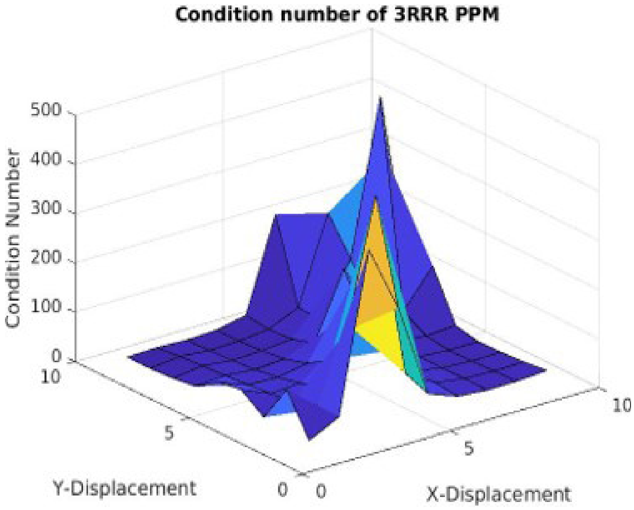

**Figure 5:** The condition number spread on the workspace of 3RRR PPM (plot X axis and Y axis indicates the movement of end effector (moving platform CG). **Case-III:** The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.8 and b1 = 0.8 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

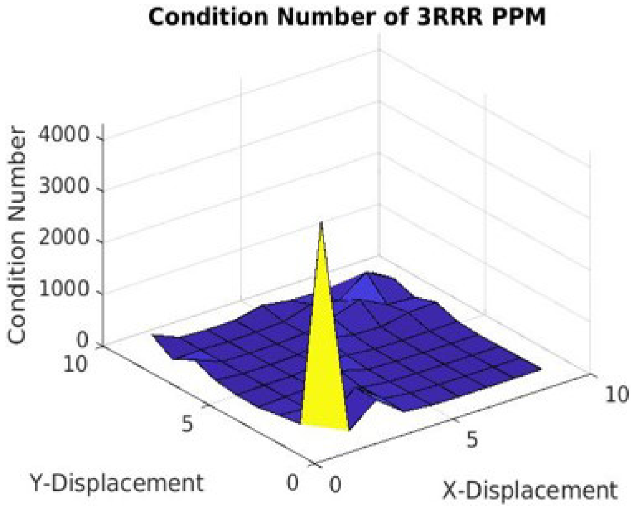

**Figure 6:** The condition number spread on the workspace of 3RRR PPM (plot X axis and Y axis indicates the movement of end effector (moving platform CG). **Case-IV:** The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 0.2 and b1 = 1 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

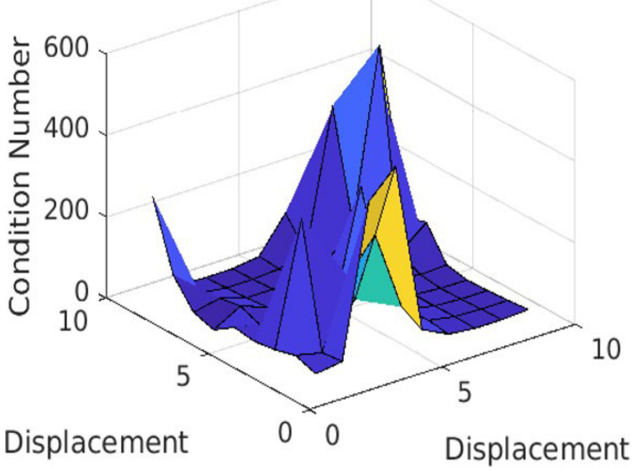

**Figure 7:** The condition number spread on the workspace of 3RRR PPM (plot X axis and Y axis indicates the movement of end effector (moving platform CG). **Case-V:** The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 1 and b1 = 1 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

## Case-V

The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 1 and b1 = 1 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

## Case-VI

The condition number circulation on the workspace of the 3RRR ppm is obtained when the link lengths a1 = 1.15 and b1 = 1 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

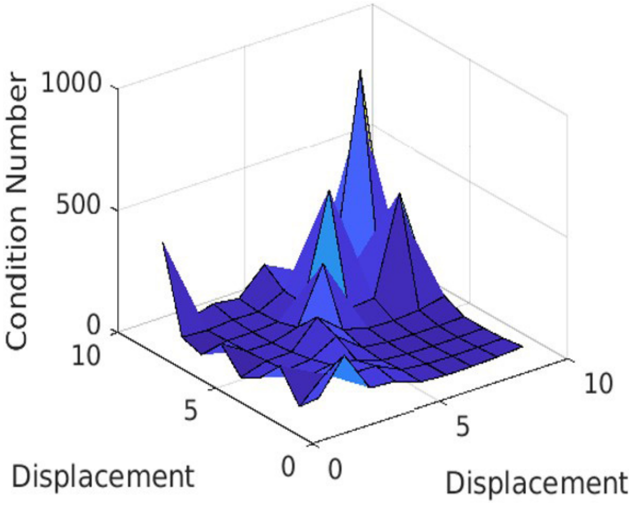

**Figure 8:** The condition number spread on the workspace of 3RRR PPM (plot X axis and Y axis indicates the movement of end effector (moving platform CG). **Case-VI:** The condition number circulation on the workspace of the 3RRR PPM is obtained when the link lengths a1 = 1.15 and b1 = 1 are considered, combinedly total length of one unit the figure represents the plot of the results obtained from MATLAB.

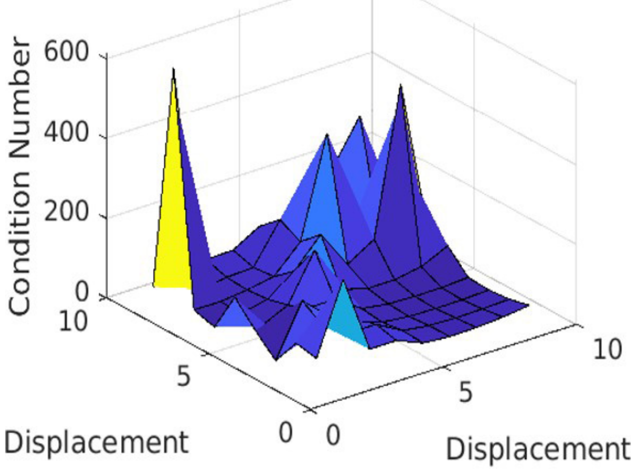

**Figure 9:** The condition number spread on the workspace of 3RRR PPM (plot X-axis and Y-axis indicates the movement of end effector (moving platform CG).

# Results and Discussion

The condition number analysis of a 3RRR PPM, considering link lengths a1 = 1 and b1 = 1, reveals that these lengths are appropriately distributed within the workspace. The maximum condition number obtained is 888.932639. It is observed that a smaller length for the second link yields the best results. The analysis of the manipulator's condition number provides valuable insights into its performance under different design parameters. By assessing the sensitivity of the manipulator's motion to small changes in the input parameters, the condition number serves as a metric for evaluating accuracy and stability. A higher condition number indicates a greater sensitivity to parameter variations, which can potentially lead to decreased accuracy and stability. The modelling and condition number analysis of a 3RRR PPM by varying link lengths is a valuable tool for improving the performance and reliability of the manipulator and can help to optimize its design for specific applications.

To understand the impact of varying link lengths on the condition number and overall performance of the 3RRR PPM, it is possible to experiment with different configurations. This evaluation can be carried out through analytical methods or numerical techniques such as finite element analysis. Conducting this analysis allows designers to optimize the link lengths based on desired performance criteria. By carefully selecting appropriate link lengths, the manipulator's accuracy, stability, and overall effectiveness can be enhanced.

## Conclusion

The robot manipulator link length selection is a tedious task. The optimized link lengths of the 3RRR PPM can significantly improve its performance, including its precision, accuracy, and stability. Reducing the condition number, the manipulator can become less sensitive to changes in the input parameters, which can lead to more reliable and consistent performance. The robot manipulator link length selection will depend on the specific results obtained for the manipulator under consideration, as condition number alone is not sufficient to select the appropriate link length and best work posture. The other kinematic and dynamic analysis is helpful along with condition number analysis. Additionally, optimizing the link lengths can also improve the workspace of the manipulator, making it more versatile and suitable for a wider range of applications. From the results it is concluded that the smaller length of second manipulator link gives the best results compared to the smaller length of base link.

## Acknowledgements

None.

## Conflict of Interest

None.

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