Kinematic Analysis and Optimum Design of 8-8 Redundant Spatial In-Parallel Manipulator

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Abstract- The quality index considered will assist the designer to choose the relative dimensions of the fixed and moving platforms, locate joint centers in the fixed and moving platforms, determine an optimum position which would be an 'ideal' location of the workspace center, and determine acceptable ranges of pure translations and pure rotations for which the platform is stable Symbolic expressions are derived for the quality indices for different configurations like central symmetric configuration, vertical and horizontal translation of moving platform and rotation of the platform about transverse and vertical axis of symmetry. Jocobin matrice are derived by using ball's screw theory that is in particular plucker line coordinates. The forward kinematic analysis of the 8-8 redundant in-parallel manipulators to determine the position and orientation of the platform for the given the leg lengths is also studied in the project work. A computer program in matlab 7.0 is written for finding the quality index of the manipulator. Graphs are also plotted by using the same matlab program

KEYWORDS: Manipulators, six-degree-of-freedom, Stewart Platform

I. INTRODUCTION

Parallel manipulators possess significant advantages over serial manipulator in terms of dynamic properties, load-carrying capacity, high accuracy as well as stiffness. This is because parallel manipulators are characterized by several kinematic chains connecting the base to the end-effectors, which allows the actuators to be located on or near the base of the manipulator. Therefore, parallel manipulator can be used in many applications where these properties are of primary importance while a limited workspace is acceptable. *Gough* built the first hexapod to test tires. This parallel manipulator is commonly referred to as "Gough-Stewart platform" and now generally accepted in the robotics and manipulators community. But the most common application of parallel manipulators is undoubtedly in flight simulation, as originally proposed by Stewart. Although flight simulators have been used for several years, it was only in the 1970's that Hunt introduced the concept of parallel manipulator and suggested, in his book, using this type of manipulator in robotics. Since then, parallel manipulators have been given considerable attention. The number of applications in which parallel manipulators are used has been steadily increasing and several prototype manipulators have been built. For instance, parallel manipulators can also be used as machine tools or even for medical purpose. So far, many types of parallel manipulators have been proposed. Parallel manipulators have been studied extensively over the last decade with their high structural stiffness, position accuracy and good dynamic performance Usually they have the same number of actuators as their degree of freedom, but in some cases, it may be interesting to have more actuators than needed to overcome disadvantages of the non redundant parallel manipulators. A parallel manipulator can be defined as a manipulator, which is made up of a closed-loop kinematic chain. Parallel manipulators are classified as Planar, Spherical and Spatial manipulators in accordance with their motion characteristics. A parallel manipulator typically consists of a moving platform that is connected to a fixed base by several limbs or legs. Typically, the number of limbs is equal to the number of degrees of freedom such that one actuator controls every limb and all the actuators can be mounted at or near the fixed base. For this reason, parallel manipulators are sometimes called as platform manipulator. Because the actuators can share the external load, parallel manipulators tend to have a large load-carrying capacity[1,15]

II. Advantages of Parallel manipulators over Serial manipulators

- High stiffness
- Low inertia
- Large payload capacity

However, they suffer the problems of relatively small useful workspace and design difficulties. Furthermore, their direct kinematics is a very difficult problem.

Applications of parallel manipulators: Parallel manipulators can be found in many applications.

- Such as in Airplane and automobile simulators
- Adjustable articulated trusses
- Mining machines
- High speed/high-precision milling machines.
- Walking machines.
- Machine centers
- Photonics / Fiber alignment.

2.1 Parallel-Link Robots

By far the most widely used commercial robots are the serial-link manipulators, whose links and joints alternate with one another in an open kinematic chain. This serially connected configuration is similar to that of the human arm, with each link connecting only to two neighboring links through either prismatic or revolute joints, except for the last link which attaches to the end effector and the robot base which attaches to the floor. The advantage of the serial chain structural arrangement is that it provides a large work volume and dexterous manipulability; however, it suffers from a lack of rigidity and from accumulated actuator errors. Especially at high speed and high dynamic loading operating conditions, the serial-link manipulators show poor dynamic performance. To improve the dynamic performance and achieve high precision operations, the robot links must be made with high rigidity, which results in heavy robots with low force-output-to-manipulator-weight ratio. On the other hand, if the links can be arranged parallel to one another in a closed kinematic chain structure such that the major force components add together, then high precision operations and high force-output-to-manipulator-weight ratios can be achieved.[5,18]

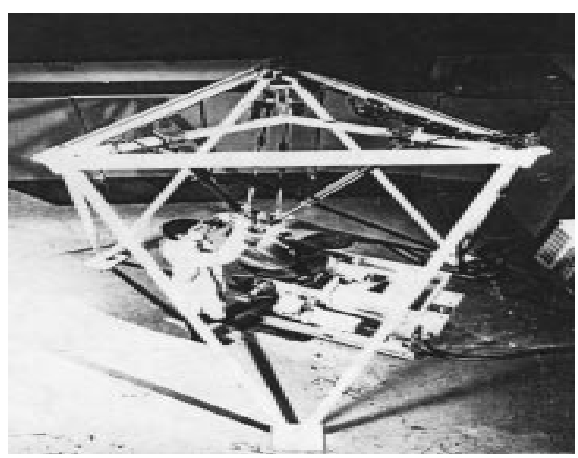

Fig: 1 six-degree-of-freedom Stewart platform manipulator : 2 Stewart platform automated surface finishing cell.

2.2 The Stewart Platform

The most popular and successful parallel mechanical structure is the so-called Stewart platform, which was first proposed by Stewart in 1965. As a manufacturing manipulator, the Stewart platform has two fundamental characteristics which set it apart from machine tools and industrial robots — it is a closed kinematic system with parallel links. The Stewart platform link ends are simply supported, making the manipulator system far more rigid in proportion to size and weight than any serial link robot. Furthermore, the links of the Stewart platform are arranged so that the major force components of the six actuators add together, yielding a force-output-to-manipulator-weight ratio more than one order of magnitude greater than most industrial robots. The original Stewart platform was designed for an aircraft simulator and consisted of six linear hydraulic actuators acting in parallel between the base and the upper platform. All the links are connected both at the base and at the upper platform. Thus, by changing the length of each link, the position and orientation of the upper platform are able to be controlled manipulator

III.QUALITY INDEX OF 8-8 IN-PARALLEL ROBOT MANIPULATOR

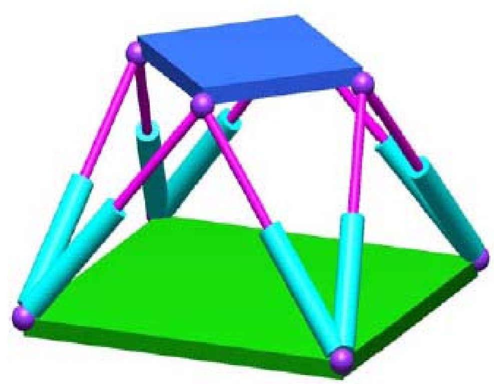

Fig: 5.1 Redundant 8-8 in-parallel

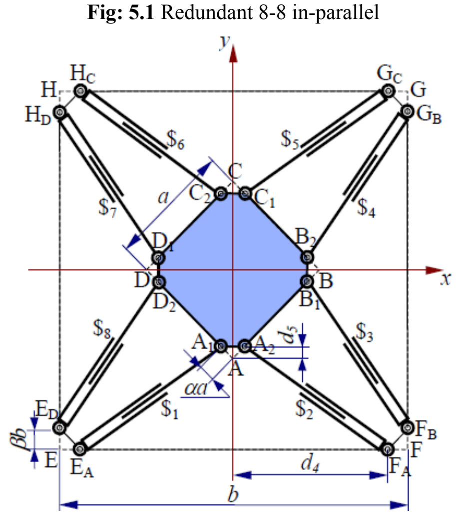

Fig: 5.2 Plan view of the redundant 8-8 in-parallel manipulator

5.1 Quality index for central symmetrical configuration

The moving platform of the redundant 8-8 parallel manipulator is located at its central symmetrical configuration and is parallel to the base with a distance *h*. At this configuration, the manipulator is fully symmetric and each leg has the same length. Clearly, at such position the platform is most stable from the geometric static point of view. When the platform departs from this central symmetric position, the platform will lose its geometric symmetry and the eight leg lengths will be different. Therefore, it is reasonable to assume that at the central symmetric configuration, it is possible to determine the values of square base side *b* and height *h* based on square platform side *a* so that a maximum value of the square root of the determinant of the product of the manipulator Jacobian by its transpose, i.e., may be obtained. [6,17]

Firstly, the coordinates of the points *A*, *B*, *C*, and *D* on the platform and *E*, *F*, *G*, and *H* on the base are determined with the origin of a fixed coordinate system placed at the center of the square base, and

$$A_1\begin{pmatrix} -d_5 & d_5-\frac{\sqrt{2}a}{2} & h \end{pmatrix}, \qquad A_2\begin{pmatrix} d_5 & d_5-\frac{\sqrt{2}a}{2} & h \end{pmatrix},$$

$$B_1\begin{pmatrix} \frac{\sqrt{2}a}{2}-d_5 & -d_5 & h \end{pmatrix}, \qquad B_2\begin{pmatrix} \frac{\sqrt{2}a}{2}-d_5 & d_5 & h \end{pmatrix},$$

$$C_1\begin{pmatrix} d_5 & \frac{\sqrt{2}a}{2}-d_5 & h \end{pmatrix}, \qquad C_2\begin{pmatrix} -d_5 & \frac{\sqrt{2}a}{2}-d_5 & h \end{pmatrix},$$

$$D_1\begin{pmatrix} d_5-\frac{\sqrt{2}a}{2} & d_5 & h \end{pmatrix}, \qquad D_2\begin{pmatrix} d_5-\frac{\sqrt{2}a}{2} & -d_5 & h \end{pmatrix}$$

Then, using the Grassmann method to calculate the Plücker line coordinates of the eight leg lines, i.e., counting the 2×2 determinants of the various arrays of the joins of the pairs of points *EA*, *FA*, *FB*, *GB*, *GC*, *HC*, *HD*, and *ED*. For example, the coordinates of the line \$1 are obtained using the coordinates of points *E* and *A* in to form the array

$$\mathbf{J}=\frac{1}{l}\begin{bmatrix} \frac{b}{2} & -\frac{b}{2} & d_1 & d_1 & -\frac{b}{2} & \frac{b}{2} & -d_1 & -d_1 \\ -d_1 & -d_1 & \frac{b}{2} & -\frac{b}{2} & d_1 & d_1 & -\frac{b}{2} & \frac{b}{2} \\ h & h & h & h & h & h & h & h \\ -\frac{bh}{2} & -\frac{bh}{2} & -\frac{bh}{2} & \frac{bh}{2} & \frac{bh}{2} & \frac{bh}{2} & \frac{bh}{2} & -\frac{bh}{2} \\ \frac{bh}{2} & -\frac{bh}{2} & -\frac{bh}{2} & -\frac{bh}{2} & -\frac{bh}{2} & \frac{bh}{2} & \frac{bh}{2} & \frac{bh}{2} \\ \frac{\sqrt{2}ab}{4} & -\frac{\sqrt{2}ab}{4} & \frac{\sqrt{2}ab}{4} & -\frac{\sqrt{2}ab}{4} & \frac{\sqrt{2}ab}{4} & -\frac{\sqrt{2}ab}{4} & \frac{\sqrt{2}ab}{4} & -\frac{\sqrt{2}ab}{4} \end{bmatrix}$$

Where

$$d_1=\frac{\sqrt{2a}-b}{2},$$

Using equation (5.13), the determinant of the product $\mathbf{J}\,\mathbf{J}^{\mathbf{T}}$ can be expressed in the Form

$$\det \mathbf{JJ}^{\mathrm{T}} = \frac{1}{l^{12}} \begin{vmatrix} d_2 & 0 & 0 & 0 & -d_3 & 0 \\ 0 & d_2 & 0 & d_3 & 0 & 0 \\ 0 & 0 & 8h^2 & 0 & 0 & 0 \\ 0 & d_3 & 0 & 2b^2h^2 & 0 & 0 \\ -d_3 & 0 & 0 & 0 & 2b^2h^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & a^2b^2 \end{vmatrix}$$

Where

$d_2 = 2\left(a^2 - \sqrt{2}ab + b^2\right),$

$d_3 = \left(\sqrt{2}a - 2b\right)bh.$

The variation of the quality index now is investigated for a number of simple motions of the top platform. Here, an optimal redundant 8-8 parallel manipulator with platform side a = 1, and thus base side b = is taken as an example.[4,16]

5.2 Quality index for vertical translation of the moving platform

First, consider a pure vertical translation of the platform from the central symmetric position along the z-axis while remaining parallel to the base. For such movement, , the quality index is given by

Height h	**Quality index λ**
0.01	0.00
0.26	0.20
0.38	0.40
0.42	0.60
0.49	0.80
0.72	1.00
1.0	0.85
1.1	0.8
1.35	0.6
1.5	0.44
1.6	0.4
2.0	0.25
2.2	0.2
2.5	0.17
3	0.11

Table 1. Quality index for platform vertical movement

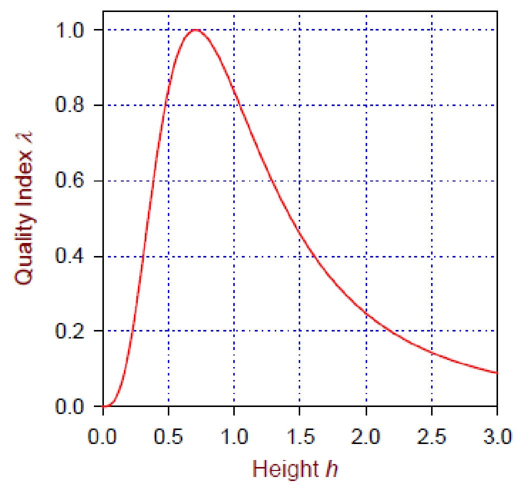

Fig: 5.4 Quality index for platform vertical movement

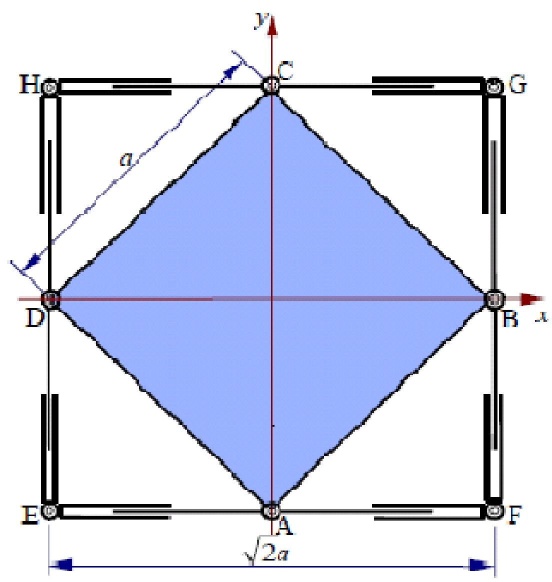

Fig: 5.5 plan view of the optimal configuration of the redundant 8-8 in-parallel manipulator with the maximum quality index

It shows that at height the quality index of the redundant 8-8 parallel manipulator has a maximum value, λ =1.

5.3 Quality index for horizontal translation of moving platform

Assume the center of the moving platform to move to point (*x*, *y*, *h*), then the coordinates of the points *A*, *B*, *C*, and *D* on the platform become

$$A\left(x\ y-\frac{\sqrt{2}a}{2}\ h\right), \qquad B\left(x+\frac{\sqrt{2}a}{2}\ y\ h\right), \tag{5.29}$$

$$C\left(x \quad y + \frac{\sqrt{2}a}{2} \quad h\right), \qquad D\left(x - \frac{\sqrt{2}a}{2} \quad y \quad h\right),$$

The coordinates of points *E*, *F*, *G*, and *H* on the base can be found from (5.1). Thus, the Plücker line coordinates for each of the eight leg lines can be determined as

$$\hat{s}_1 = \left[x + \frac{b}{2}, y -, \right. \qquad (5.30)$$

$$\hat{s}_2 = \left[x - \frac{b}{2}, y - \frac{\sqrt{2}c}{2}, \right. \qquad (5.31)$$

$$\hat{s}_3 = \left[x + \frac{\sqrt{2}a - b}{2}, y, \right. \qquad (5.32)$$

$$\hat{s}_4 = \left[x + \frac{\sqrt{2}a - b}{2}, \right. \qquad (5.33)$$

$$\hat{s}_5 = \left[x - \frac{b}{2}, y + \frac{\sqrt{2}c}{2}, \right. \qquad (5.34)$$

$$\hat{s}_6 = \left[x + \frac{b}{2}, y +, \right. \qquad (5.35)$$

$$\hat{s}_7 = \left[x - \frac{\sqrt{2}a - b}{2}, \right. \qquad (5.36)$$

$$\hat{s}_8 = \left[x - \frac{\sqrt{2}a - b}{2}, y, \right. \qquad (5.37)$$

The above coordinates are not normalized and each row must be divided by the corresponding leg length. The Jacobian matrix **J** then can be constructed by using (5.11). Further, substituting and expanding yields

$$\sqrt{\det JJ^T} \qquad (5.38)$$

where the leg lengths are

With $a = 1$, $b =$, and $h =$, from (5.27) and (5.38), the quality index λ becomes

$$\lambda = \frac{\sqrt{\det J J^T}}{\sqrt{\det J_m J_m^T}} = \frac{}{(x^4 + 2x^2 y^2} \qquad (5.39)$$

Fig 5.7 shows the contours of the quality index for this platform horizontal movement. The contours are labeled with values of constant quality index and they are close to being concentric circles of various radii. When x or y is infinite, λ =0, and when x=y=0, λ =1.

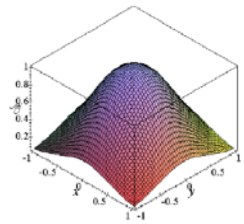

Fig. 5.6 Quality index for platform horizontal translation

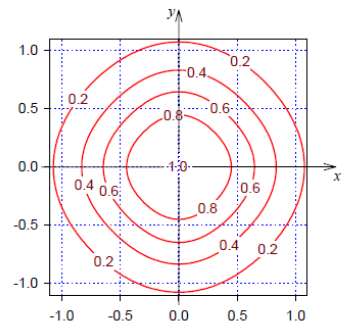

Fig.5.7 The Contour plot of Quality Index for platform horizontal translation

V.CONCLUSIONS

The quality index for redundant parallel manipulators has been defined as a dimensionless ratio which takes a maximum value of 1 at a central symmetrical configuration that is shown to correspond to the maximum value of the square root of the determinant of the product of the manipulator Jacobian by its transpose. A quality index has two clear meanings so far. When λ =0, a platform is in singular condition and when λ =1, it is in its optimal geometry static configuration. However, when λ is neither zero nor one, it is hard to say exactly how much one configuration is better than another. One can not say that a configuration with λ =0.8 is twice as good as a configuration with λ =0.4 without further analyses. However, a quality index helps in the design platforms by setting dimensions that give best quality index value. Also, it gives an idea of certain designs that must be prevented as they would lead to zero or lower quality indexes. The quality index reflects singularities, and therefore gives an indication of the safe regions within which the manipulator can be maneuvered and controlled. Using quality index, variable motions are investigated for which a moving Platform rotates about a central axis or moves parallel to the base. It shows that the wider the range of high quality index, the better the design of a parallel manipulator. Thus, the quality index can be used as a constructive measure not only of an acceptable operating workspace but also of acceptable and optimum design proportions. Additionally, the redundant 8-8 parallel manipulator contains double-spherical joints. There are eight of them and they are the source of critical practical difficulties since they can produce serious mechanical interference. There appears to be no reasonable alternative than to accept a reduction in the maximum quality index through separation by fairly short distances of some or all of the double-spherical joints Redundant in-parallel manipulators present many interests in various applications: increase dexterity, reduce or even eliminate singularities, increase reliability, simplify the forward kinematics, and improve load distribution in actuators.

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