 ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

Orientation Workspace Analysis of a 3-DoF Planar Parallel Kinematic Machine

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Abstract

In this paper, kinematic and workspace analysis of 3-DoF planar Parallel Kinematic Machine (PKM) is carried out. The mechanism consists of three legs in which two legs have Prismatic-Revolute-Prismatic joints and other leg has Prismatic-Prismatic-Revolute joints, it termed as 2-PRP and 1-PPR planar parallel kinematic machine. By these joints, the mechanism can achieve two translational motions and one rotational motion. The kinematic analysis is carried out to find the joint positions for a particular position of moving platform. Afterwards, the two types of orientation workspace, namely, inclusive workspace and total orientation workspace are studied. Moreover, non-dimensional performance indices that depict the workspace characteristics of the mechanism, namely, Workspace Index, Global Dexterity Index are also determined.

Keywords

PKM, Inclusive Workspace, Total Orientation Workspace, Workspace Index, Global Dexterity Index.

I. Introduction

Many industrial machine tools have a serial kinematic mechanism i.e., each axis has to carry the following one including its actuators and joints. In high speed machining applications, it gives some drawbacks: the machine accuracy is less due to the last link has less stiffness as compared to the previous one and limits the dynamic performances of the feed axes. PKM's attract more researchers and industries, because they have several advantages over their serial counterparts, like high structural rigidity and high dynamic capacities.

A parallel kinematic machine consists of a fixed platform, connected to a moving platform by means of a number of legs. These legs often consist of an active prismatic joint, connected to the platforms through passive (i.e. not actuated), spherical and/or universal joints. Hence, the links feel only traction or compression, not bending, which increases their position accuracy and allows a lighter construction. There are some advantages over serial manipulators are precision and accuracy are high due to less error and more stiffness, load carrying capacity is high, rigidity to weight ratio is high and inertia is less and one of the drawback in PKM, has limited workspace, motion platform gets caught up in singular configuration.

PKMs have drawn continuous interest in both industry and academia in the Machine tool/robot sectors since the 1990s because of their potentially desirable fast dynamic performance, rigidity, and acceptable accuracy. In the recent past, parallel mechanisms with less than 6 DOF, especially 2 and 3 DOF, have increasingly attracted more and more to industry applications. Although numerous PKMs with different architectures have been developed previously, the Hexapods, Hexaglide, and Delta robot, few of them really possess true re-configurability because of the limited modularization at the component level. Today, various versions of the PKM have been successfully used as machine tools and/or robots for high-speed milling, drilling, deburring, welding, as well as assembling in the aerospace and automotive. PKMs took long time before they appeared in the industry, particularly, for machine tool applications. This is mainly due to their complex closed-loop parallel kinematic chains that make their analysis and control difficult.

PKMs are developed on the basis of parallel manipulators which were performing in high speeds because every leg (or) link connected to the moving platform from the base [1, 2]. Higher kinematical precision, less in weight with better stiffness, greater load bearing capacity are some advantages of parallel architectures when compared to derail kinematic chains [3]. The forward kinematics problem for a broad class of planar parallel manipulators [4] and inverse kinematic solution for three different 3-DoF for planar parallel robots is performed by [5] which is used to perform kinematic analysis of present work. [6, 7] each also studied about kinematical study of a planar parallel robot. The numerical solution for the both types of kinematics for planar parallel robot is given by [8]. The paper [9] study gives an idea about two types of kinematics and dynamic modelling of a planar PKM. The singularities can be identified readily for most of 2-DoF and 3-DoF parallel mechanism. For this reason, such type of mechanisms which have less than 6-DoFs, particularly 2 and 3 DoFs have attracted by more researchers and industrial experts [10 – 14]. For this type of robots, the study of singular conditions and velocity concepts is presented in [15].

Dextrous workspace boundary was determined by geometric approach in [16]. The geometric algorithms for total orientation workspace and inclusive workspace for robotic manipulators were presented in [17]. The constant and total orientation workspace characteristics for Hexaslide which is used for machine tool applications and global dexterity index (one of the performance indices of PKM) were studied in [18]. Various shapes of workspace due to change in link length was studied in [19] and a study of workspace and singularity characteristics for two common types of 3-DoF planar parallel manipulators is given in [20].

Workspace is the region where the tool can reach conveniently to a specified position. The tool orientation capability is an important index for kinematic design and trajectory planning of manipulator. It gives the ability of approaching one position point from different directions by the end-effector. Dextrous workspace or a partial dextrous workspace is formed by these points, if it can be reached by the end-effector from any direction or a certain range of directions respectively.

The schematic representation of 3-DoF planar (2-PRP and PPR) PKM is shown in fig. 1. In 2-PRP and PPR, wherein P represents prismatic and R represents revolute and the underline represents actuator.

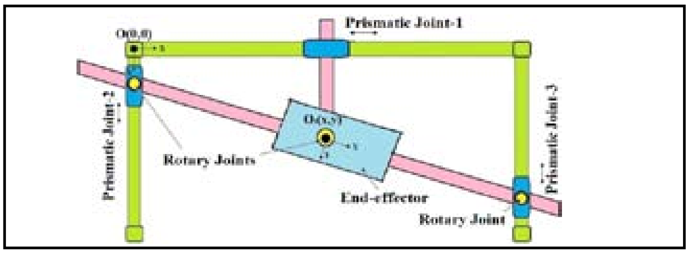

Fig. 1: Mechanism of 3-DoF planar Parallel Manipulator

Motions of the moving platform are achieved by the combinations of the movements of the sliders that can be transmitted to the platform by the prismatic and revolute joints. The moving platform can achieve two translation motions in X and Y directions and one rotation about the axis which is normal to the XY plane.

II. Kinematic Analysis

Kinematics deal with the study of the manipulator motion as constrained by the geometry of the links. Typically, the study of manipulator kinematics is divided into two parts, inverse kinematics and forward (or direct) kinematics. The kinematics of a PKM is the study of relationship between its joints and the end-effector motions without referring to the causes of these motions.

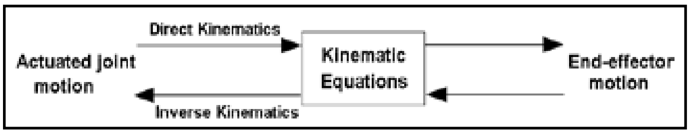

Fig. 2: Illustration of Direct and Inverse Kinematics

In kinematics, the joint parameters can be derived for a particular position of the moving platform and vice-versa. The kinematic arrangement of the PKM is shown in fig. 2. By actuating the prismatic joints 2 and 3, the vertical movement of the moving platform can be achieved. By actuating the prismatic joint-1 the horizontal movement of the moving platform can be achieved and the orientation of the end effector can be achieved by providing the relative motion between the two prismatic joints which has motion in Y direction. The moving platform requires three translational inputs, namely r_1, r_2, and r_3. The fixed coordinate system O (0, 0) is incorporated at top left corner of the machine, and let x and y directions are positive and the moving coordinate system O_1 (x, y) at centre of the moving platform as shown in fig. 3.
The two basic tasks in kinematics are: Forward kinematics and Inverse kinematics.

A. Forward Kinematics

This type of kinematics refers to use of kinematic equations of the platform to determine the position (x, y) and the orientation (θz) of the end effector using the joint space parameters (r_1, r_2, r_3). The resulted equations obtained from the forward kinematics are:

$x = r_1$

$y = r_2 + [r_1 (r_3-r_2)]/s$

$\theta_z = \tan^{-1}(r_3-r_2)/s$

B. Inverse Kinematics

Inverse kinematics refers to the use of the kinematics equation of a robot to determine the joint parameters that provide a desired position of the end-effector.

$r_1 = x$

$r_2 = y - x\tan\theta_z$

$r_3 = y + (s-x)\tan\theta_z$

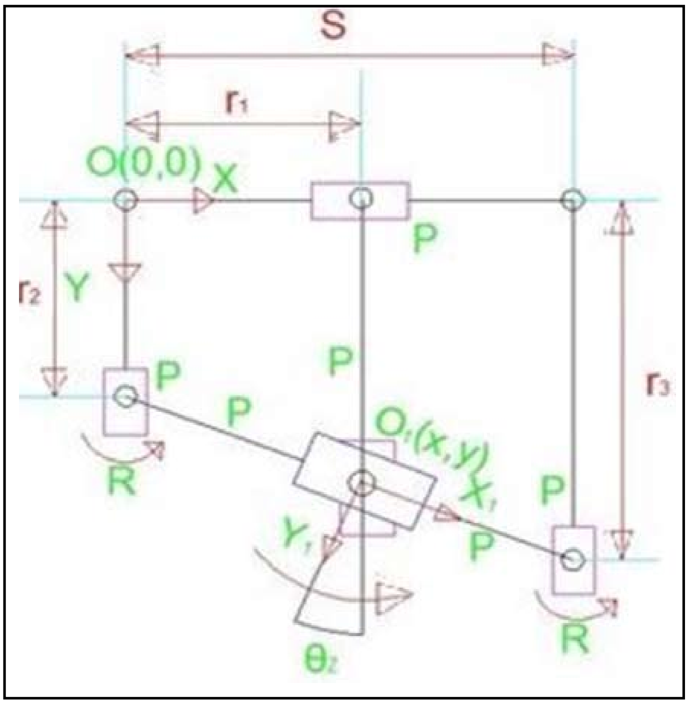

Fig. 3: Kinematic Arrangement of PKM

where, r_1, r_2, and r_3 are the translational inputs, means joint parameters and x, y, and tanθz are the parameters of the moving platform which are used to define the position of the moving platform. Jacobian matrix relates the joint parameters and moving platform parameters. The relation between the joint variables and end effector variables are given by

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \Theta_z \end{bmatrix} = J \begin{bmatrix} \dot{r}_1 \\ \dot{r}_2 \\ \dot{r}_3 \end{bmatrix}$$

$$\text{where, } J = \begin{bmatrix} 1 & 0 & 0 \\ \frac{(r_3-r_2)}{s} & 1-\frac{r_1}{s} & \frac{r_1}{s} \\ 0 & -\cos^2\Theta_z & \cos^2\Theta_z \end{bmatrix}$$

III. Performance Measures

A 3-DoF planar PKM showing motion joints as shown in fig.1. The parameters S, r_1, r_2, r_3, Θ_z are the horizontal span, distance from the origin to prismatic joint-1, distance from the origin to prismatic joint-2, distance from the origin to prismatic joint-3, angle between the vertical axis and tool respectively. The size of PKM would be the area of that machine. Various performance indices considered for the study of workspace characteristics are:

A. Workspace Index (WI)

Workspace Index (WI) is defined as the ratio of the workspace area to the total area of the machine which essentially includes workspace.

B. Global Dexterity Index (GDI)

The dexterity of a machine is the ability to arbitrarily change its position and orientation during machining. The Global Dexterity Index considers the dexterity of the manipulator over the entire or a reasonable central portion of the workspace [18], [21] and is given by

ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

$$\mathrm{GDI} = \frac{\int_W \left(\frac{1}{k}\right) dW}{\int dW}$$

where dW is an infinitesimal small element representing one of the workspace points and k is the condition number of the Jacobian at that point and it can be taken as $k = \|J\|\|J^{-1}\|$, where refers to the 2-norm. This index represents the uniformity of manipulability within the entire workspace. To know the behaviour of the PKM, the condition number plays a key role and it is defined as the ratio of the maximum singular value to the minimum singular value of the Jacobian matrix. The condition number varies from 1 to ∞ (infinity) and the reciprocal of condition number varies from 0 to 1. If it has value 0, then it represents the tool platform is in bad condition and at that particular position and orientation. On the other hand, if it has value 1, then it represents the tool platform is in well conditioned state.

IV. Workspace Characteristics of 3-Dof Planar PKM

Various performance indices are determined by taking the tool orientation range Θ_{z45} = [-45°, 45°]. The horizontal and vertical spans of the machine are considered as 0.3 m [9].

A program has been developed in MATLAB to model a 3-DoF planar PKM, to determine the workspace index, global dexterity index and to know the behaviour of the PKM. From fig. 4, it may be observed that the graph is drawn by taking the position coordinate (x, y) on X and Y-axis respectively and reciprocal of condition number (RCNM) on Z-axis by writing a code in MATLAB. In program, the code has written to check the condition number of the tool at each and every position for every angle of orientation. The colours in the graph represent reciprocal of condition number values at different positions of tool. Finally, we can say that PKM has good characteristics at the middle of the horizontal span because it has good condition number as compared to other positions and has bad characteristics at the end points.

Two types of orientation workspace, namely, inclusive workspace and total orientation workspace are determined. Total orientation workspace is the region reachable by the moving platform with any orientation. Inclusive workspace is the region reachable by the moving platform where in each position with at least one orientation. Inclusive workspace and total orientation workspace are determined in the range Θ_{z45} = [-45°, 45°], it means the tool will orient from the angle -45° to 45°. As in fig. 5, the variables remain same on X and Y-axis and Θz in degrees on Z-axis is plotted to depict the minimum and maximum angles of orientation of tool as shown in fig. 5. For this, a code is written in MATLAB, to know the minimum and maximum angles of orientation of tool at each position for at least one orientation in the given range for inclusive workspace. For total orientation workspace, the program is written to check the minimum and maximum angles of orientation of tool at each location for any orientation in the given region as shown in fig. 6. In inclusive workspace we can say that, the tool has minimum range of tool orientation at start and end points of X-axis, has increased from starting point and has maximum range of tool orientation at centre position which has flat portion. This figure depicts that the tool orientation capability for each position in the workspace region of the PKM. Here, the upper portion represents maximum values and lower portion represents minimum values of tool orientation.

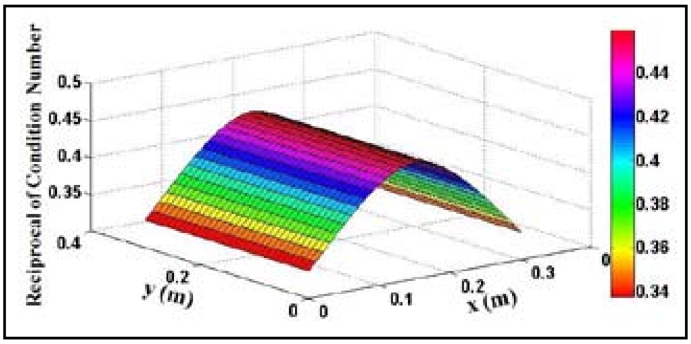

Fig. 4: Variation of Reciprocal of Condition Number

From fig. 6, we can say that the tool has capability for any orientation in the given range at each position, so in the plot it represents as flat surface. As in fig. 5, the upper and lower parts of the plot represent maximum and minimum angles of orientation of tool respectively.

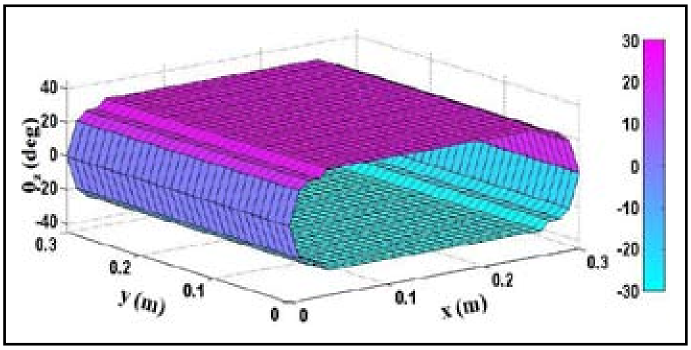

Fig. 5: Inclusive Workspace for Θ_{z45} = [-45°, 45°]

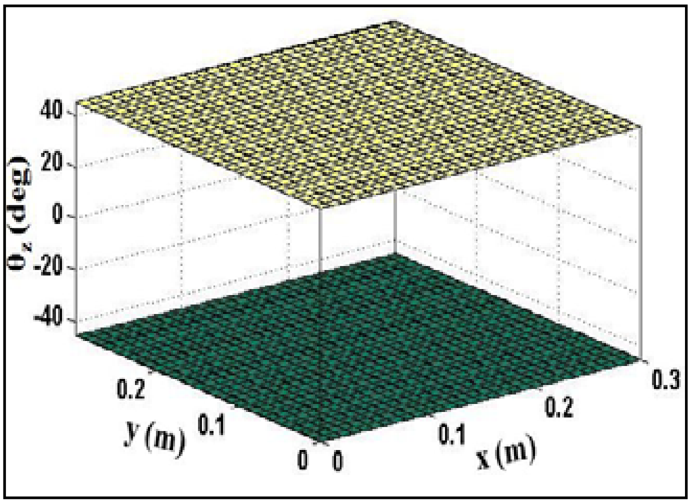

Fig. 6: Total Orientation Workspace for Θ_{z45} = [-45°, 45°]

Table 1: Comparison of Performance Indices between Inclusive and Total Orientation Workspace

Performance Indices	Inclusive Workspace	Total Orientation Workspace		
		Θ_{z45}	Θ_{z30}	Θ_{z15}
Workspace Index	1.0678	1.0678	1.0678	1.0678
Global Dexterity Index	0.4545	0.4077	0.4457	0.4523

where in Θ_{z45} = [-45°, 45°]; Θ_{z30} = [-30°, 30°]; and Θ^{z15} = [-15°, 15°].

Total orientation workspace is determined for different ranges and is presented in Table 1. It may observe that the workspace index is same for all the three ranges and global dexterity index is increasing by decreasing the range. It means for less range of tool orientation, the global dexterity index has high value and for large range of tool orientation, it has high value. By observing, workspace index is same for both inclusive workspace and total orientation workspace for three ranges as shown in Table 1.

V. Conclusion

The planar parallel kinematic machine has good manipulability in the middle of the horizontal span and has bad characteristics at the end points. Workspace index is same for all the three ranges in total orientation workspace and in inclusive workspace. The moving platform has ability to orient in every position in the given range throughout the span. Global Dexterity Index has less value for total orientation workspace as compared to the inclusive workspace and this value has more for small range of tool orientation at each position.

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ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

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