International Journal of Engineering & Technology, 7 (4.10) (2018) 90-94

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

A Numerical Approach for 3 PRS Parallel Manipulator

Arockia Selvakumar A[1]

[1]*Associate Professor*
SMBS, Vellore Institute of Technology,
Chennai- 600127, Tamil Nadu, India
** Corresponding author E-mail: arockia.selvakumar@vit.ac.in*

Abstract

This paper presents a numerical approach on kinematic analysis of 3-DOF parallel manipulator (PM). The proposed mechanisms constitute of PRS (Prismatic-Revolute-Spherical) parallel mechanism with two rotations and one translation. The forward and inverse kinematic equations of the PM are derived by position vector method. A total of 48 solutions are obtained for the forward kinematic equations using MATLAB.

Keywords: *Parallel manipulator, Kinematics, 3-PRS, MATLAB.*

1. Introduction

Based on the previous research, most of the parallel manipulators forward and inverse kinematics solutions are solved in closed form [1][2] and its solutions are compared by simulation results [3][4][5][6]. The kinematic design, architecture optimization and actuator layout angles of 3-PRS parallel manipulator are investigated based on the performance index and various simulation software packages are used to verify the results obtained [7][14][15]. Ghasem Abbasnejad et al explained the merits and demerits of the traditional numerical techniques to solve the kinematic equations and the results proved that that the homotopy continuation method performed better convergence to the forward kinematic problem with bad initial guesses compared to the Newton-Raphson method [8]. Similarly, a simulation and numerical analysis based on the kinematics of the PRS XY serial parallel manipulator is solved by using the steepest descent method and the motion trail of the tool tip based on the mobile platform kinematic solution is validated [9]. The PM geometric arrangement and the kinematic solutions for a large range of motion in the machine tool axis are studied and validated numerically to implement in real time machine tool control conditions [10]. To control the hybrid parallel kinematic machines, the inverse kinematics of the micro PM with the Z- axis translation, X and Y axes rotations are solved an algorithm developed for positioning the PM in micro-machining and assembly operations [11]. Similarly, the kinematic analysis of 3-UPU I and 3-UPU II parallel kinematic machines with two rotations and one translation with the geometric constraints are solved by various analytic formulae and a simulation tool is used to verify the kinematic solutions [12]. Based on the position analysis of 5-DOF PM for various geometric topologies the output motion patterns are obtained and the translational and rotational tool motions relative to the system are defined by the Newton Raphson method [13].
In what follows, first inverse and forward kinematics of the proposed PM are derived; second the various numerical results of the 3-PRS PMs are discussed in detail; finally concluding remarks are given.

2. Inverse Kinematics

The inverse kinematics is formulated by finding the joint motions when the pose of the end-effectors is known. For this kinematic analysis, the position of the MP is considered known, and is given by the position vector ‘P’, which defines the location of the center for the MP in the XYZ coordinate frame.

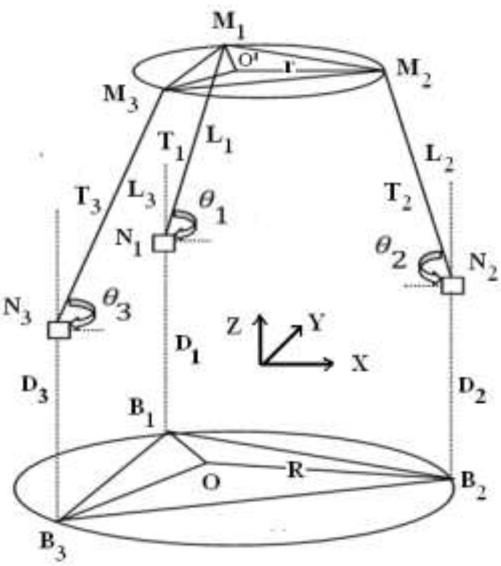

Fig1: Kinematic model of the 3-PRS PM

The orientation of the mobile platform is described by three Euler angles α, β and γ, which are angles rotated about x, y and z axis of the fixed base platform [9][16][17]. In this study, the kinematic equations have been derived for the two and three rotations of the 3-PRS PM.
For analyzing the inverse kinematics, the rotational and the translational displacements of the MP in the global coordinate system

OXYZ are $\{\alpha, \beta, 0\}$ and $\{x_p, y_p, z_p\}$ for two rotations. The rotating order is (1) rotation about the x axis (α) and 2) rotation about the y axis (β). Figure 1 shows the inverse kinematic model of the 3-PRS PM.

The general form of the spherical coordinate of the MP is represented as

$$(M_x) = \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix} \tag{1}$$

From Figure 2, the spherical coordinate points 1, 2 and 3 are,

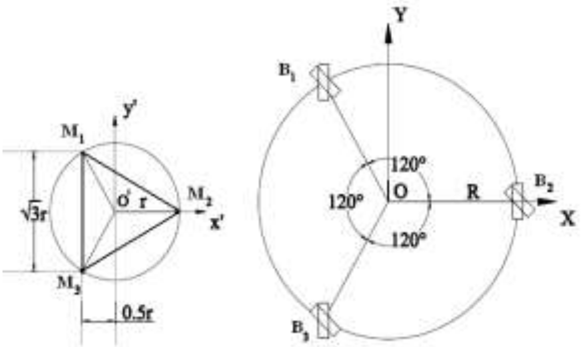

Fig. 2: Schematic representation of MP and BP

$$(M_1) = \begin{pmatrix} -\frac{1}{2}r \\ \frac{\sqrt{3}}{2}r \\ 0 \end{pmatrix} \quad (M_2) = \begin{pmatrix} r \\ 0 \\ 0 \end{pmatrix}$$

$$(M_3) = \begin{pmatrix} -\frac{1}{2}r \\ -\frac{\sqrt{3}}{2}r \\ 0 \end{pmatrix} \tag{2}$$

For the base platform, the pin joints co-ordinate points 1, 2 and 3 are calculated as

$$(B_1) = \begin{pmatrix} -\frac{1}{2}R \\ \frac{\sqrt{3}}{2}R \\ D_1 \end{pmatrix} \quad (B_2) = \begin{pmatrix} R \\ 0 \\ D_2 \end{pmatrix}$$

$$(B_3) = \begin{pmatrix} -\frac{1}{2}R \\ -\frac{\sqrt{3}}{2}R \\ D_3 \end{pmatrix} \tag{3}$$

The general form of rotation is expressed as,

$$(M_1)_R = Q(M)_r + (O')_R \tag{4}$$

Here, the rotation of the MP takes place about the x and the y axes only. Hence

x and y = 0

The first link rotation matrix is calculated as follows,

$$(M)_R = \begin{bmatrix} -\frac{1}{2}r\cos\beta \\ -\frac{1}{2}\sin\alpha\sin\beta + \frac{\sqrt{3}}{2}r\cos\alpha \\ \frac{1}{2}r\cos\alpha\sin\beta + \frac{\sqrt{3}}{2}r\sin\alpha + z \end{bmatrix} \tag{5}$$

The Length between the two joints (M1and B1) of link1 is,

$$L = \| MR - BR \| \tag{6}$$

$$D_1 = E_3 \pm \sqrt{E_1 - E_2} \tag{7}$$

$$E_1 = L^2 - \left[-\frac{R}{2} + \frac{r\cos\theta}{2}\right]^2 ,$$

$$E_2 = \left[\frac{\sqrt{3}}{2}R + \frac{1}{2}r\sin\beta\sin\alpha - \frac{\sqrt{3}}{2}r\cos\alpha\right]^2 ,$$

$$E_3 = \left[-\frac{1}{2}r\cos\alpha\sin\beta - \frac{\sqrt{3}}{2}r\sin\alpha - z\right]$$

The second link rotation matrix is calculated as follows,

$$(M_2)_R = \begin{pmatrix} r\cos\beta \\ r\sin\beta\sin\alpha - \frac{\sqrt{3}}{2}r\cos\alpha \\ -r\cos\alpha\sin\beta + z \end{pmatrix} \tag{8}$$

The Length between the two joints (M2 and B2) of link 2 is,

$$D_2 = E_6 \pm \sqrt{E_4 - E_5} \tag{9}$$

$$E_4 = L^2 - [R - r\cos\beta]^2 , \qquad E_5 = (r\sin\beta\sin\alpha)^2 ,$$

$$E_6 = (r\cos\alpha\sin\beta + z)$$

The third link rotation matrix is calculated as follows,

$$(M_3)_R = \begin{pmatrix} -\frac{1}{2}r\cos\beta \\ -\frac{1}{2}r\sin\beta\sin\alpha - \frac{\sqrt{3}}{2}r\cos\alpha \\ \frac{1}{2}r\cos\alpha\sin\beta - \frac{\sqrt{3}}{2}r\sin\alpha + z \end{pmatrix} \tag{10}$$

The Length between the two joints (M2 and B2) of the link is,

$$D_3 = E_9 \pm \sqrt{E_7 + E_8} \tag{11}$$

$$E_7 = L^2 - \left[\frac{R}{2} - \frac{r\cos\beta}{2}\right]^2 ,$$

$$E_8 = \left[-\frac{\sqrt{3}}{2}R - \frac{1}{2}r\sin\beta\sin\alpha + \frac{\sqrt{3}}{2}r\cos\alpha\right]^2 ,$$

$$E_9 = \left[-\frac{1}{2}r\cos\alpha\sin\beta - \frac{\sqrt{3}}{2}r\sin\alpha + z\right]$$

where,

D_1, D_2 and D_3 are the distances moved in the links 1, 2, 3, by the nuts in the respective links.

2.1. Numerical Verification for Two Rotations

To apply the inverse kinematic equations mentioned in Equations (7), (9) and (11), an example of the inverse kinematics solution for a 3-PRS manipulator with two rotations is considered, and the manipulator parameters and input angles are as follows,

$L_1 = L_2 = L_3 = 200$, $R = 135$, $r = 90$, $Z = 194.87$

When $\alpha = \beta = 0°$

$D_1 = D_2 = D_3 = 0$

When $\alpha = 30°$, $\beta = 0°$

$D_1 = -41.35$, $D_2 = 0$, $D_3 = 36.59$

When $\alpha = 30°$, $\beta = 30°$

$D_1 = -64.90$, $D_2 = 34.46$, $D_3 = 18.86$

3. Forward Kinematics

The forward kinematic equations are derived, based on the kinematic model shown in Figure 1. The connecting links $N_1 M_1$, N_2

M_2 and N_3 M_3 rotate on their corresponding planes O B_1 N_1M_1, O B_2 N_2 M_2 and O B_3 N_3 M_3.
where,
Bi=vertices of the base platform, Mi=vertices of the mobile platform, Ni= vertices of the nut,
The unit vector Ti (i=1,2,3) is given as follows,

$$T_1 = \{\cos\theta_{L1}\ \sin\psi i, -\cos\theta_{L1}\ \cos\psi j, \sin\theta_{L1}\ k\} \quad (12)$$

$$T_2 = \{-\cos\theta_{L2}\, i, 0\, j, \sin\theta_{L2}\ k\} \quad (13)$$

$$T_3 = \{\cos\theta_{L3}\ \sin\psi\, i, \cos\theta_{L3}\ \cos\psi\, j, \sin\theta_{L3}\ k\} \quad (14)$$

where,
θi, j, k = inclined angle between the XYZ axes and Ti.
ψ = bisect angle of base platform equal to $\frac{\pi}{6}$ or 300
Position vectors of Bi are expressed as,
$OB_1 = \{-\frac{1}{2}Ri + \frac{\sqrt{3}}{2}Rj + D1k\}$, $OB_2 = \{ Ri + 0j + D2k\}$,
$OB_3 = \{\{-\frac{1}{2}Ri - \frac{\sqrt{3}}{2}Rj + D1k\}$
where,
R = radius of the base platform, Di =distances moved in the link L_1, L_2 and L_3.
With the link length L, the position vectors of Pi are written as
$P_1 = OB_1 + L\ T_1$

$$= \left\{\left(-\frac{1}{2}R + \frac{1}{2}L\cos\theta_{L1}\right) i + \left(-\frac{\sqrt{3}}{2}R + \frac{\sqrt{3}}{2}L\cos\theta_{L1}\right) j + (L\sin\theta_{L1} + D_1)k\right\}^T \quad (15)$$

$P_2 = OB_2 + L\ T_2$

$$= \left\{\left(R - \frac{1}{2}L\cos\theta_{L2}\right) i + 0j + (L\sin\theta_{L2} + D_2)\, k\right\}^T \quad (16)$$

$P_3 = OB_3 + L\ T_3$

$$= \left\{\left(-\frac{1}{2}R + \frac{1}{2}L\cos\theta_{L3}\right) i + \left(\frac{\sqrt{3}}{2}R - \frac{\sqrt{3}}{2}L\cos\theta_{L3}\right) j + (L\sin\theta_{L3} + D_3)k\right\}^T \quad (17)$$

Since the distances between the spherical joints on the mobile platform are equal, the norm of the position vectors (Pi) should satisfy the following constraint equations;

$$|P_1 - P_2|^2 = (\sqrt{3}r)^2,\ |P_2 - P_3|^2 = (\sqrt{3}r)^2,$$
$$|P_3 - P_1|^2 = (\sqrt{3}r)$$

Substituting equation P_1 and P_2 in equation
$|P_1 - P_2|^2 = (\sqrt{3}r)^2$
gives,

$$G_1\cos\theta_1 + G_2\cos\theta_2 + G_3\sin\theta_1 + G_4\sin\theta_2 + G_5\cos\theta_1\cos\theta_2 + G_6\sin\theta_1\sin\theta_2 + G_7 = 0 \quad (18)$$

where,
$G_1 = G_2 = -3RL, G_3 = 2LD_1 - 2LD_2, G_4 = -G_3, G_5 = L^2, G_6 = -2G_5, G_7 = 3R^2 + 2L^2 + (D_1 - D_2)^2$

The Equation $|P_2 - P_3|^2 = (\sqrt{3}r)^2$ is written as,

$$G_1\cos\theta_2 + G_2\cos\theta_3 + G_8\sin\theta_2 - G_8\sin\theta_3 + G_5\cos\theta_2\cos\theta_3 + G_6\sin\theta_2\sin\theta_3 + G_9 = 0 \quad (19)$$

where,
$G_1 = G_2 = -3RL, G_5 = L^2, G_6 = -2G_5, G_8 = 2LD_2 - 2LD_3, G_9 = 3R^2 + 2L^2 + (D_2 - D_3)^2$

Similarly equation $|P_3 - P_1|^2 = (\sqrt{3}r)^2$ gives,

$$G_1\cos\theta_1 + G_2\cos\theta_3 + G_{10}\sin\theta_1 - G_{10}\sin\theta_3 + G_5\cos\theta_1\cos\theta_3 + G_6\sin\theta_1\sin\theta_3 + G_{11} = 0 \quad (20)$$

Where,
$G_1 = G_2 = -3RL, G_5 = L^2, G_6 = -2G_5, G_{10} = 2LD_3 - 2LD_1,\ G_{11} = 3R^2 + 2L^2 + (D_3 - D_1)^2$

Substituting $\cos\theta_i = \frac{1-x_i^2}{1+x_i^2}$ and $\sin\theta_i = \frac{2x_i}{1+x_i^2}$ in the above Equations (18), (19) and (20) and solving them, we get the following polynomials:

$$(-G_1-G_2+G_5+G_7)\, x_1^2\, x_2^2 + (2G_4)x_2 x_1^2 + (-G_1+G_2-G_5+G_7)\, x_1^2 + (2G_3)\, x_2^2 x_1 + (4G_6)x_2 x_1 + (2G_3)x_1 + (G_1-G_2-G_5+G_7)\, x_2^2 + (2G_4)x_2 + (G_1+G_2+G_5+G_7) = 0 \quad (21)$$

$$(-G_1-G_2+G_5+G_7)\, x_1^2\, x_3^2 + (2G_4)x_3 x_1^2 + (-G_1+G_2-G_5+G_7)\, x_1^2 + (2G_3)\, x_3^2 x_1 + (4G_6)x_3 x_1 + (2G_3)x_1 + (G_1-G_2-G_5+G_7)\, x_3^2 + (2G_4)x_3 + (G_1+G_2+G_5+G_7) = 0 \quad (22)$$

$$(-G_1-G_2+G_5+G_7)\, x_2^2\, x_3^2 + (2G_4)x_3 x_2^2 + (-G_1+G_2-G_5+G_7)\, x_2^2 + (2G_3)\, x_3^2 x_2 + (4G_6)x_3 x_2 + (2G_3)x_2 + (G_1-G_2-G_5+G_7)\, x_3^2 + (2G_4)x_3 + (G_1+G_2+G_5+G_7) = 0 \quad (23)$$

By solving the above Equations (21) to (23) by MATLAB, the x1, x2, x3 are obtained, hence that the position and orientation of the MP are determined.

3.1. Numerical Verification for Forward Kinematics

As an example of the forward kinematics solution for a 3-PRS manipulator, let the manipulator parameters be taken as $L_1 = L_2 = L_3 = 200$, R = 135, r = 90 and $D_1 = D_2 = D_3 = 0$.
The numerical values are substituted in Equations 21 to 23, and solved using MATLAB. The equation solved in MATLAB is

[x_1, x_2, x_3] = solve ('312375 x_{12} x_{22} + 0 $x_{12}x_2$ + 70375 x_{12}+ 0 x_1 x_{22}-320000x_1x_2 + 0x_1+ 70375 x_{22}+ 0x_2 -11625= 0' , '312375 x_{12} x_{32}+ 0 $x_{12}x_3$ + 70375 x_{12}+ 0 $x_{32}x_1$ -320000x_3x_1+0x_1 + 70375 x_{32}+ 0x_3 -11625= 0", 312375 x_{22} x_{32}+ 0 $x_{22}x_3$ + 70375 x_{22}+ 0 $x_{32}x_2$ - 320000x_2x_3 + 0 x_2+ 70375 x_{32}+ 0 x_3 - 11625= 0') (24)

Similarly,

$L_1 = L_2 = L_3 = 200$, R = 135, r = 90, D_1 =10, D_2 =D_3= 0
[x_1, x_2, x_3] = solve ('312475 x_{12} x_{22} + 8000 $x_{12}x_2$ + 70475 x_{12}-8000 x_1 x_{22}-320000x_1x_2 -8000x1+ 70475 x_{22}+ 8000x_2 -11525= 0' , '3124375 x_{12} x_{32} - 8000 $x_{12}x_3$ + 70475x_{12}+ 8000x_1x_{32}-320000x_1x_3 +8000x_1+ 70475 x_{32}- 8000x_3 -11625= 0", 312375$x_{22}x_{32}$+ 0 $x_{22}x_3$ + 70375x_{22}+ 0$x_{32}x_2$ - 320000x_2x_3 + 0 x_2+ 70375x_{32}+ 0x_3 - 11625= 0') (25)

4. Results and Discussion

The inverse kinematics is derived, using trigonometric relations and Position vector method and the results are discussed below. The forward kinematics equations are solved and 48 solutions are obtained from the MATLAB. The results are tabulated in Tables 1 to 3 for the geometrical parameters of a Link length of 200 mm, MP radius of 90 mm, base platform radius of 135 mm and nut displacements D1=D2=D3=0.

Table 1: Forward kinematics solution for θ1 (Link 1 angle with Base Platform)

Sl. No	Value of 'x' from MATLAB Solution	Angle of link 1 (θ1) by Sin θi	Angle of link 1 (θ1)by Cos θi
1	0.24	27.27	27.27
2	-0.24	27.27	-27.27
3	1.25	102.68	77.32
4	-1.25	102.68	-77.32
5	0.80	77.00	77.00
6	-0.80	77.00	-77.00
7	0.15	17.55	17.55
8	-0.15	17.55	-17.55
9	0.24	27.27	27.27
10	-0.24	27.27	-27.27
11	0.80	77.00	77.00
12	-0.80	77.00	-77.00
13	0.24	27.27	27.27
14	-0.24	27.27	-27.27
15	0.80	77.00	77.00
16	-0.80	77.00	-77.00

In numerical verification, when the nut displacements are zero, the initial angle between the base platform and link1is equal to 77°. From the results of Table 1, it is observed that most of the solutions are equal to 77°; hence, the inverse kinematics solution obtained from MATLAB is found to be the correct one.

Table 2: Forward kinematics solution for θ2 (Link 2 angle with Base Platform)

Sl. No	Value of 'x' from MATLAB Solution	Angle of link 2 (θ2) by Sin θi	Angle of link 2 (θ2)by Cos θi
1	0.24	27.27	27.27
2	-0.24	27.27	-27.27
3	1.25	27.27	27.27
4	-1.25	27.27	-27.27
5	0.80	77.00	77.00
6	-0.80	77.00	-77.00
7	0.15	77.00	77.00
8	-0.15	77.00	-77.00
9	0.24	102.68	77.32
10	-0.24	102.68	-77.32
11	0.80	17.55	17.55
12	-0.80	17.55	-17.55
13	0.24	27.27	27.27
14	-0.24	27.27	-27.27
15	0.80	77.00	77.00
16	-0.80	77.00	-77.00

Similarly, when the nuts displacements are zero, the initial angle between the base platform and the link 2 is equal to 77°. From the results of Table 2, it is observed that most of the solutions are equal to 77°.

Table 3: Forward kinematics solution for θ3 (Link 3 angle with Base Platform)

Sl. No	Value of 'x' from MATLAB Solution	Angle of link 3 (θ3) by Sin θi	Angle of link 3 (θ3) by Cos θi
1	0.24	27.27	27.27
2	-0.24	27.27	-27.27
3	1.25	27.27	27.27
4	-1.25	27.27	-27.27
5	0.80	77.00	77.00
6	-0.80	77.00	-77.00
7	0.15	77.00	77.00
8	-0.15	77.00	-77.00
9	0.24	27.27	27.27
10	-0.24	27.27	-27.27
11	0.80	77.00	77.00
12	-0.80	77.00	-77.00
13	0.24	102.68	77.32
14	-0.24	102.68	-77.32
15	0.80	17.55	17.55
16	-0.80	17.55	-17.55

When the nuts displacements are zero, the initial angle between the base platform and the link 3 is equal to 77°. From the results of Table 3, it is observed that most of the solutions are equal to 77°.

5. Conclusion

The forward and inverse kinematic analyses are conducted on 3-PRS PM. Based on the study the following concluding remarks are made,

- Kinematic equations of 3-PRS PM are derived from the Position vector approach.
- The kinematic results show that the maximum MP tilt of the 3-PRS PM for the given geometrical parameters is found to be 31.64° for the linear displacement of nut 73.5 mm.
- The derived forward kinematic equations are solved by using MATLAB. From the MATLAB results, 48 forward kinematic solutions were obtained. The forward kinematic solution is numerically verified.

References

[1] Díaz-Rodríguez, M. J. A. Carretero, and R. Bautista-Quintero(2016). Solving the dynamic equations of a 3-PRS Parallel Manipulator for efficient model-based designs. Mechanical Sciences. 7(1),1-9.

[2] Enferadi, Javad, and Mohammad Tavakolian(2017). Lagrangian Dynamics Analysis of a XY-Theta Parallel Robotic Machine Tool. Periodica Polytechnica Mechanical Engineering, 61(2), 107-114.

[3] Dunlop, G.R. and Jones, T.P(1997). Position analysis of a 3–DOF parallel manipulator. Mechanism and Machine Theory, 32, 903-920.

[4] Verdes Dan, Sergiu-Dan Stan, Milos mani and Radu balan (2010). Mechatronic design, kinematics analysis of a 3 DOF medical parallel robot. Proceedings of the IEEE symposium on Resilience Control Systems, Idaho, 101-106.

[5] Yangmin Li and Qingsong Xu (2006). Kinematic analysis and design of a new 3-DOF translational parallel manipulator. Journal of Mechanical Design, 128, 729-737.

[6] Yangmin Li and Qingsong Xu (2004). Optimal kinematic design for a general 3-PRS spatial parallel manipulator based on dexterity and workspace. The Eleventh International Conference on Machine Design and Production, Antalya, Turkey, 1-14.

[7] Yangmin Li and Qingsong Xu (2007). Kinematic analysis of a 3-PRS parallel manipulator. Robotics and Computer-Integrated Manufacturing, 23, 395-408.

[8] Ghasem Abbasnejad, Soheil Zarkandi and Misagh Imani (2010). Forward kinematic analysis of a 3-PRS parallel manipulator. World academy of science, Engineering and Technology, 61, 329- 335.

[9] Sun hongchang, Dai Yi, Zhang Jianmin and Li Lina (2010). Simulation and numerical analysis based on kinematics of PRS -XY serial parallel PKM. Proc. of 2010 IEEE, International Conference on Mechatronics and Automation, China, 1531-1536.

[10] Fan Zhang, Dan Zhang, Jianguo Yang and Beizhi Li (2005). Inverse kinematics and dynamics of the 3-RRS parallel platform. Proceedings of the IEEE International Conference on Robotics and Automation, Niagra falls, Canada, 2117-2122.

[11] Ng, C.C. Ong, S.K. and Nee, A.Y.C.(2006). Design and development of 3-DOF modular micro parallel kinematic manipulator. International Journal of Advanced Manufacturing Technologies, 31, 188-200.

[12] Yi Lu, Yan Shi and Bo Hu (2008). Kinematic analysis of two novel 3UPU I and 3UPU II PKMs. Robotics and Autonomous Systems, 56, 296-305.
[13] Oscar Altuzarra, Yon san martin, Enrique Amezua and Alfonso Hernandez (2009). Motion pattern analysis of parallel kinematic machines: A case study. Robotics and Computer Integrated Manufacturing, 25, 432– 440.
[14] Clement, M. Gosselin, Louis Perreault and Charles Vaillancourt (1993). Simulation and computer aided design of spherical parallel manipulators. Proceedings on Engineering in harmony with ocean, 2,301-306.[10]
[15] Merlet, J.P(2005). Optimal design of robots. Online Proceedings of Robotics: Science and Systems. Boston, 1–8.
[16] Arockia Selvakumar and M. Arul Kumar (2014). Experimental Investigation on Position Analysis of 3–DOF Parallel Manipulators.. Procedia Engineering 97, 1126-1134.
[17] Arockia Selvakumar, Babu, R. P., Sivaramakrishnan, R (2012). Simulation and singularity analysis of 3-PRS parallel manipulator. IEEE International Conference on Mechatronics and Automation (ICMA), China, 2203-2207.