ISSN: 0974-2115
www.jchps.com Journal of Chemical and Pharmaceutical Sciences

# Design and Kinematic Analysis of a 6-DOF Parallel Manipulator for Pharmaceutical Application

**Joe Johnson, Ranjith Pillai R, S M Vignesh, A. Lakshmi Srinivas***
Department of Mechatronics, SRM University, Tamil Nadu, India
***Corresponding author: E-Mail: lakshmisrinivas.a@ktr.srmuniv.ac.in**

**ABSTRACT**

The parallel platform with 6-DOF has better force-to-weight ratio and positioning accuracy than any conventional serial-link-arm. This paper focuses on designing and prototyping of stable parallel platform with rotary actuators for control system testing. Kinematic analysis based on DOF control and transformation matrix is illustrated in the paper. First, the prototype is designed and implemented using DOF control method and later used inverse kinematics transformation matrix for simulation and analysis. Results from simulation and physical system are compared for position control accuracy. Finally, the control parameters are obtained from analysis and implemented in controller for physical system prototype.

**KEY WORDS:** Parallel platform, rotary actuator, DOF control, kinematics, computer simulation, control test platform.

## 1. INTRODUCTION

The parallel manipulator has been area of interest for many researchers due to their advantage of high payload, high accuracy and high stiffness over conventional serial-link manipulator. 6-DOF parallel manipulator is generally known as Stewart platform after Stewart illustrated the use of hydraulic parallel structure. All link ends are supported, which makes the manipulator system far more rigid in proportion to size and weight. Parallel robots consist of two platforms and several legs. One platform is fixed to the ground, called the base platform and the other is movable, called the moving platform.

Analysis of 6-DOF parallel manipulator with prismatic actuator is common, less-studied area is parallel manipulator with revolute actuators. Parallel manipulator with revolute actuators is faster than hydraulic prismatic actuator since they use electric motors and motors are mounted on the base platform. Several 6-DOF parallel manipulator with revolute actuators are proposed with various direction for the joint axis. In this paper, it is focused on a new type of parallel manipulator with little difference with other design. The control of 6-DOF parallel manipulator with rotary actuator has been studied.

Design and control parameters of a PID controller for a 6-DOF parallel platform with rotary actuator are done by Simulink simulation. Developed parallel platform can be used as control algorithm testing platform. Parallel manipulators can be used in applications in flight and vehicle simulators, high precision machining centers, mining machines, medical instruments, spatial devices, etc. However there are some drawbacks of relatively small workspace and forward kinematics problems. Forward kinematics of parallel manipulator is very complicated to solve because of the nonlinearity and complexity of the equations. The error correction can be done by implementing PID or Fuzzy logic controller for position control of manipulator. For more accurate analysis of system, the platform is modeled in simulation and control parameters are chosen. The system performance can be obtained by comparison and error analysis between actual prototype using position sensor and simulated result. The control parameter can be obtained by modeling the entire platform and simulating to obtain the desired response for given input.

**Mechanism description:** The physical system is made up of two platforms, base and moving platform shown in Fig.1.

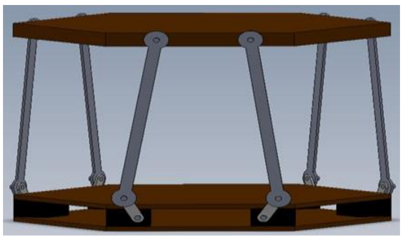

**Fig.1. CAD Model of Parallel Manipulator**

Six legs with two link and one rotational joint each is connected between base platforms fixed to the ground and moving platform. The lower link of leg is connected to motor shaft through a revolute joint and upper link is connected to moving platform through a rotational joint as shown in Fig.2.

Xp, Yp and Zp : translational coordinate of the Top platform.

$\alpha$, $\beta$ and : Rotational angle of the moving platform.

$\theta i$ : Motor angle

$\varphi i$ : Rotational joint angle

Equating the arc distance traversed by the link ‘r’ attached to servo motor shaft, added with major link ‘L’ gives the total link length for each leg as shown in Fig. 3. Equation for arc and effective link length are given,

$S=r^* \theta$ (1), $L\_eff= L + S$ (2)

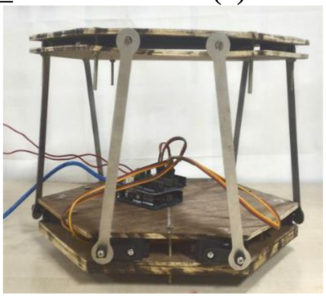

Fig.2. Actual Parallel Manipulator Prototype

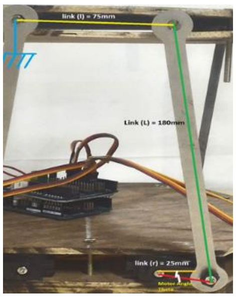


Fig.3. Description of Links associated with Leg

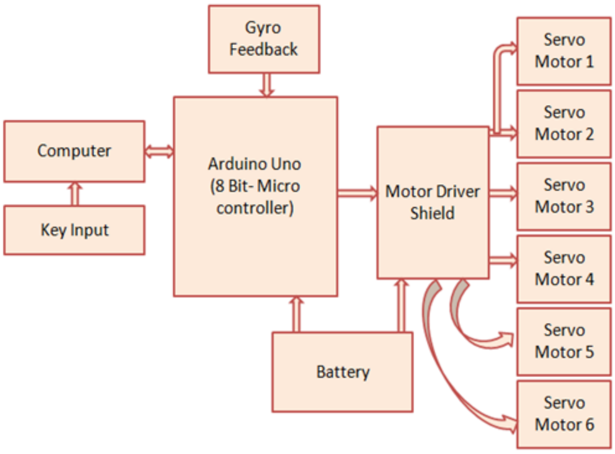


Fig.4. Block Diagram of Hardware connection

Figure 4 describes the overall hardware connections and components required for complete system.

## 2. MODELING AND SIMULATION OF TEST PLATFORM

**System Modeling:** The physical modeling of 6 DOF parallel test platform is developed using MATLAB/SIMMECHANICS. The 6 DOF test platform has a top and a base plate connected with 6 links. The links are actuated using servo motor.

The model developed has not considered any servo motor parameters. The model is developed to verify the kinematics and controller performance of the system. The links are represented by two bodies defined by its mass and inertial tensor on each axis. The bottom link as shown in Fig.5 kept at 90° from the previous link at initial condition represents the motor shaft. The links are connected using rotational joints. The rotational joints are actuated using the simulink force from the controller governed by the kinematic equations. The joints are also provided with the sensors for the feedback to the controller. The servo motor shaft end is grounded to the base using rotational joints. The modeling coordinate frame involves two coordinate systems namely world coordinate OXYZ and local coordinate system O’X’Y’Z’. The world coordinate system is assumed to be fixed on the top platform whereas the local coordinate system is fixed on the base. Initially both are assumed to be coinciding for measuring the coordinate points of the body and joints including centre of gravity.

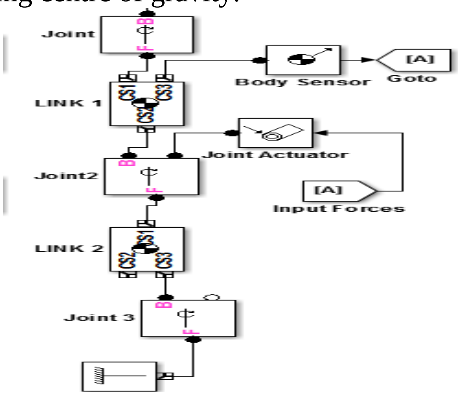


Fig.5. Simmechanics model of single leg

**Kinematics:** Kinematics is the science of motion that treats subject without regards to the forces that cause it. The Kinematics include forward and inverse kinematics. To overcome the complexity of using forward kinematics in parallel manipulators, inverse kinematics is presented in the paper. The inverse kinematics involves finding the length of each link for a particular pose of top platform. The inverse kinematics is presented using DOF control matrix and transformation matrix.

**Kinematics using DOF Control matrix:** The DOF matrix and the equations governing the displacement of link for a defined input is derived as below

The link displacement is derived from the equation

[Trajectory space] X [DOF control matrix]T = [Link Disp]

Where trajectory is a 1X6 matrix, DOF control matrix is a 6x6 matrix and link displacement is a 1X6 matrix.

The DOF control matrix is given by

$$\begin{bmatrix} X \\ Y \\ Z \\ \alpha \\ \beta \\ \gamma \end{bmatrix} \text{X} \begin{bmatrix} 0 & 1 & -1 & 0 & -1 & 1 \\ 0 & 0 & -1 & 0 & 0 & 1 \\ -1 & 1 & -1 & 1 & -1 & 1 \\ -1 & 1 & 0 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 & 1 & -1 \\ -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix} = \begin{bmatrix} L1 \\ L2 \\ L3 \\ L4 \\ L5 \\ L6 \end{bmatrix}$$

The trajectory space is the desired pose of the platform. The actual length of the links is calculated from eqn (3) and is compared with the feedback from the sensor to provide necessary forces for the actuation.

**Inverse Kinematics using Transformation matrix:** Parallel manipulator with six identical rotary actuators as shown in Fig.2 is research interest. Base and moving platform are semi-regular hexagon, linear actuators will be called "legs" are connected to the vertices of the Base and Top with two-degree-of-freedom rotary joint, which makes the system to be 6 DOF. Inertia frame (X,Y,Z) has fixed at the center of the base with the Z axis pointing vertically upward. Moving coordinate system (x,y,z) is fixed at the center of gravity of moving platform with z axis pointing outward. Two coordinates system are called the BASE frame and TOP frame, respectively and illustrated in Fig.6.

Lengths of the legs are denoted by L1, L2, L3, L4, L5 and L6. Location of the origin of the TOP frame with respect to BASE frame is denoted by [Px,Py,Pz]T. rotation angles are denoted by (α,β,γ) defined by rotating the TOP frame first about the X axis with α degrees, then about the Y axis with β degrees and then about the Z axis with γ degrees. According to basic definition of orientation is that there is one-to-one transformation between the definition and the system configuration. The position and orientation of the moving platform is given by X(T-O) = [Px,Py,Pz,α,β,γ]T. Mapping from X(T-O) to Li are illustrated in inverse kinematics. It is known that vertices to which leg is connected to base and moving platform, the coordinate points are fixed with respect to BASE frame shown in Fig. 7.

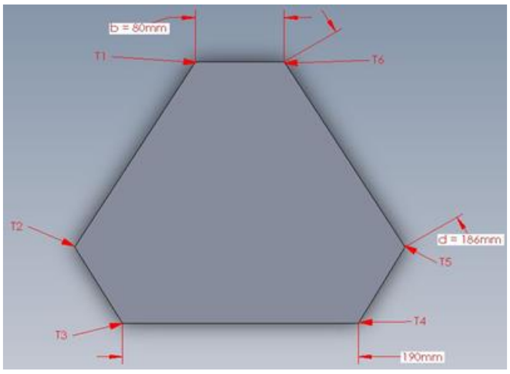

**Fig.6. CAD Model of Moving Platform**

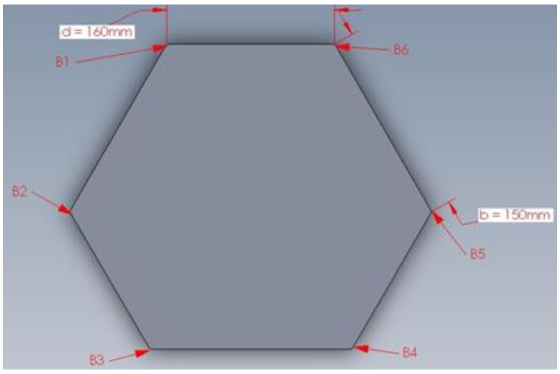

**Fig.7. CAD Model of Base Platform**

Values of Base and TOP coordinates are calculated from following equations:

$$X1 = \frac{\sqrt{3}}{6}(2b + d), Y1 = \frac{1}{2}d, Z1 = 0 \qquad (4)$$

$$X2 = -\frac{\sqrt{3}}{6}(b - d), Y2 = \frac{1}{2}(b + d), Z2 = 0 \qquad (5)$$

$$X3 = -\frac{\sqrt{3}}{6}(b + 2d), Y3 = \frac{1}{2}b, Z3 = 0 \qquad (6)$$

$$X4 = -\frac{\sqrt{3}}{6}(b + 2d), Y4 = -\frac{1}{2}b, Z4 = 0 \qquad (7)$$

$$X5 = -\frac{\sqrt{3}}{6}(b - d), Y5 = -\frac{1}{2}(b + d), Z5 = 0 \qquad (8)$$

$$X6 = \frac{\sqrt{3}}{6}(2b + d), Y6 = -\frac{1}{2}d, \; Z6 = 0 \qquad (9)$$

Transformation matrix for homogeneous transformation from the TOP to the BASE frames is given by

$$T = \begin{bmatrix} cos\beta cos\gamma + sin\alpha sin\beta sin\gamma & -cos\beta sin\gamma + sin\alpha sin\beta cos\gamma & cos\alpha sin\beta & Px \\ cos\alpha sin\gamma & cos\alpha cos\gamma & sin\alpha & Py \\ -sin\beta cos\gamma + sin\alpha cos\beta sin\gamma & sin\beta sin\gamma + sin\alpha cos\beta cos\gamma & cos\alpha cos\beta & Pz \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

If values of X(T-O) is given, consequently the coordinates of the moving platform's vertices in terms of base platform can be calculated through

$$\begin{bmatrix} X_{Ti} \\ Y_{Ti} \\ Z_{Ti} \\ 1 \end{bmatrix} = T * [P_x \quad P_y \quad P_z \quad \alpha \quad \beta \quad \gamma] \begin{bmatrix} x_{Ti} \\ y_{Ti} \\ Z_{Ti} \\ 1 \end{bmatrix} \; i = 1,2,3 \qquad (11)$$

Since the coordinates of the vertices of the Base and the Top are given in terms of the same reference frame, it is straightforward to determine the lengths of the legs Li using

L1= ((XT1-d/2$\sqrt{3}$-b/$\sqrt{3}$)2 + (YT1-d/2)2 + $Z_{T1}^2$))$^{\frac{1}{2}}$ (12)

L2= ((XT1-d/2$\sqrt{3}$+b/2$\sqrt{3}$)2 + (YT1-d/2-b/2)2 + $Z_{T1}^2$))$^{\frac{1}{2}}$ (13)

L3= ((XT2+d/$\sqrt{3}$+b/2$\sqrt{3}$)2 + (YT1-d/2)2 + $Z_{T2}^2$))$^{\frac{1}{2}}$ (14)

L4= ((XT2+d/$\sqrt{3}$+b/2$\sqrt{3}$)2 + (YT1+d/2)2 + $Z_{T1}^2$))$^{\frac{1}{2}}$ (15)

L5= ((XT1-d/2$\sqrt{3}$+b/$\sqrt{3}$)2 + (YT1+b/2+d/2)2 + $Z_{T1}^2$))$^{\frac{1}{2}}$ (16)

L6= ((XT1-d/2$\sqrt{3}$-b/$\sqrt{3}$)2 + (YT1+d/2)2 + $Z_{T1}^2$))$^{\frac{1}{2}}$ (17)

Inverse kinematics solutions for all six legs are provided by these equations. To obtain rotational angle given as input to servo motor from link length obtained from inverse kinematics transformation, the following equations are used

$$\theta = \frac{(L_{eff}-L)*180}{r*\pi} \qquad (18)$$

**Control Design:** The controller was implemented using MATLAB/SIMULINK. Normal PID controller is implemented to achieve the position tracking of the system. The gains are fine-tuned using MATLAB and implemented in the prototype model. PID controller scheme is shown in the block diagram Fig.8

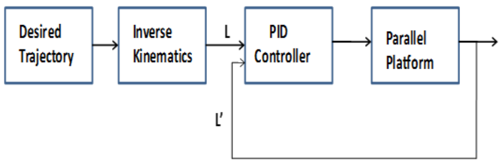


**Fig.8. Block diagram for PID controller feedback**

The length of each link from the desired trajectory is calculated using inverse kinematics equation and is compared with the feedback length from the sensor attached to the link of the model. The error in length drives the controller output which provides necessary actuation to the link.

**Simulation:** The parallel test platform is developed in the SIMMECHANICS environment and the controller was developed using SIMULINK. The complete working model is obtained by interfacing both the environment. The top level simmechanics model is shown in Fig.9.

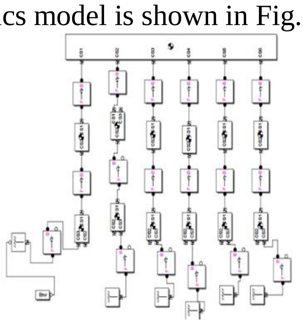

**Fig.9. Top level Simmechanics model**

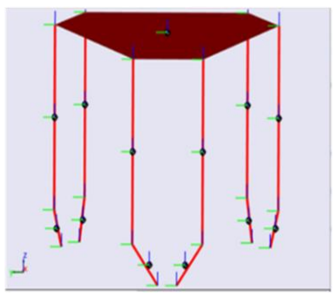

**Fig.10. Simulated 3D model of parallel platform**

The 3D model was obtained from the simulation as shown in Fig.10. The simulation was carried out in forward dynamics mode using ADAMS solver. The simulation was done for different trajectories and the results are plotted. For better simulated result the mass of link and upper platform is taken as 15g and 100g respectively.

## 3. RESULTS

Table 1 illustrates various link length computed by using inverse kinematics for given input in desired axis. Various simulations and real time experiments have been conducted for various position input, Table 2 gives the comparison between the theoretical, actual and simulated result for same given input in different axis. Performance has been plotted for better understanding in Fig. 11. PID controller has been implemented in simulated model and prototype implementation. It has been observed that actual and simulated output has tolerable error in all axes. Better control algorithms can provide more accurate results and can be a scope of further studies.

**Table.1. Link length for actuators w.r.t different axis for given input**

| **Dimension** | **in Cms** | | | | | | |
|---|---|---|---|---|---|---|---|
| Motion Axis | Required input for platform | L1 | L2 | L3 | L4 | L5 | L6 |
| X axis linear motion | 1 | 0.34 | 0.78 | 0.64 | 0.64 | 0.78 | 0.34 |
| Y axis linear motion | 1 | 0.55 | 0.54 | 0.48 | 0.85 | 0.71 | 0.38 |
| Z axis linear motion | 1 | 0.55 | 0.54 | 0.48 | 0.85 | 0.71 | 0.38 |

**Table.2. Results and error analysis for different axis**

| **Dimension** | **in Cms** | | | | |
|---|---|---|---|---|---|
| **Motion Axis** | **Actual output (Prototype)** | **Theoretical output** | **Simulated Output** | **Error b/w actual and theory** | **Error b/w Simulated and theory** |
| X axis linear motion | 0.8 | 1 | 0.8 | 0.2 | 0.2 |
| Y axis linear motion | 1.3 | 1 | 0.8 | -0.3 | 0.2 |
| Z axis linear motion | 1.2 | 1 | 0.6 | -0.2 | 0.4 |

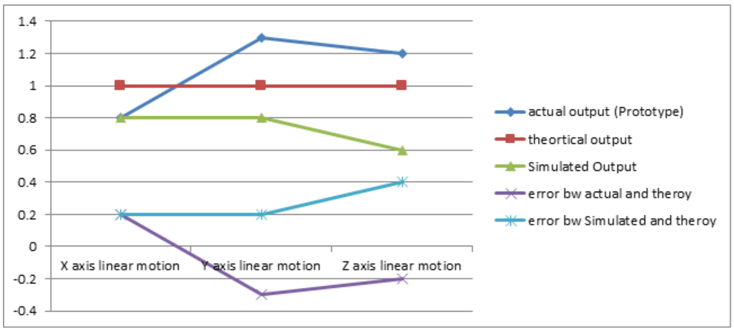


**Fig.11. Performance and error analysis between Theoretical, actual and simulated results**

## 4. CONCLUSION

A new kind of 6-DOF parallel manipulator with rotary actuator was introduced in this paper. The major difference between the prototype with conventional design was about the linkage and joints configuration of six links. This paper implements DOF control and inverse kinematics transformation methods to obtain desired position/orientation in the reachable workspace of the manipulator. In order to validate the proposed PID controller for position control, numerous experiments using prototype were performed and compared with computer simulated results. The analysis of the results has been described. For better simulated result from simulation, the mass of legs are considered and since more accurate simulated results are obtained.

## REFERENCES

Ana C Majarena, Jorge Santolaria, David Samper and Juan J Aguilar, An Overview of Kinematic and Calibration Models Using Internal/External Sensors or Constraints to Improve the Behavior of Spatial Parallel Mechanisms, Sensors, 10, 2010, 10256-1029.

Azizan H, Keshmiri M, and Jafarinasab M, Designing a Stable Model-Based Fuzzy Controller for a Novel 6-DOF Parallel Manipulator with Rotary Actuators, in Magnetism, 2011 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2011) Budapest, Hungary, 2011.

Chifu Yang, Qitao Huang, Jingfeng He, Hongzhou Jiang and Junwei Han, Model-based Control for 6-DOF Parallel Manipulator, International Asia Conference on Informatics in Control, Automation, Robotics, 2009.

Control with Gravity Compensation in Simulink/ADAMS, International Workshop on Modelling, Simulation and Optimization, 2008.

Ghobakhloo A, Eghtesad M, and Azadi M, Position Control of a Stewart-Gough Platform Using Inverse Dynamics Method with Full Dynamics, 50-55, AMC'06-Istanbul, Turkey, 2006.

Hamidreza Hajimirzaalian, Hasan Moosavi and Mehdi Massah, Analyzing and Simulating the Inverse and the Direct dynamics of Parallel Robot Stewart Platform, IEEE Second International Conference on Computer and Network Technology, 136-141, Bangkok, Thailand, 23-25 April 2010.

Jafarinasab M, Keshmiri M, Azizan H and Danesh M, Sliding Mode Control of a Novel 6-DOF Parallel Manipulator with Rotary Actuators, 2011 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2011) Budapest, Hungary, 2011.

Joe Johnson and Jesu Godwin D, Indoor Navigation of Mobile Robot Using Fuzzy Logic Controller, 2015 3rd International Conference on Signal Processing, Communication and Networking (ICSCN), 2015.

Kai Liu, John M Fitzgerald, and Frank L Lewis, Kinematic Analysis of a Stewart Platform Manipulator, IEEE Transactions On Industrial Electronics, 40 (2), 1993.

Ranjith Pillai R, Mathiazhagan1 R, Karthikeyan P, Shiju Varghese, Soni NL and Patel RJ, Modeling of 6 DOF Shake Table and Its Control, International Journal of Manufacturing System and Design, 1 (1), 2005.

Yamin Wan and Sun’an Wang, Kinematics Analysis and Simulation System Realization of Stewart Platform Manipulator, The Forth International Conference on Control and Automation (ICCA’03), Montreal, Canada, 2003.