Inverse kinematic analysis of a fixture for fine alignment of central axis of top and bottom frame using simulation

Aglawe P S 1*, Ohol S S1

1Department of Mechanical Engineering, College of Engineering Pune – 411005, Maharashtra, India

E-mail: pankajsaglawe@gmail.com

Abstract - In the field of robotics, the design and development of Stewart Platform is currently the widely discussed topic because of its complexity as well as the usefulness in many fields like military operations, biomedical, Stealth operations, etc. This research work focuses on designing of fixture using rotary actuators and Simulation of Stewart Platform in MATLAB. Fixture consists of controlling of different degrees of freedom of the module, precise linear as well as rotary motion and motor position controller for every degree of freedom and enhanced real time control of each module. Inverse kinematic analysis of a fixture using Sim-mechanics of MATLAB is carried out. This fixture has a unique design considering space constraints and weight constraints. Above research work for automatic alignment of parallel robot with a payload of @5kg can be useful for many applications.

Keywords: Simscape. PS-Simulink, Stewart Platform, MATLAB Sim-Mechanics

1. Introduction
The Stewart platform (SP) has been a popular research topic in robotics since its first appearance on the scientific agenda in 1965 in the renowned work by Stewart. Many publications concerning its kinematics, dynamics, work space estimation, path planning and force sensing applications have been published since the time of Stewart’s original publication.

Stewart [3] “describes a mechanism, which has six degrees of freedom (DOF) controlled in any combination by six motors each having a ground abutment”. Stewart platform which is parallel link manipulator is used as a flight simulator to train the helicopter pilots.

Lee ,Shah and Denavit and Hartenberg [1,2] developed Kinematic equations for parallel manipulator . Artificial Neural Network (ANN) Algorithm for solution of inverse kinematics of hexapod is devised by many researchers [4-7].The authors [8] briefly studied various methods used for deformity correction for automatic bone alignment. Morishita and Tojo [9] used fuzzy logic method for inverse kinematic analysis of multi joint robot manipulator. Many researchers simulated series robots using MATLAB driven inverse kinematic analysis to obtain desired trajectory [14, 15, 16]. Inverse and forward kinematic solution of robot manipulator is also described [10, 11, 13]. Chiddarwar and Babu proposed Artificial neural network model for inverse kinematics of serial manipulator[12].Author proposed adapted PSO algorithm for inverse kinematic solution to medical robot which is used for fracture treatment .Author tested on medical robot and results are compared with made classical PSO
Arockia and Arulp - performed kinematic analysis of tri-Glide and tripod parallel manipulator and experimental results are verified using ADAMS. This research work presents an approach to understand and realize motion of real and it through several electric actuators. Designing of fixture using rotary actuators and observations of simulation of fixture in MATLAB has been discussed in details. The fixture movement is obtained by controlling of different degrees of freedom of the module, precise linear as well as rotary motion. The motor position controller for every degree of freedom and enhanced real time control of each module achieves synchronised motion for desired movements. Solid model is imported in MATLAB function block, using inverse kinematic equation, desired rotation of motor is carried out which is useful in desired motion of top plate. Using Simulink-PS converter block physical signal which is used as input to plot the graph. This signal was using Scope Block and the graph of position, velocity, acceleration & torque vs time is obtained for 3 simulations of top plate namely A) linear motion along X, Y, Z axis. B) Yaw and C) along an inclined plane.

2. Inverse Kinematics for the Customised Stewart platform (fixture).

The purpose of inverse kinematics is to determine six leg lengths with respect to the position and the orientation of the moving frame.

**Kinematics:**
The precise locations of the actuator frames Bi and top platform frames Pi were obtained through CAD software and later through external measurements using Coordinate Measuring Machine (CMM).

The position vector of the \( i \)th joint on the top platform with respect to the \( i \)th actuator frame is given by

\[
L_i = t + R_o . (p_i) - b_i
\]

\( R_o \) is the combined rotation matrix of the moving frame with respect to the bottom fix frame. \( O(X, Y, Z) \).

\[
R_o = R_x(\theta_3) . R_y(\theta) . R_z(\psi)
\]

\[
\theta_3 = \sin^{-1} \frac{x_i}{a_2} \text{ and } a_2' = a_2 \cos \theta_3
\]
\[ \theta_2 = \cos^{-1} \left[ \frac{y_i^2 + z_i^2 - (a_1^2 + a_2^2)}{2a_1a_2} \right] \]  

(4)

\[ \phi = \tan^{-1} \frac{a_2 \sin \theta_2}{a_1 + a_2 \cos \theta_2} \]  

(5)

\[ y_i = A \left[ \cos \phi \cos \theta_1 - \sin \phi \sin \theta_1 \right] = A \cos (\theta_1 + \phi) \]  

(6)

\[ \theta_1 = \cos^{-1} \left( \frac{y_i}{A} - \phi \right) \]  

(7)

Using equation (7) the final solution for joint angle of the \( i^{th} \) actuator was obtained. On successive evaluations of the top frame locations \( P_i \) for any given pose of the moving platform and base frame locations \( B_i \), the joint angles of of all the active joint actuators for \( I = 1, 2, 3, 4, 5, \) and 6 were obtained

3. Design Constraints

3.1. Space constraints

4. The robot should not exceed the dimension 300mm \( \times 300mm \times 300mm \) and should not be less than the dimension 50mm \( \times 50mm \times 50mm \).

These dimension limits are selected considering the following points:

1. All kinds of degrees of motion those are possible by a fixture. To acquire this dimension constraints are necessary.
2. It should be easy to move the top plate from one place to another.
3. It should be easy to handle (operate).

3.2 Weight Constraints

The robot module should not be more than 5kg. This weight limit is considering the following points:

1. It should be moderately portable.
2. Its motors should sustain its load

| Table 1. Weight of components of Customized Stewart Platform (fixture) |
|---------------------------------------------------------------|
| **Top Platform** | **Weight in kg** |
| Motors           | 1               |
| Crank with pin   | 0.9             |
| Connecting Rod   | 0.3             |
| Bottom Platform  | 0.4             |
| Top Platform     | 1.1             |

4. Basic Structure of the Robot

The robot is basically motor operated robot with a cluster of modules. The main components that will be used for making this robot are Servo motors for each degree of freedom in motion.

Some other design considerations are:

1. It should be able to communicate with other modules without using external input device.
2. It should be environment friendly and also able to avoid danger and obstacle.
The actual model and the designed model have components of same mass and the centre of gravity is located at the same location of actual model and designed model. It has same link lengths and same spherical joints.

Figure 2: solid model of Customized Stewart platform for MATLAB Simulink (Sim-Mechanics)

5. SimMechanics

5.1. MATLAB function block.
MATLAB function block helps in getting the desired output by processing the inputs given by the user by interpreting the equations written in the block. The equations of inverse kinematics are coded in the MATLAB function block and produced the desired output of rotation of the motors. This output was then used to get the desired motion of the platform.
Interfacing the output given by the MATLAB function block with the input of the platform.
This output was given as the actuation to the revolute joint between the motor and the crank.
The output was converted in the Physical signal by using Simulink-PS converter block and then was provided as input. The output from the revolute joint was converted into Simulink signal using PS-Simulink converter block.
This signal was then traced using Scope Block and the graphs of Position, Velocity, Acceleration, actuator Torque against Time was obtained.
The Simulation was then run in the Mechanics explorer.
Following 3 simulations are carried out:
1-Top plate moving in linear motion along X, Y, Z axis.
2-Top plate rotating and moving in linear direction(yaw)
3-Top plate moving along an inclined plane.
5.2. Plant model of Stewart Platform using SimMechanics

Simulink is a graphical programming environment developed by Mathwork. It is widely used in automatic control and digital signal processing for multidomain simulation and Model-Based Design.
Using MATLAB Simulink [18] plant model of fixture (customised Stewart Platform) created as shown in Figure 6.

![Plant model of Stewart Platform using SimMechanics](image)

**Figure 6:** Plant model of Stewart Platform using SimMechanics

### 6. Analysis of motion of Stewart’s Platform

Graphs of position, velocity acceleration and torque versus time are plot. They are as follows Mat lab Simulation results- (GRAPHS)

| Graph 1: Angular displacement of Customized Stewart platform(fixture) |
|---------------------------------------------------------------|
| ![Graph 1](image)                                              |

| Graph 2: Angular velocity of Customized Stewart platform(fixture) |
|----------------------------------------------------------------|
| ![Graph 2](image)                                              |

| Graph 3: Angular acceleration of Customized Stewart platform(fixture) |
|---------------------------------------------------------------|
| ![Graph 3](image)                                              |

| Graph 4: Angular torque of Customized Stewart platform (fixture) |
|----------------------------------------------------------------|
| ![Graph 4](image)                                              |
Graph Analysis of graph

| Graph | Analysis of graph |
|-------|-------------------|
| Graph 1: Angular displacement Customised Stewart platform (fixture) | It is a shifted sine curve. The maximum displacement of shaft from its zero position is 1 radian, in clockwise direction. |
| Graph 2: Angular velocity of Customised Stewart platform (fixture) | It is sine curve. The maximum velocity of shaft from its zero position is 5 rad/sec. |
| Graph 3: Angular acceleration of Customised Stewart platform (fixture) | The maximum acceleration of shaft from its zero position is 8 rad/sec². |
| Graph 4: Angular torque of the Customised Stewart platform (fixture) | The maximum torque for shaft from its zero position is 0.03 Nm. |
| Graph 5: Angular displacement of Customised Stewart platform (fixture) | It is a shifted sine curve. The maximum displacement of shaft from its zero position is 1.2 radian, in clockwise direction. |
| Graph 6: Angular velocity of Customised Stewart platform (fixture) | It is sine curve. The maximum velocity of shaft from its zero position is 5 rad/sec. |
| Graph 7: Angular acceleration of Customised Stewart platform (fixture) | The maximum acceleration of shaft from its zero position is 6 rad/sec². |
| Graph 8: Angular torque of the Customised Stewart platform (fixture) | The maximum torque for shaft from its zero position is 0.045 Nm. |

The same curve is traced by all the motors when alternate motors moving in clockwise and remaining alternate in counter-clockwise direction. Above graphs are obtained for Top plate moving in linear motion along X, Y, Z axis.
The same curve is traced by all the motors when alternate motors moving in clockwise and remaining alternate in counter-clockwise direction. Above graphs are obtained for Top plate rotating and moving in linear direction (yaw).

| Graph | Analysis of graph |
|-------|-------------------|
| Graph 9: Angular displacement of Customised Stewart platform (fixture) | The Top Platform is slowly coming downwards. |
| Graph 10: Angular acceleration of Customised Stewart platform (fixture) | The maximum acceleration of shaft from its zero position is \(0.175 \text{ rad/sec}^2\). |
| Graph 11: Angular displacement of Customised Stewart platform (fixture) | The displacement of shaft from its zero position is increasing. The same curve is traced by all the motors when alternate motors moving in clockwise and remaining alternate in counter-clockwise direction. |
7. Results and Discussions

This paper aims at designing of fixator using rotary actuators and simulation of fixator in MATLAB. It consists of controlling of different degrees of freedom of the module, precise linear as well as serpentine motion and motor position controller for every degree of freedom and enhanced real time control of each module in assistance with feedback from proximity/visual sensory system.

To obtain linear movement in x, y, z axis in both direction (positive & negative direction), sine wave is used as an input for angular displacement and angular velocity. [9] Amplitude of displacement is 0.5 rad. Therefore, maximum velocity amplitude is 0.5 rad/sec.

Software mathematical operation on given input to obtained required output i.e. acceleration & torque. From graph no. 3 & graph no.4 it is observed that maximum angular acceleration is +0.8 rad/sec$^2$. Also from graph no.4 maximum angular torque is +0.03 N-m & minimum angular torque is -0.03 N-m. Therefore, the optimum torque is 0.025Nm.

This paper focuses designing of fixture using rotary actuators and simulation of Stewart Platform in MATLAB, fixture consists of controlling of different degrees of freedom of the module, precise linear as well as rotary motion and motor position controller for every degree of freedom and enhanced real time control of each module for inverse kinematic analysis of a fixture Sim-mechanics of MATLAB.

8. Conclusions

In this work, modified 6-DOF parallel manipulator with rotary actuator which is designed for effective scheduled micro movement of all possible alignments, has been discussed. This work, based on inverse kinematics, will provide a baseline for determining the six leg lengths corresponding to the position and the orientation of the moving platform. The simulation of Stewart platform and designing of the rotary actuator assisted fixture is also discussed. Simulink module of the MATLAB software is used for completing simulation while estimating maximum angular displacement, velocity along angular acceleration and torque. The maximum values obtained for displacement, velocity and acceleration using simulation are 0.5 rad, 0.5 rad/sec and 0.8 rad/sec$^2$. The maximum and minimum values of angular torque are in the range of ±0.03 N-m.

Therefore this simulation predicting the working range of fixture can be helpful for various applications related to fine alignment in all possible directions.

References

[1] Lee K M and Shah D K. 1998. Kinematic analysis of a three-degree-of-freedom in-parallel actuated manipulator. *IEEE Journal of Robotics and Automation; 4*:354-60.

[2] Denavit J and Hartenberg R S. 1955. A kinematic notation for lower-pair mechanisms based on matrices. *Transaction of ASME Journal of Applied Mechanics; 22*: 215-21.

[3] Hostens I, Anthonis J and H Ramon. 2005. New design for a 6 dof vibration simulator with improved reliability and performance. *Mechanical Systems and Signal Processing; 19*, 1, (105):(2005).

[4] Cheng Y, Ren G and Liang Dai S. 2004. The multi-body system modeling of the Gough–Stewart platform for vibration control. *Journal of Sound and Vibration; 271*, (599):3-5.

[5] Navvabi H and Markazi A H D. 2018. New AFSMC Method for Nonlinear System with State-dependent Uncertainty: Application to Hexapod Robot Position Control. *Journal of Intelligent & Robotic Systems. 10.1007/s10846-018-0850-4*.

[6] Djukic D J, Zhukov Yu A, Korotkov E B, Moroz A V and Slobodzian N S. 2018. Hexapod digital control using the inverse dynamics and it implementation on the radiation-resistant arm-microcontroller. *Issues of radio electronics;7*:103-10.

[7] Zhukov Y A, Korotkov E B, Moroz A V, Zhukova V V and Abramov A M. 2018. A control of
hexapod based on the neural networks solution for forward kinematics. *IOP Conference Series: Materials Science and Engineering; 441*:1757-899.

[8] Aglawe P S, and Ohl S S.2020. Deformation correction methods for fracture bone alignment: an overview. *International Conference on Mechanical Engineering for Sustainable Development (ICMESD-2020); Feb 17-18, 2020*:466-71.

[9] Morishita T and Tojo O.2012. Integer inverse kinematics method using Fuzzy logic. *Intelligent Service Robotics, 6*:101-08.

[10] Wenjun L, Yufeng L, Tingli Y, Zhixing S and Meitao F.2010. Numerical study on inverse kinematic analysis of 5R serial robot. *International Forum on Information Technology and Applications (IFITA)*.

[11] Jha P and Biswal B B.2013. Inverse Kinematic Solution of Redundant Robot Manipulator using Artificial Neural Network. *Proceedings of International Conference on Advances in Mechanical Engineering ; May 29-31, 2013, COEP, Pune*.

[12] Chiddarwar S S and Babu N R.2010. Comparison of RBF and MLP neural networks to solve inverse kinematic problem for 6R serial robot by a fusion approach. *Engineering Applications of Artificial Intelligence; 23*: 1083–92.

[13] Jha P, Biswal B B, and Sahu O P.2015. Inverse kinematic solution of robot manipulator using hybrid neural network. *International Journal of Materials Science and Engineering; 3*: 31-38

[14] Wei W, Xin Z, Han Li-li, Min W and Zhong You-bo.2018. Inverse kinematics analysis of 6 – DOF Stewart platform based on homogeneous coordinate transformation. *Ferroelectrics; 522*:108-21.

[15] Zhukov Y A, Korotkov A B, Moroz A V, Zhukova V V and Abramov A M.2018. Adaptive neural network control of hexapod for aerospace application. *IOP Conf. Series: Materials Science and Engineering; 441*.doi:10.1088/1757-899X/441/1/012001 IOP Publishing.

[16] Sancaktar I, Tuna B, Ulutas M.2018. Inverse kinematics application on medical robot using adapted PSO method. *Engineering Science and Technology, an International Journal; 21*: 1006–10.

[17] Arockia S A and Arul K M.2014. Experimental investigation on position analysis of 3 – DOF parallel manipulators. *Procedia Engineering; 97*:1126 – 34.

[18] MathWorks. Simulink. [Online]. Available: https://en.wikipedia.org/wiki/Simulink